Rare Decays

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on behalf of the ATLAS, CMS & LHCb Collaborations

Imperial College London

LHCb

Introduction

- Virtual contributions from particles in loop processes → deviations that have often preceded the direct observation of new particles:
  - Suppression of $K^0 \to \mu\mu$ → GIM mechanism (charm quark)
  - B-$\bar{B}$ oscillations → heavy top quark
  - $B(B^0 \to K^{*0}\gamma)$ → indirect evidence top quark (and nothing else)
  - …

- Theoretical basis : The Operator Product Expansion

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

"Wilson Coefficients" C_i

"Operators" O_i

→ **Form a complete basis – can put in all operators from NP/SM**

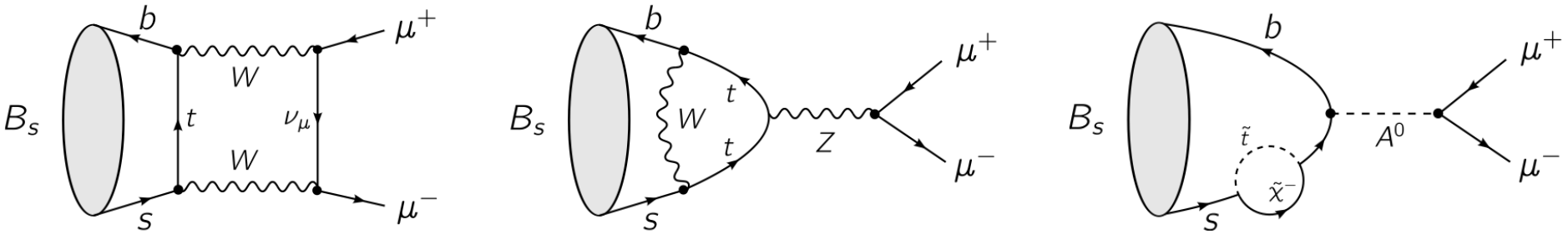
- In *certain* observables the uncertainties on the operators cancel out – measuring the Wilson Coefficients tells us about the heavy degrees of freedom – *independent of model*

Outline

- An extended Higgs sector? ($B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$)
- New particles, vector (axial-) couplings?
  - Angular analysis of the decay $B^0 \to K^{*0}\mu\mu$
  - Isospin Asymmetry in $B \to K^{(*)}\mu^+\mu^-$ decays
- New sterile Majorana neutrinos? ($B^+ \to h^-\mu^+\mu^+$)
- Lepton flavour violation? ($\tau \to \mu\mu\mu$)

The decays $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$

- The branching ratios of the decays $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ allow the parameters of any extended Higgs sector to be probed



- The decays are doubly suppressed in the SM
  - Flavour Changing Neutral Currents
  - Helicity suppression

  However, rates well calculable – in the SM,

  $B(B_s^0 \to \mu^+\mu^-) = 1.1 \times (3.2 \pm 0.2) \times 10^{-9}$

  [*Buras et al., arXiv:1007.5291*
  De Bruyin et al., *arXiv:*1204.1735]

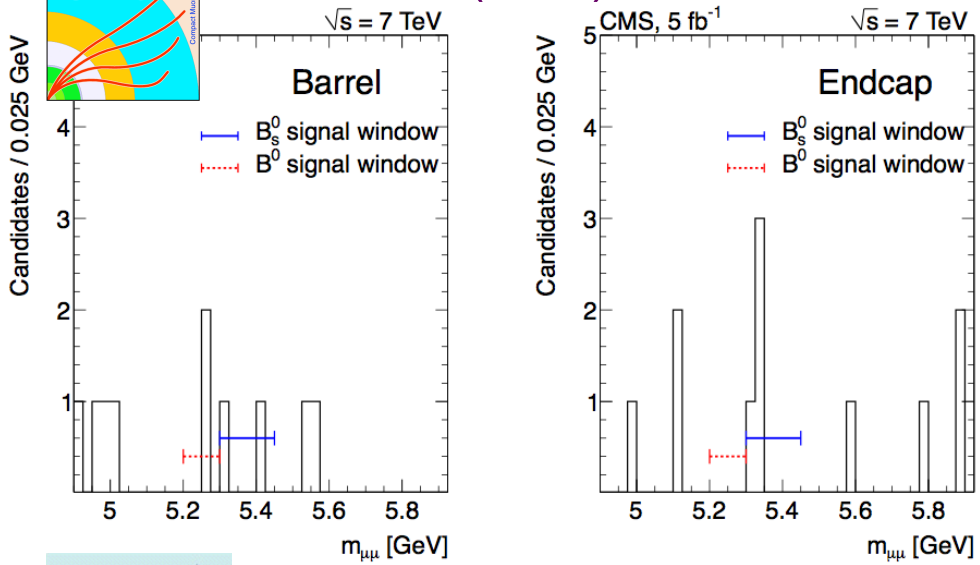
- Sensitive to NP contributions in the scalar/pseudo-scalar sector:

$$\left(C_{S,P}^{MSSM} \right)^2 \propto \left(\frac{m_b m_\mu \tan^3 \beta}{M_A^2} \right)^2$$

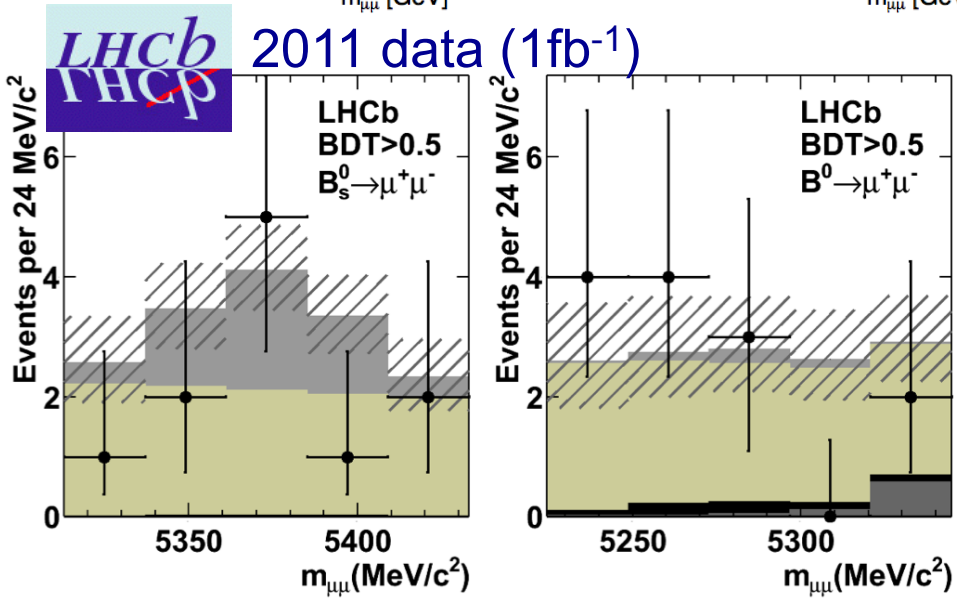
MSSM, large tanβ approximation

Latest Experimental Results

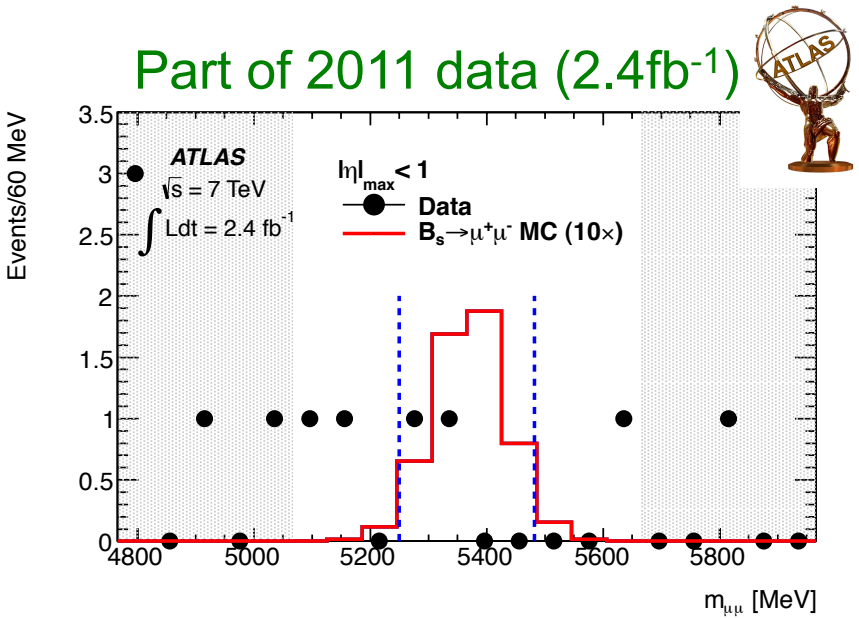
2011 data (5fb^{-1})



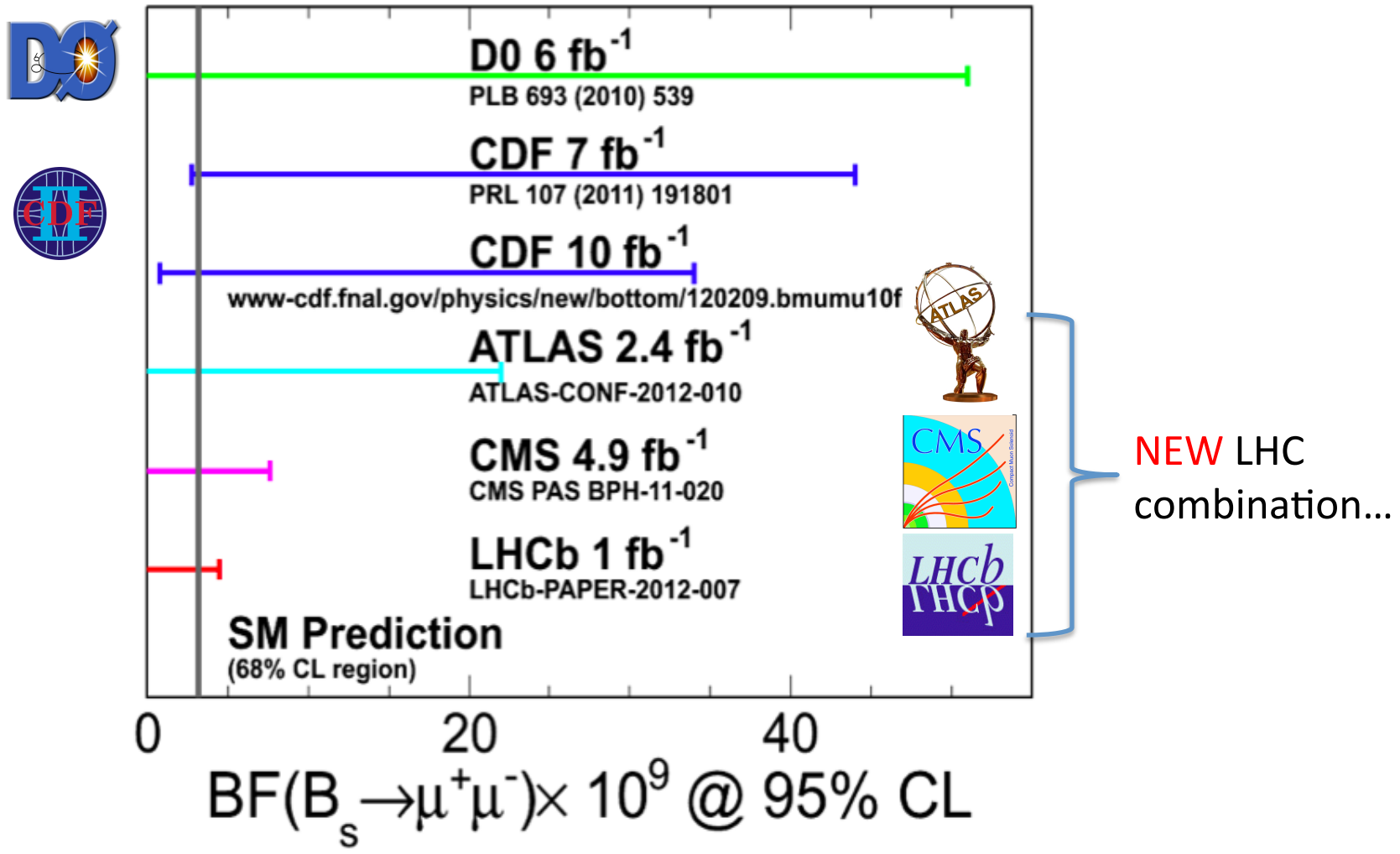
2011 data (1fb^{-1})



Part of 2011 data (2.4fb^{-1})



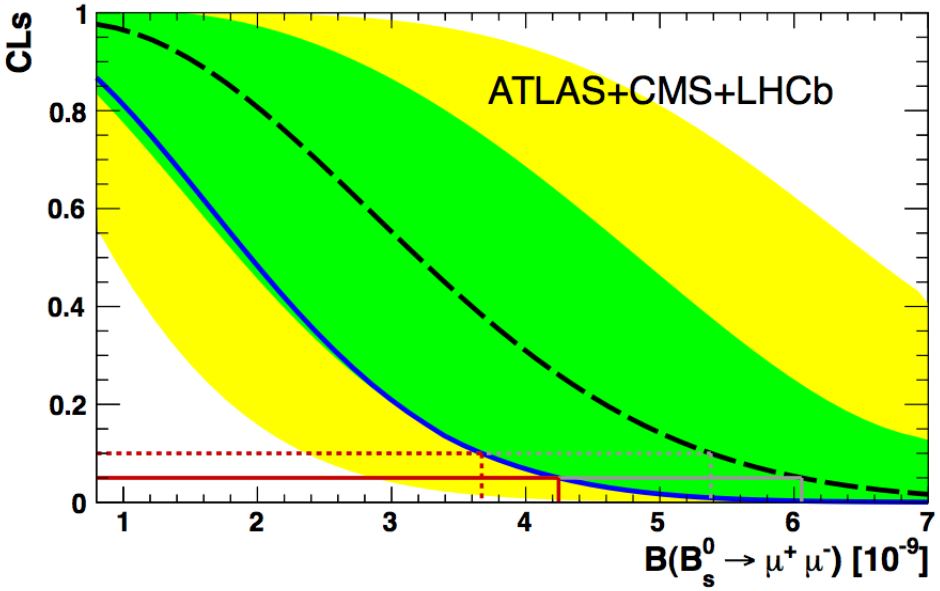
Experimental Status



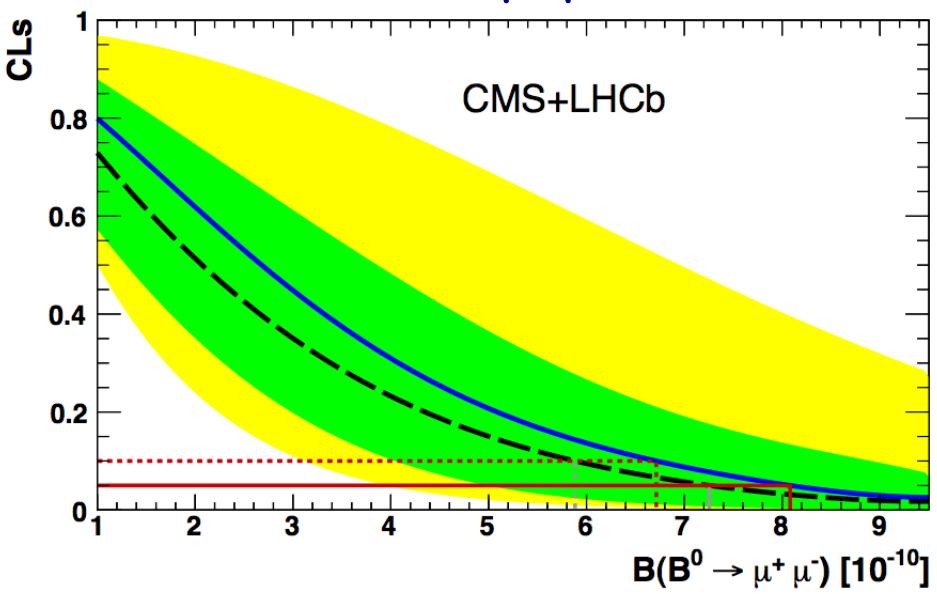
LHC Combination

- (NEW) ATLAS, CMS and LHCb results have now been combined:
  BPH-12-009 ATLAS-CONF-2012-061 LHCb-CONF-2012-017

$B_s^0 \to \mu^+\mu^-$



$B^0 \to \mu^+\mu^-$



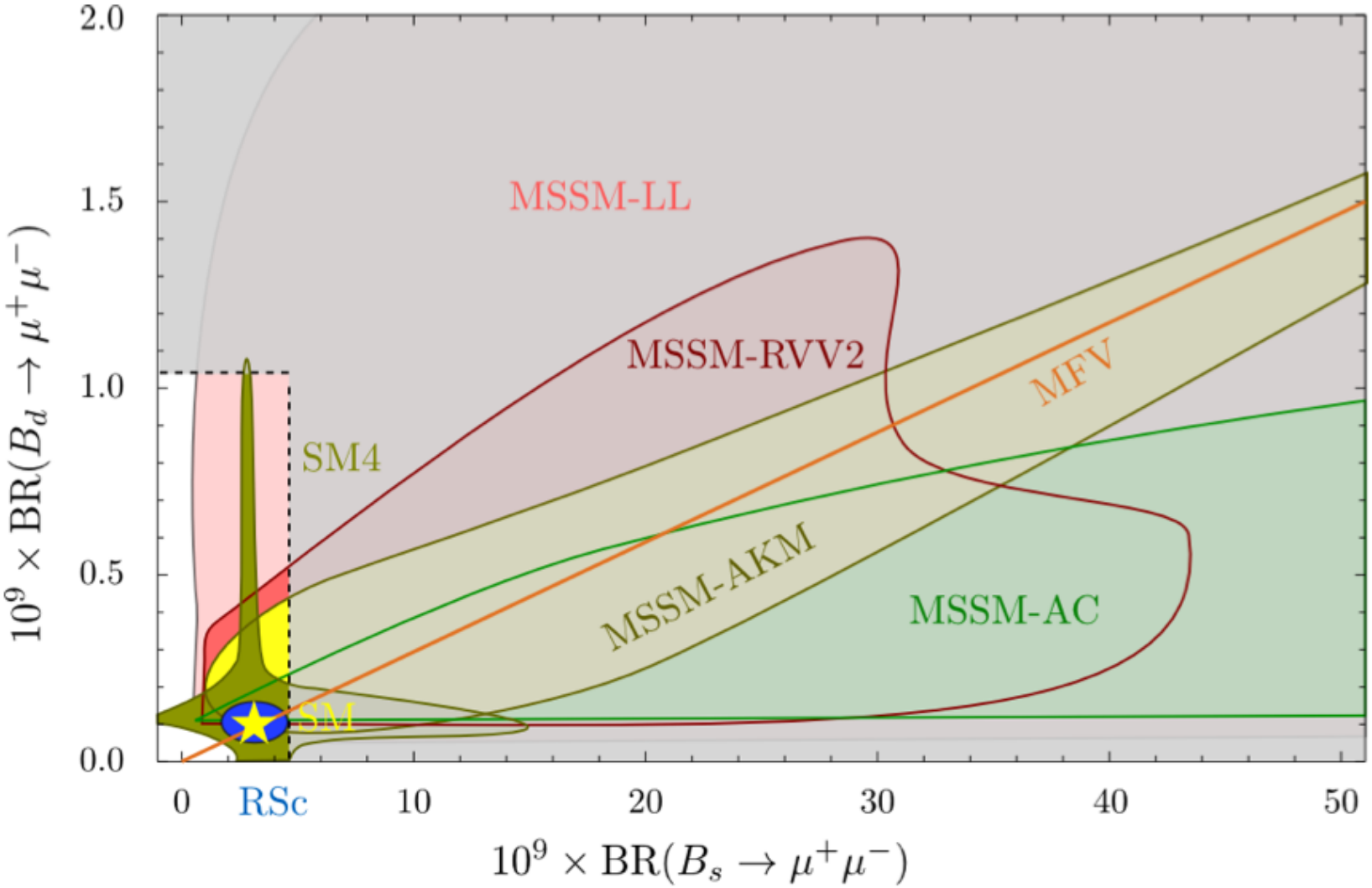
$B(B_s^0 \to \mu\mu) < (3.7\ (4.2)) \times 10^{-9}$ at 90(95) % C.L.

- Excess over background at ~2σ level (1-CL_b (p-value)=5%)
- Compatible with SM at 1σ (1-CL_{s+b}=84%)

$B(B^0 \to \mu\mu) < (0.67\ (0.81)) \times 10^{-9}$ at 90(95) % C.L.

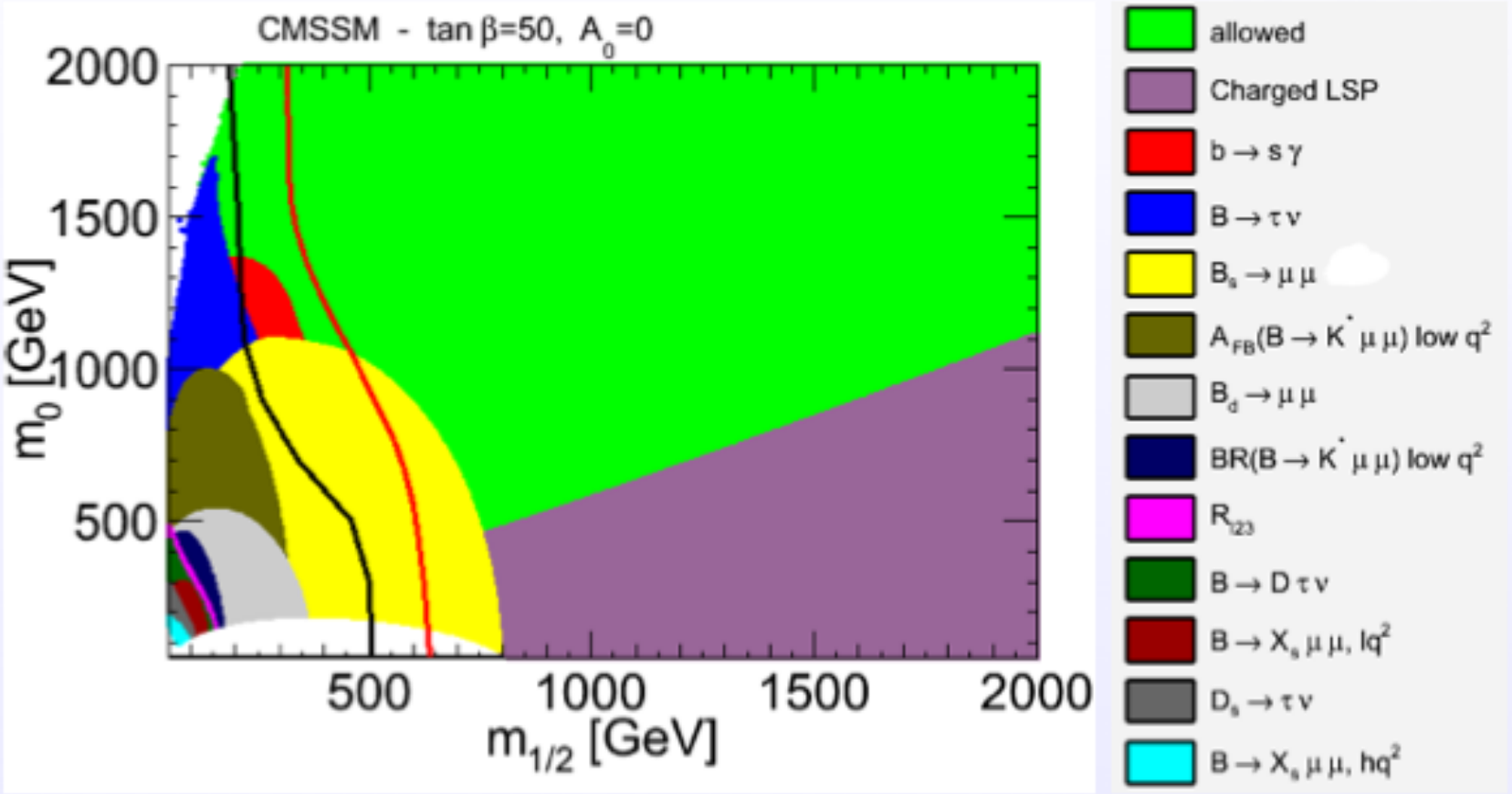
Impact

From [arXiv:1205.6094]



Impact

- From [arXiv:1108.3018v2]



Black line: CMS exclusion limit with 1.1 fb^{-1} data
Red line: CMS exclusion limit with 4.4 fb^{-1} data

Impact

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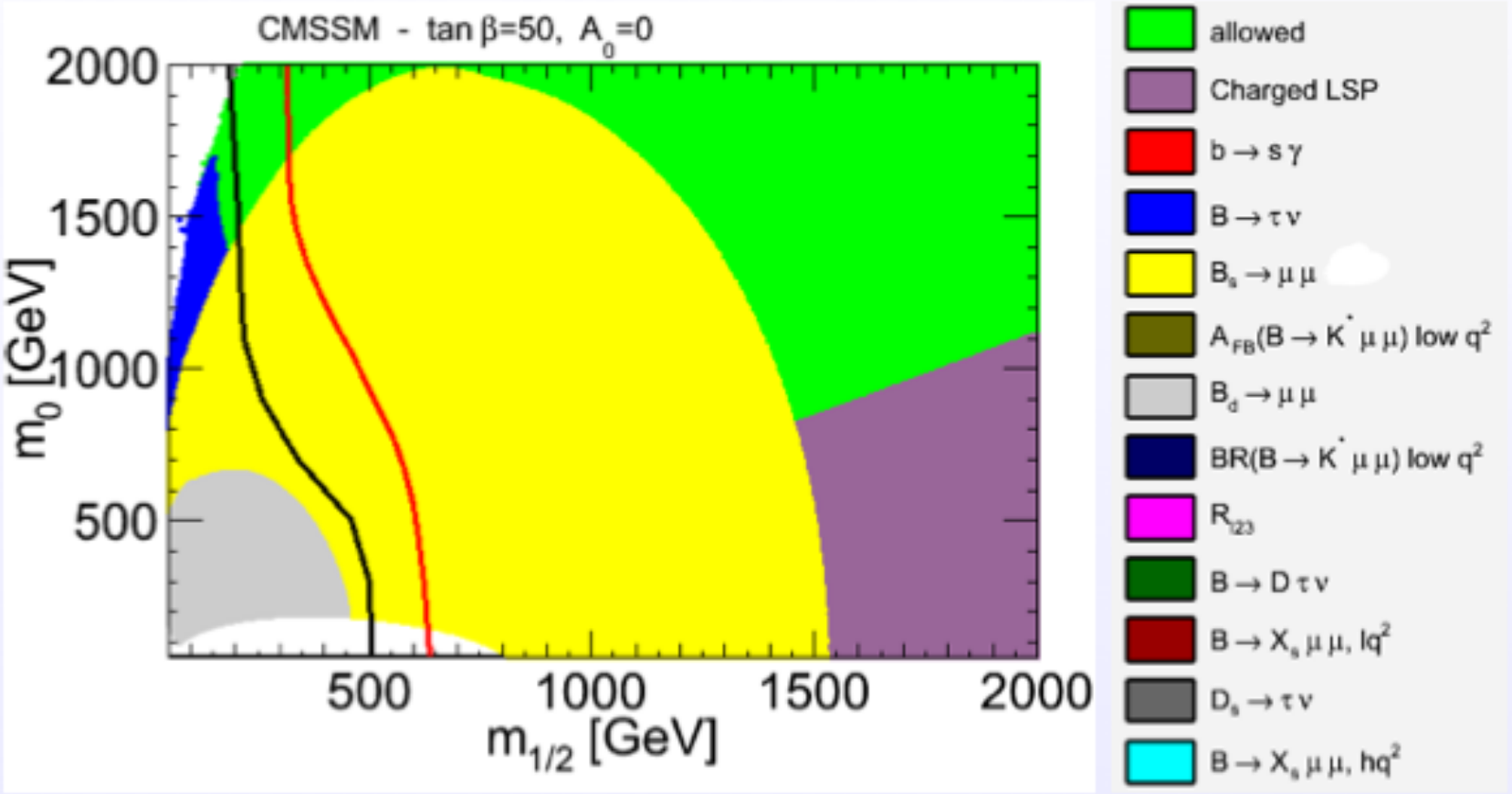
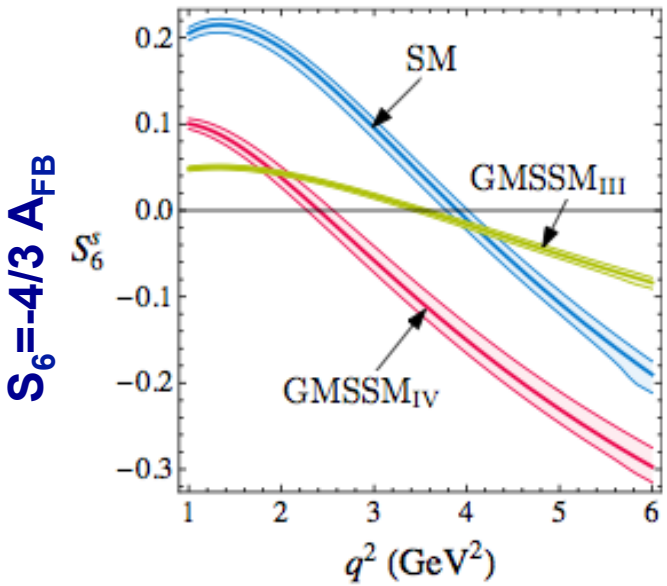


Black line: CMS exclusion limit with 1.1 fb^{-1} data
Red line: CMS exclusion limit with 4.4 fb^{-1} data
New LHCb limits for BR($B_s \to \mu^+\mu^-$) and BR($B_d \to \mu^+\mu^-$)

The interest in $B^0 \to K^{*0}\mu\mu$

- Flavour changing neutral current → loop
- Highly sensitive to NP contributions to $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$
- $K^{*0} \to K\pi$: self-tagging – angular analysis allows to probe helicity structure

[arXiv:0801.1214]

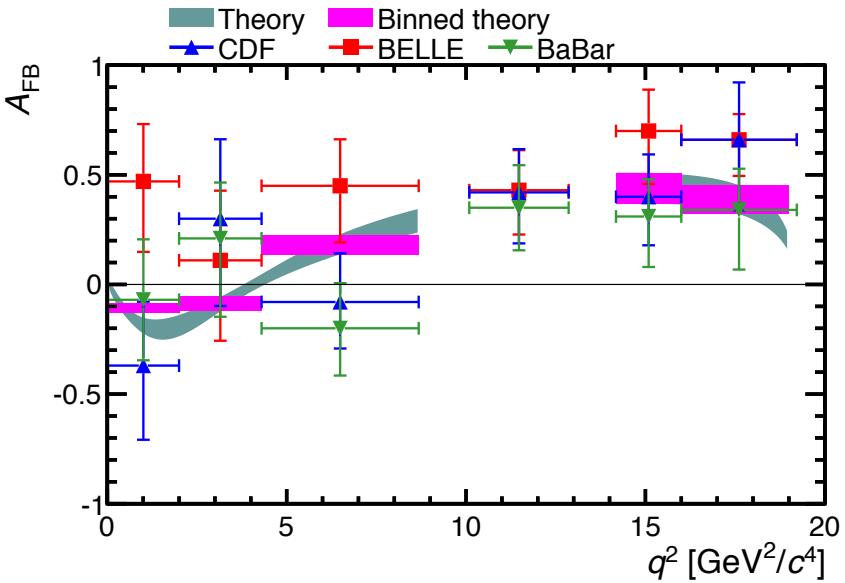


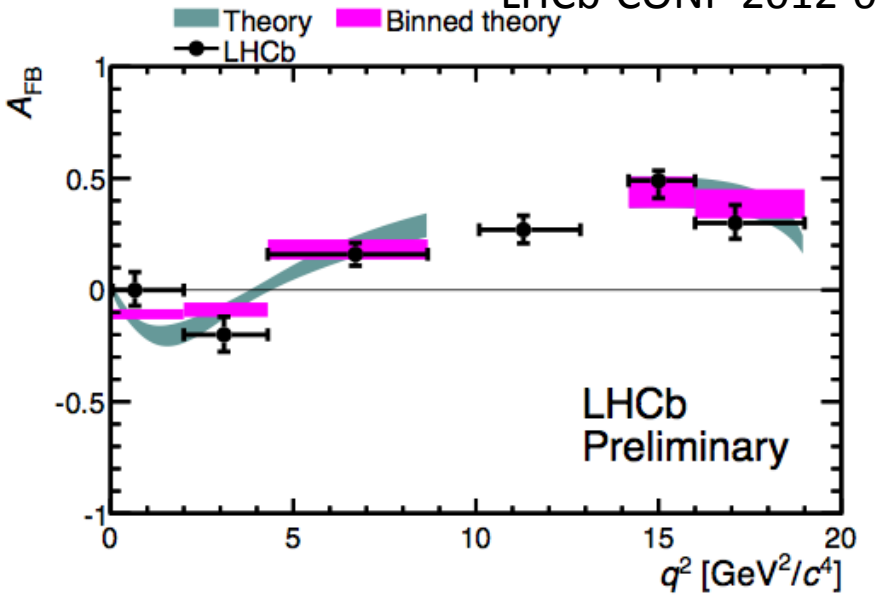
- Can measure a number of angular observables where the hadronic uncertainties are under control
  - A_{FB}, the forward-backward asymmetry – and zero-crossing point (asymmetry in number of muons that go forward, backward)
  - F_L, the fraction of K^{*0} longitudinal polarisation
  - $S_3 \propto A^2_T(1-F_L)$, the asymmetry in K^{*0} transverse polarisation

Angular Analysis Results : A_{FB}

- (Pre-LHC) measurements of ang. asymm. A_{FB} but errors are such that there is no real discrimination between models

LHCb-CONF-2012-008





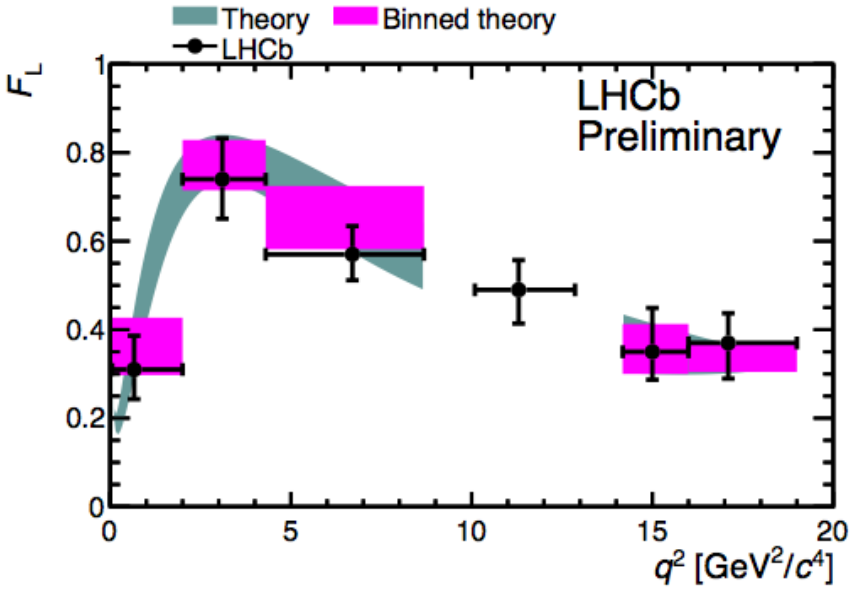
- LHCb measurements are the most precise to-date – completely consistent with the SM prediction
- Also make worlds first measurement of zero-crossing point q_0^2, at $q_0^2 = 4.9^{+1.1}_{-1.3}$ GeV^2/c^4 – again completely consistent with SM

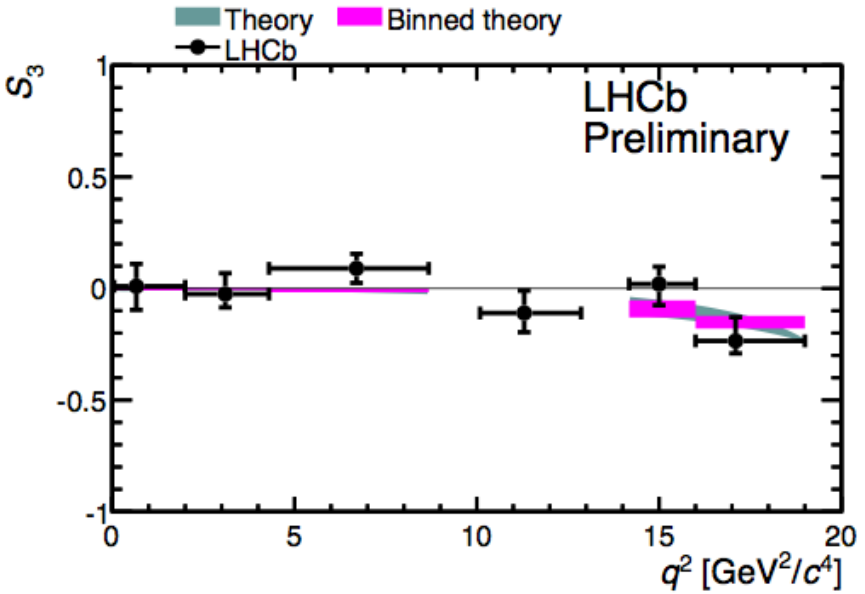
Theory prediction from C. Bobeth et al. [arXiv:1105.0376] (and ref. therein)

Angular Analysis Results : S_3, F_L

- Other observables show similarly spectacular agreement with SM predictions, again most precise measurements to-date

LHCb-CONF-2012-008





- F_L, the fraction of K^{*0} longitudinal polarisation
- $S_3 \propto A^2_T(1-F_L)$, the asymmetry in K^{*0} transverse polarisation

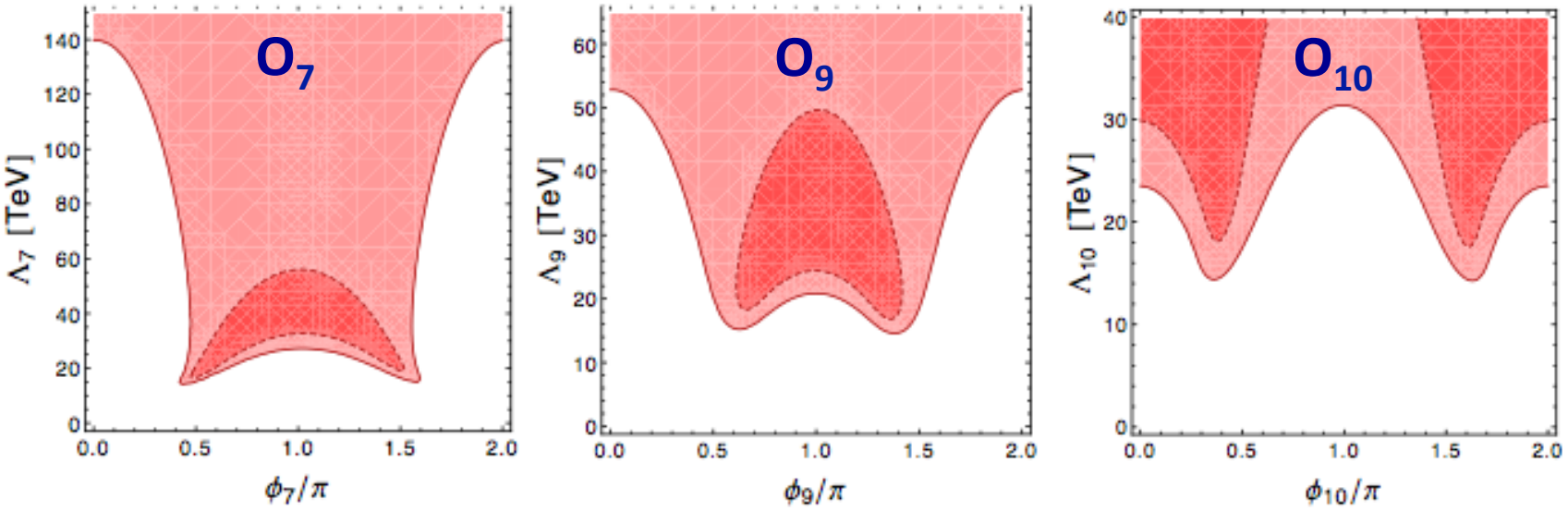
Impact – with tree level FV

From arXiv:1111.1257, JHEP 1202:106

Results can be interpreted as bounds on the scale of new physics:

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_{j=7,9,10} \frac{e^{i\phi_j}}{\Lambda_j^2} \mathcal{O}_j$$

~tree level generic flavour violation



– With coupling O(1) → NP at mass scales > O(15 TeV) – O(140 TeV)

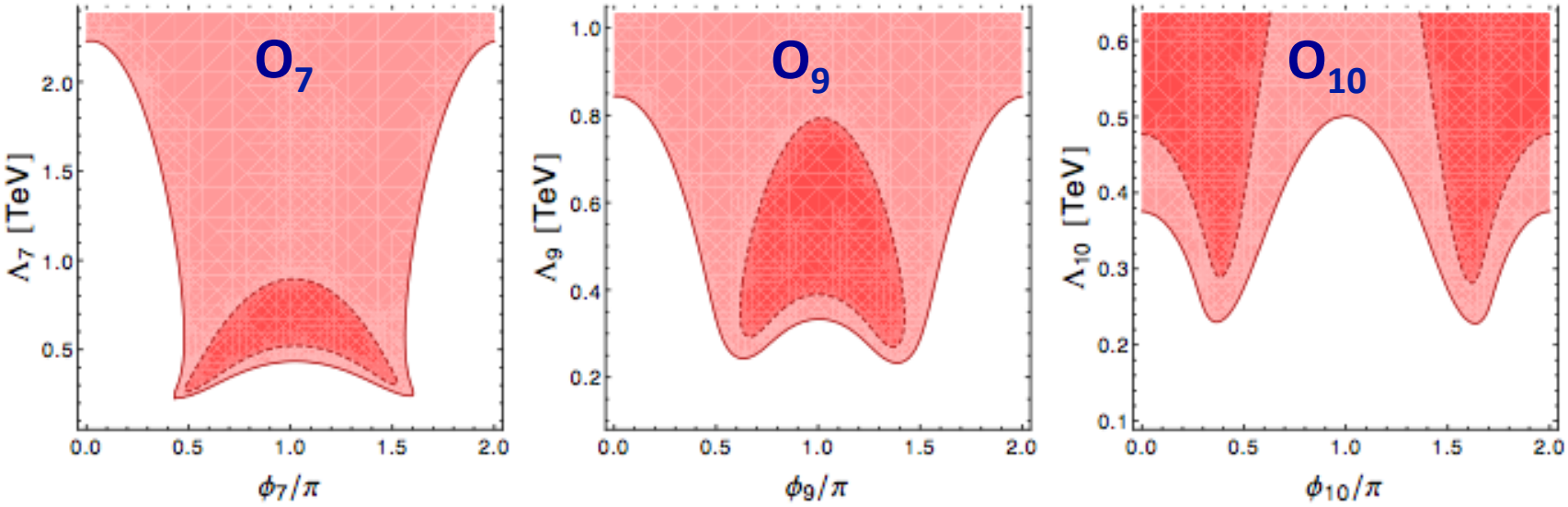
Impact – with loop CKM-like FV

From arXiv:1111.1257, JHEP 1202:106

Results can be interpreted as bounds on the scale of new physics:

$$\mathscr{L} = \mathscr{L}_{SM} - \sum_{j=7,9,10} \frac{V_{tb}V_{ts}^*}{16\pi^2} \frac{e^{i\phi_j}}{\Lambda_j^2} \mathcal{O}_j$$

~loop level CKM-like flavour violation



– With coupling O(loop, CKM supn) → NP at > O(0.3 TeV) – O(2 TeV)

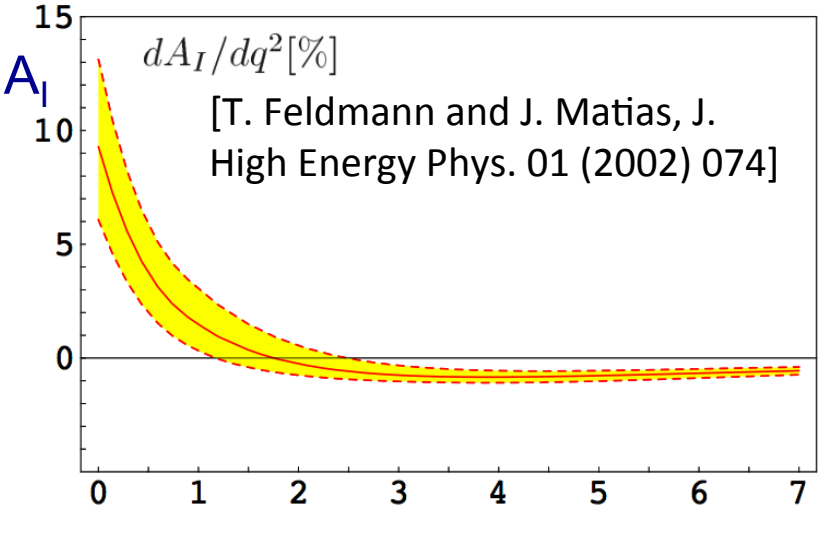
Isospin Asymmetry in $B \to K^{(*)}\mu^+\mu^-$

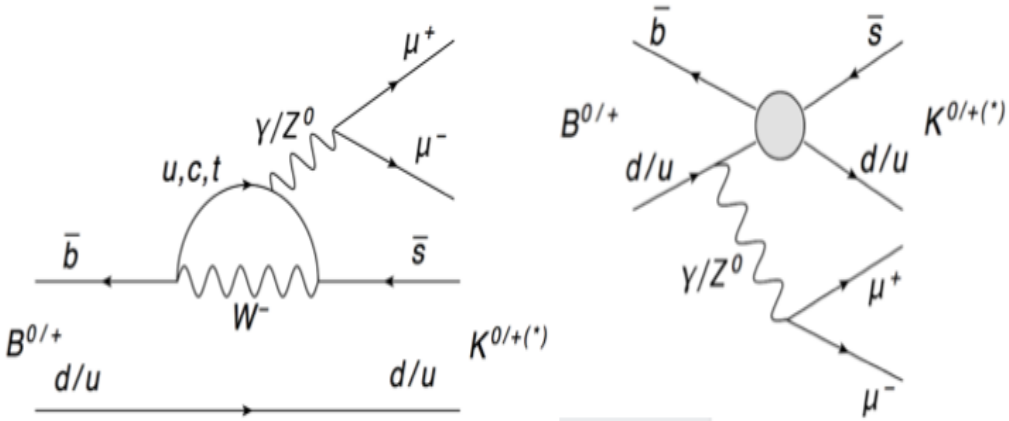
- The isospin asymmetry of $B \to K^{(*)}\mu^+\mu^-$, A_I is defined as:

$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}$$

can be more precisely predicted than the branching fractions

- A_I is expected to be very close to zero in the SM e.g. for $B \to K^*\mu^+\mu^-$:



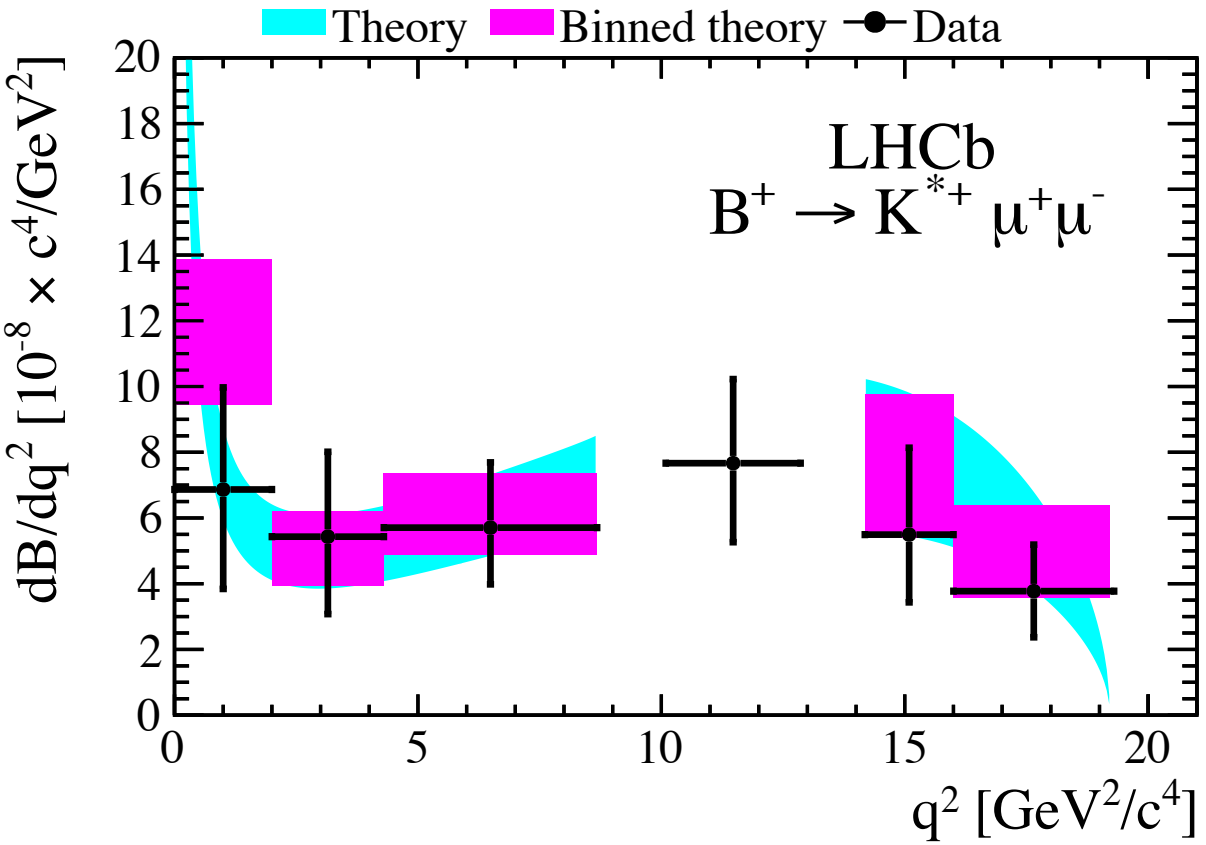


- A_I=(5.2±2.6)% has been measured in $K^*\gamma$ decay modes, agrees with SM

$dBF/q^2(B^+ \to K^{*+}\mu^+\mu^-)$

- Measurements are consistent with the SM :

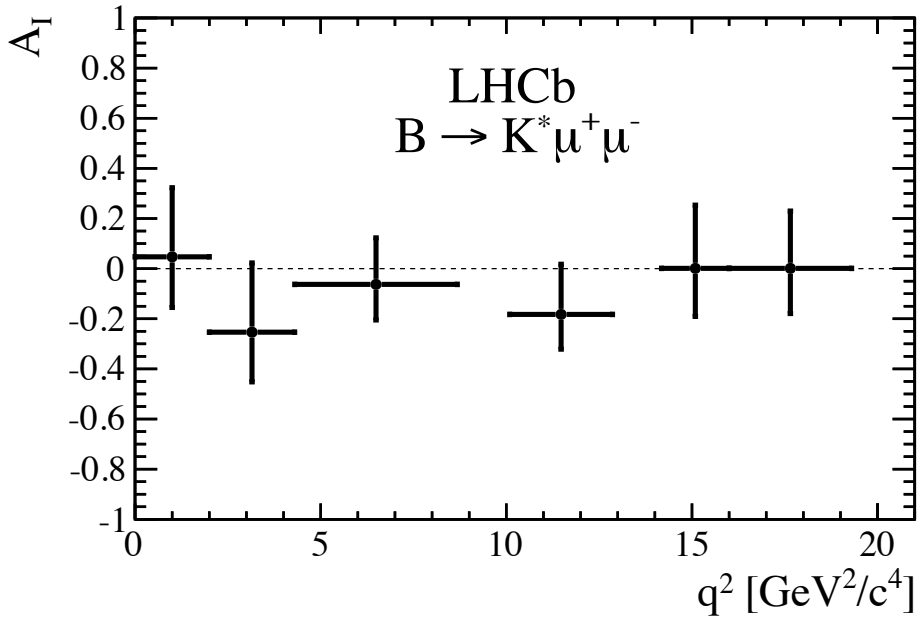
[LHCb-PAPER-2012-011]

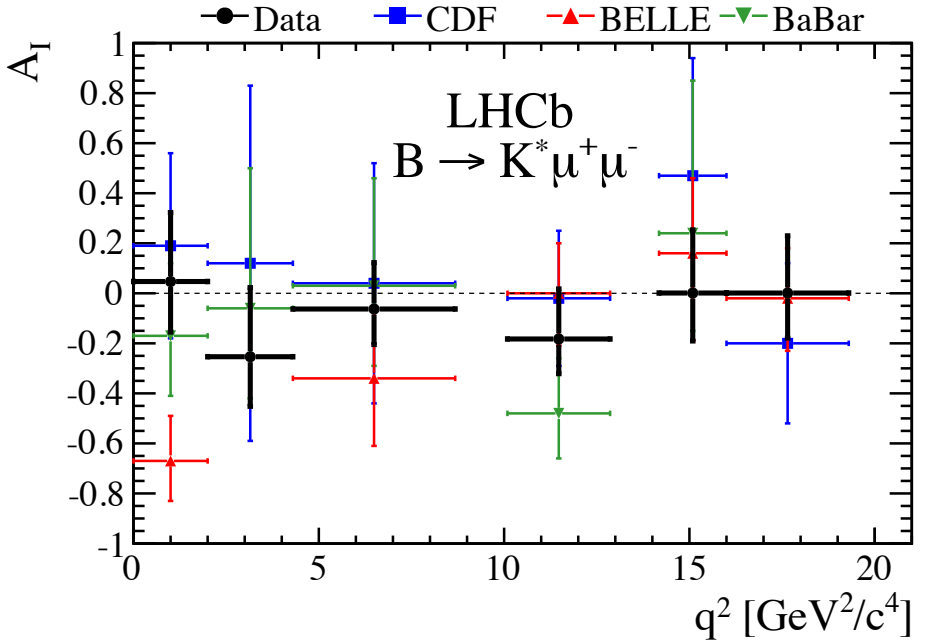


Theory prediction from [C. Bobeth, G. Hiller, and D. van Dyk, JHEP (2011) 067, arXiv:1105.0376]

A_I for $B \to K^* \mu^+ \mu^-$

- A_I for $B \to K^* \mu^+ \mu^-$ is consistent with zero, as predicted by the SM
- LHCb results in agreement with previous measurements



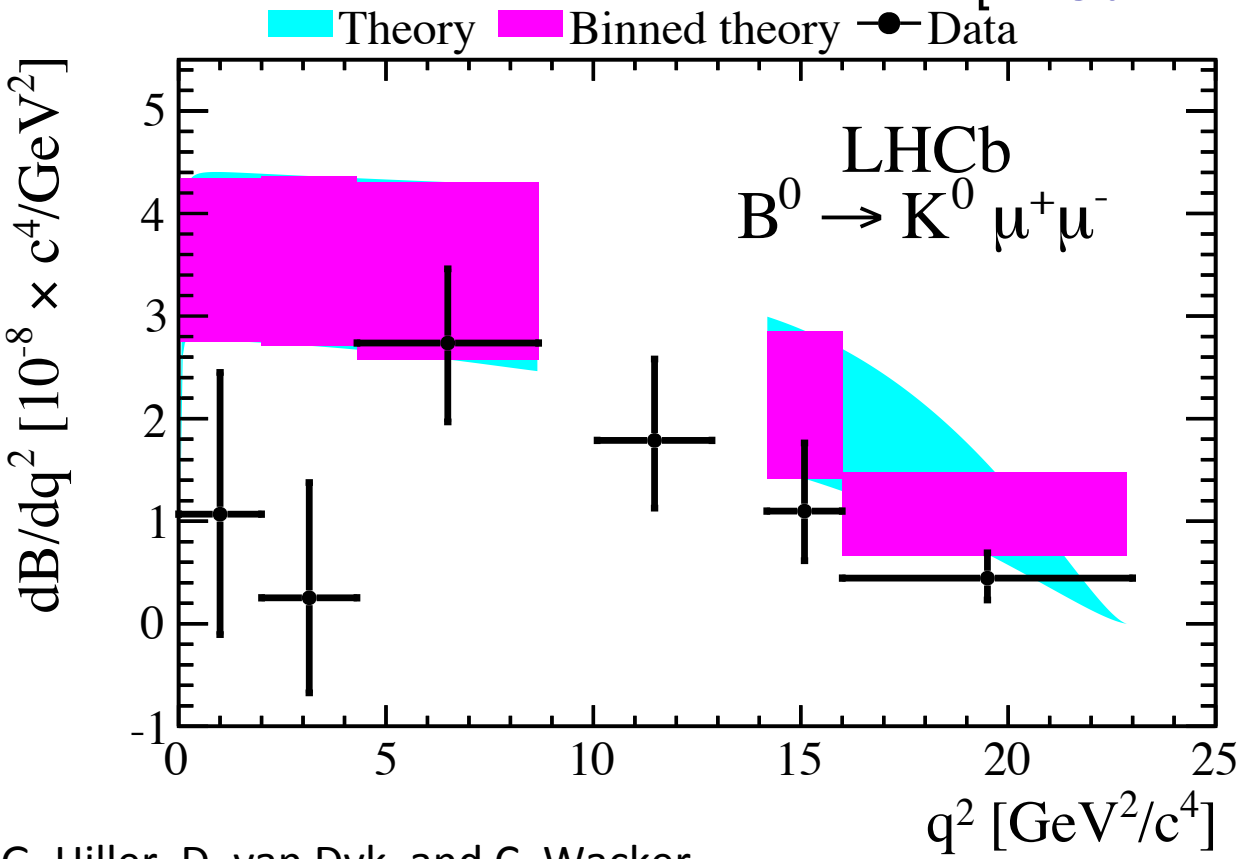


[LHCb-PAPER-2012-011]

$dBF/q^2(B^0 \to K^0 \mu^+ \mu^-)$

- There is a deficit of $B^0 \to K^0 \mu^+ \mu^-$ signal, particularly in the q^2 regions which are not adjacent to the charmonium resonances

[LHCb-PAPER-2012-011]

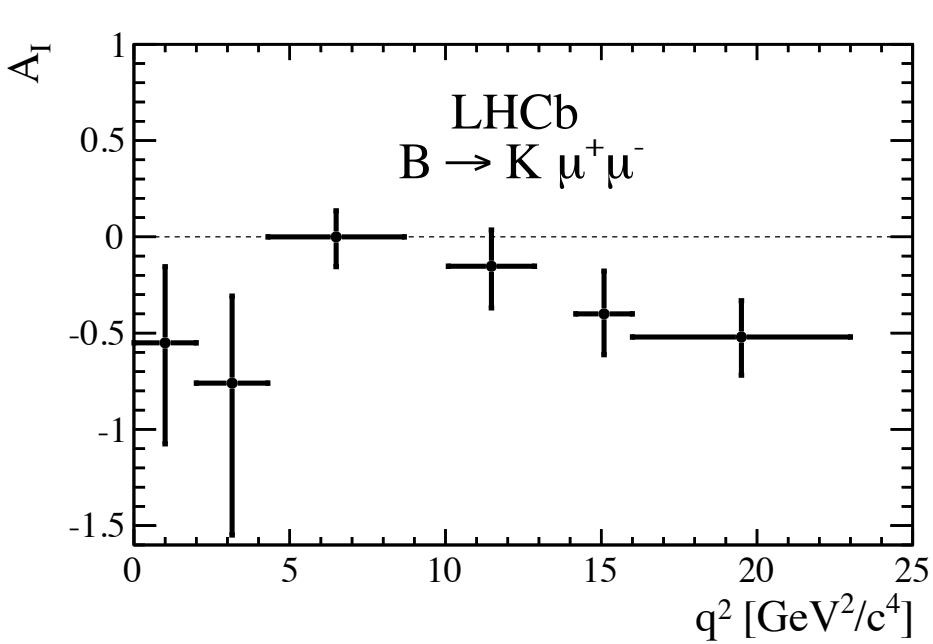


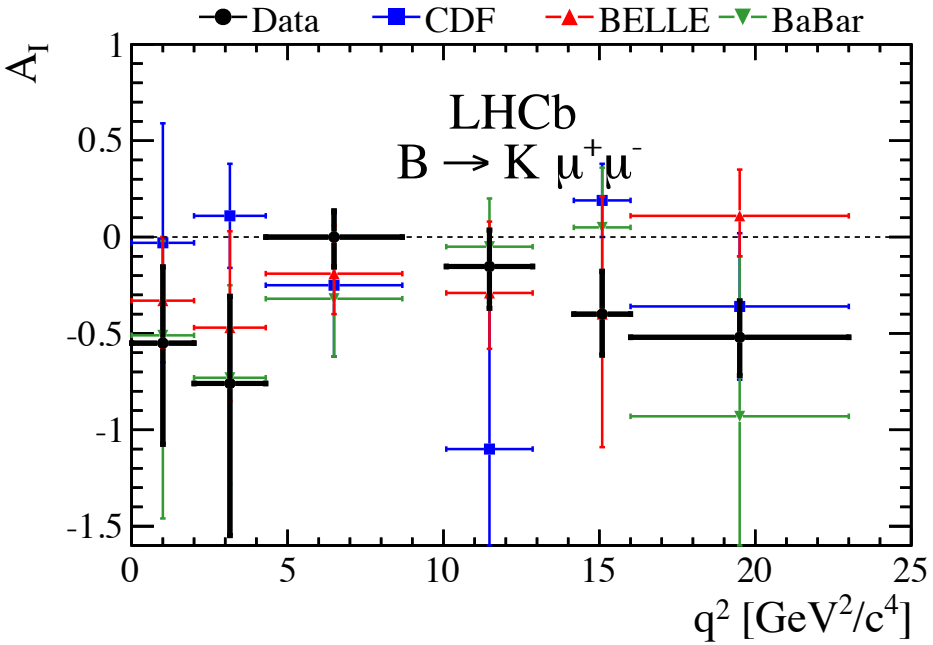
C. Bobeth, G. Hiller, D. van Dyk, and C. Wacker, JHEP 1201 (2012) 107, arXiv:1111.2558.

A_I for $B \to K\mu^+\mu^-$

- As a result, A_I for $B \to K\mu^+\mu^-$ tends to sit below the SM prediction
- Ignoring the small correlation of (syst) errors between each q^2 bin, the significance of the deviation from zero integrated across q^2 is 4.4σ (from LHCb alone)
- Results agree with previous measurements but nearly all measurements of A_I are negative

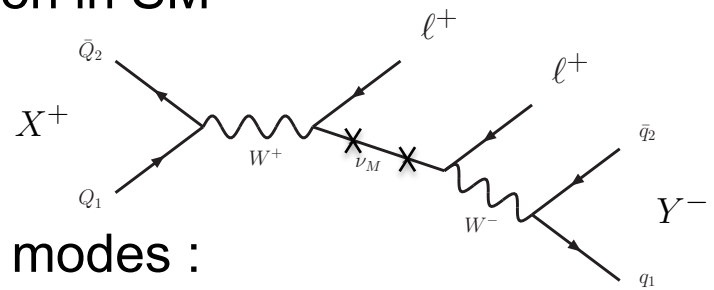
[LHCb-PAPER-2012-011]





Search for Majorana neutrinos

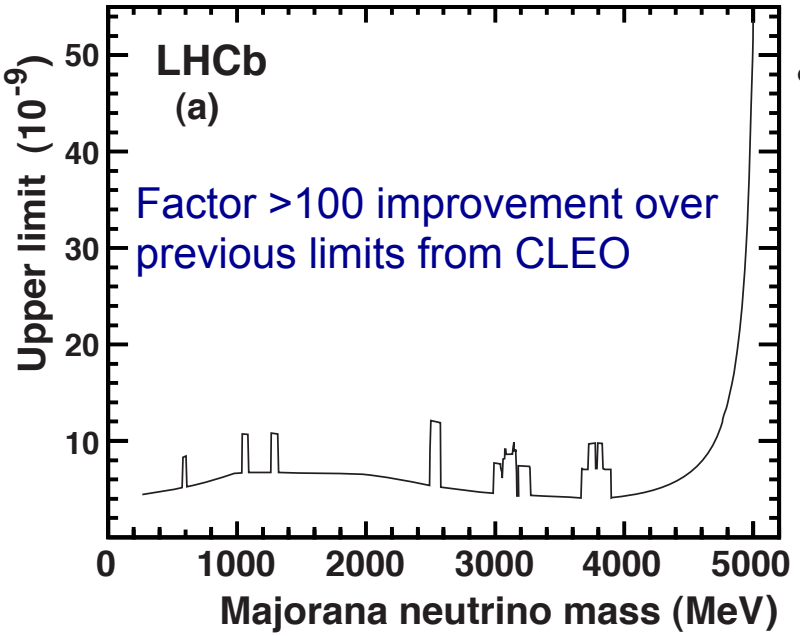
- Decays $B^+ \to h^- \mu^+ \mu^+$ are ($\Delta L=2$) strictly forbidden in SM
  - Sterile Majorana ν of mass O(1GeV/c^2) could enhance branching fraction

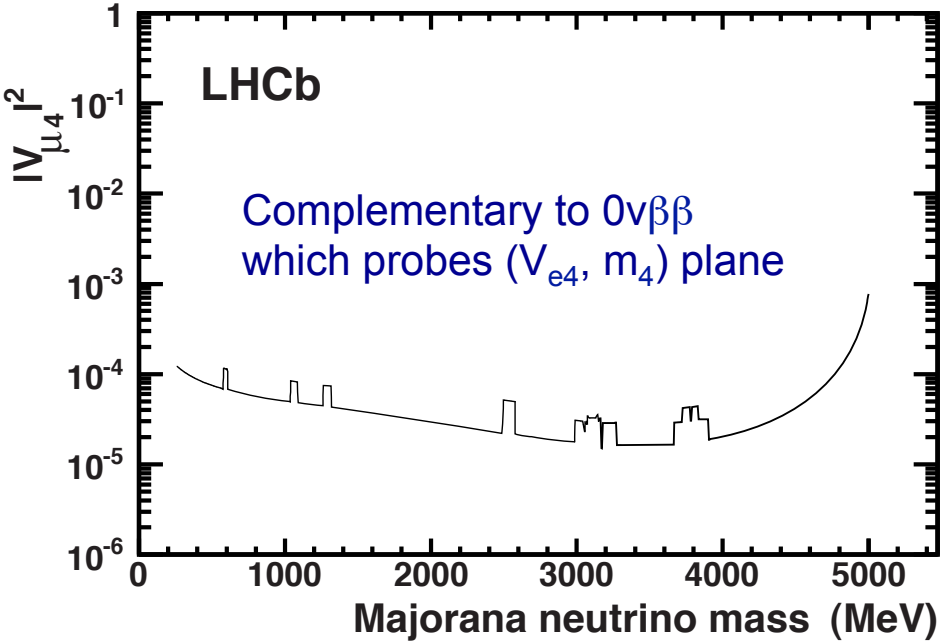


- LHCb search for a wide range of such decay modes :
  $D^- \mu^+ \mu^+$, $D^{*-} \mu^+ \mu^+$, $\pi^- \mu^+ \mu^+$, $D_s^- \mu^+ \mu^+$, $D^0 \pi^- \mu^+ \mu^+$

- No signal found - results for $B^+ \to \pi^- \mu^+ \mu^+$:

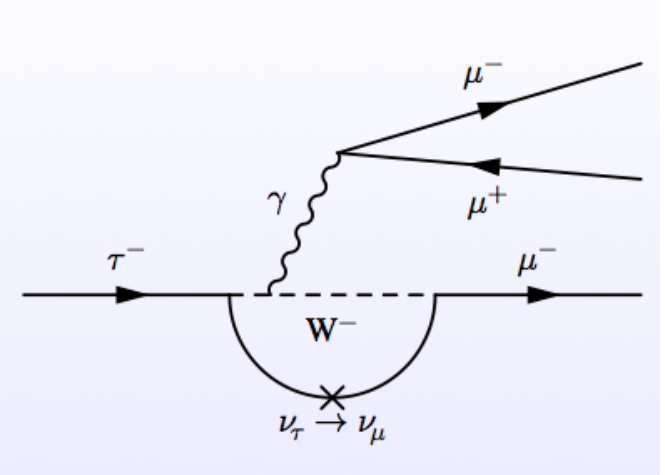
[Phys. Rev. Lett. 108 (2012) 101601
arXiv:1201.5600]





Search for $\tau \to \mu\mu\mu$

- Observation of ν-oscillation $\rightarrow$ there is LFV at some level
- Lepton flavour violating decay $\tau \to \mu\mu\mu$ predicted to have BR~O(10^{-54}) in SM
  - BSM predictions :
    - Variants of SUSY ~ 10^{-8} -10^{-10}
    - non universal Z′ ~10^{-8}



- LHCb limit from $1fb^{-1}$
  - < 6.3(7.8) x 10^{-8} at 90(95)% C.L.

  cf.
  - BaBar: <3.3 x 10^{-8} at 90% C.L ($468fb^{-1}$)
  - Belle: <2.1 x 10^{-8} at 90% C.L ($782fb^{-1}$)
- Proof of principle – measurement can be made at hadron collider
- With $1fb^{-1}$ LHCb is close to B-factory sensitivity – excellent prospects for next few years and LHCb upgrade

Conclusions

- The decays $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$
  - Existing results ruling out NP models, competitive with direct searches
  - NEW LHC combination of branching fraction limits
- Angular analysis of the decay $B^0 \to K^{*0}\mu\mu$
  - With coupling O(1) → NP at mass scales > O(15 TeV) – O(140 TeV)
  - With coupling O(loop, CKM supn) → NP at > O(0.3 TeV) – O(2 TeV)
- Isospin Asymmetry in $B \to K^{(*)}\mu^+\mu^-$ decays
  - $B \to K^*\mu^+\mu^-$, A_I results consistent with zero, as expected in SM
  - $B \to K\mu^+\mu^-$, A_I results sit below the SM expectation in the q^2 region below 4.3 GeV^2/c^4 and above 16 GeV^2/c^4
- No evidence for $B^+ \to h^-\mu^+\mu^+$ (Majorana neutrinos)
- Proof of principle for $\tau \to \mu\mu\mu$ (LFV), excellent prospects for future