Rare decays at LHCb

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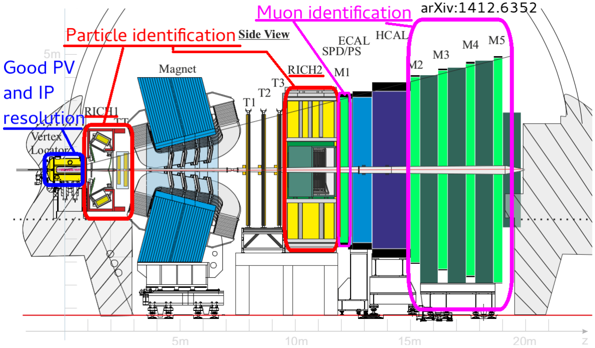
Rencontres de Blois 29 May - 3 June 2016

The LHCb detector

The LHCb detector is a single arm spectrometer which covers the forward region at LHC.



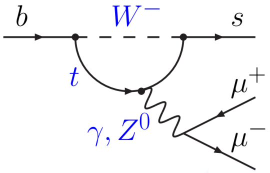
$\Delta p/p \sim 0.4\%$ at $5\,\mathrm{GeV}$, $\sigma_{IP} = 20\,\mu\mathrm{m}$ for high p_T tracks.

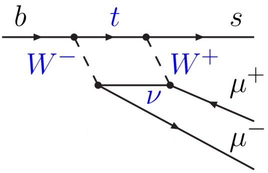
π/K **separation:** $\epsilon_K \sim 90\%$, 5% $\pi \rightarrow K$ mis-id.

π/μ **separation:** $\epsilon_\mu \sim 97\%$, 1-3% $\pi \rightarrow K$ mis-id.

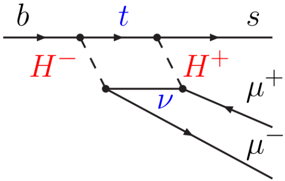
Rare decays: FCNC processes

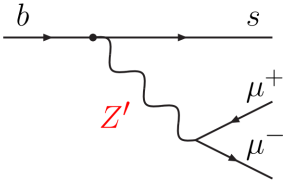
Decays mediated via Flavour Changing Neutral Currents (FCNC) occur at loop order and are suppressed in the SM.





New particles can affect the decay rates or the angular distributions of the final state particles.





Rare decays: outline

Test of the Minimal Flavour Violation hypothesis

1) Measuring V_{td}/V_{ts} using the $b \to d(s)\ell\ell$ transitions $B^+ \to \pi^+(K^+)\mu^+\mu^-$ [LHCb JHEP 10 (2015) 034]

Sensitivity to Wilson coefficients

2) Very rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ $[\mathcal{C}_{10}, \mathcal{C}_{\rm S}, \mathcal{C}_{\rm P}]$ [Nature 522 (2015) pp. 68-72]

3) Angular analyses using $b \to s\ell\ell$ transitions $[\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}]$:

- $B^0 \to K^{*0} (\to K^+\pi^-)\mu^+\mu^-$ decays [LHCb, JHEP 02 (2016) 104]
- $B_s^0 \to \Phi(K^+K^-)\mu^+\mu^-$ decays [LHCb, JHEP 09 (2015) 179]

Lepton universality

4) Branching fraction measurements of $b \to s\ell\ell$ transitions $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+ e^+e^-$ [LHCb, PRL113 (2014) 151601]

Minimal flavour violation

Comparing the CKM elements obtained via loop and tree level processes tests the MFV hypothesis that NP flavour structure = SM flavour structure.

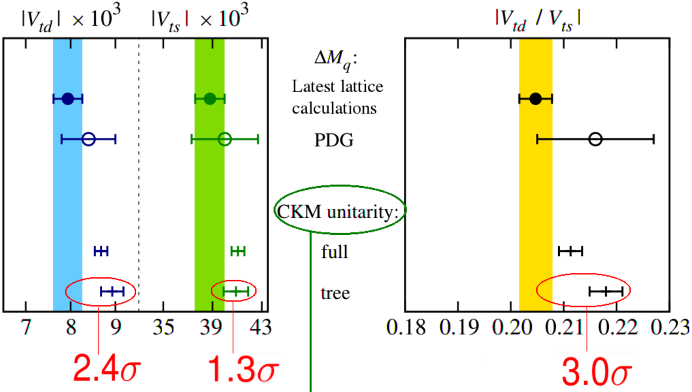
$$\Lambda > \frac{4.4\ \mathrm{TeV}}{|V_{ti}^{*}V_{tj}|/|c_{ij}|^{1/2}} \sim \begin{cases} 1.3 \times 10^{4}\ \mathrm{TeV} \times |c_{sd}|^{1/2} \\ 5.1 \times 10^{2}\ \mathrm{TeV} \times |c_{bd}|^{1/2} \\ 1.1 \times 10^{2}\ \mathrm{TeV} \times |c_{bs}|^{1/2} \end{cases}$$

Mass scale of new physics (Λ)

Lower mass limit on NP if a generic flavour structure is assumed for NP (i.e. NOT the MFV hypothesis)

arXiv:1002.0900

Testing MFV using the CKM element ratio V_{td}/V_{ts}

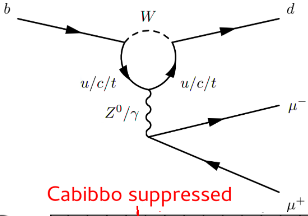


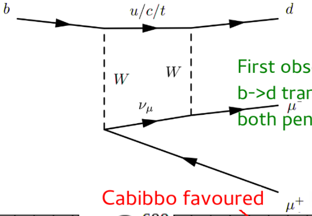
As top quarks don't hadronise, Vtd and Vts cannot be measured directly with tree diagrams,
-> use unitarity constraints from CKM matrix

A. Bazavov et. al. [arXiv:1602.03560]

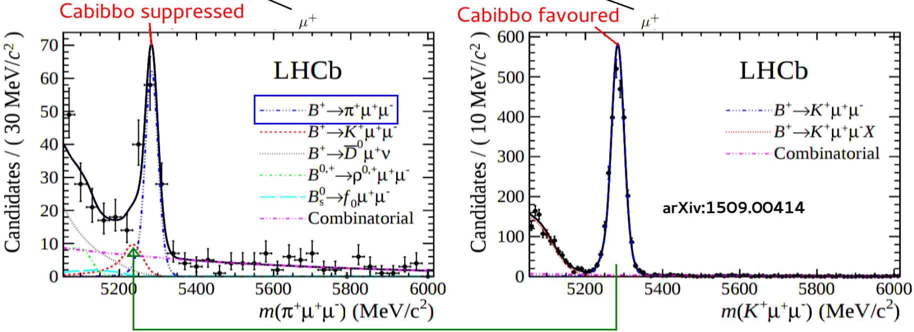
$B^+ \to \pi^+\mu^+\mu^-$: branching fraction measurement

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

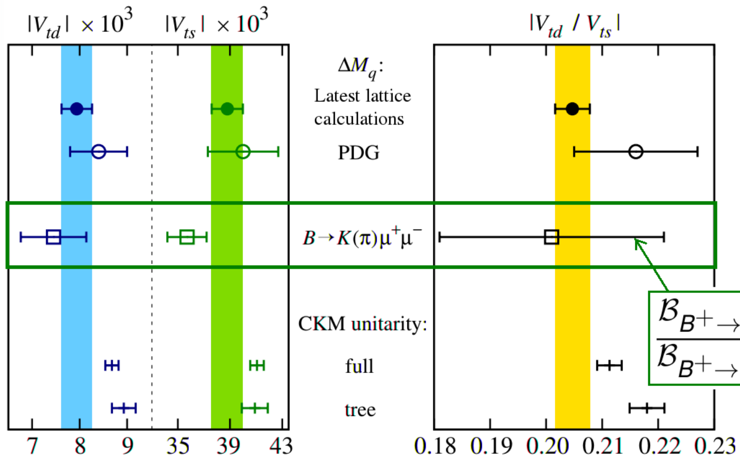




First observation of a b->d transition mediated by both penguin and box diagrams

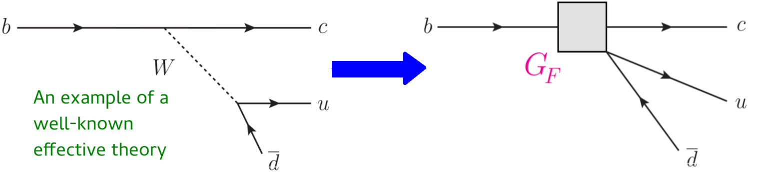


Calculating V_{td} (V_{ts}) with $B^+ \to \pi^+$ (K^+)$\mu^+\mu^-$ decays

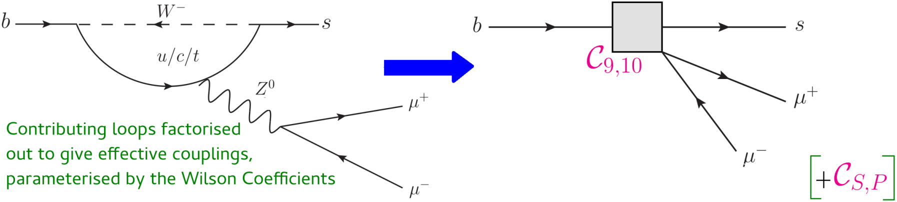


$$\frac{\mathcal{B}_{B^+\to\pi^+\mu^+\mu^-}}{\mathcal{B}_{B^+\to K^+\mu^+\mu^-}}$$

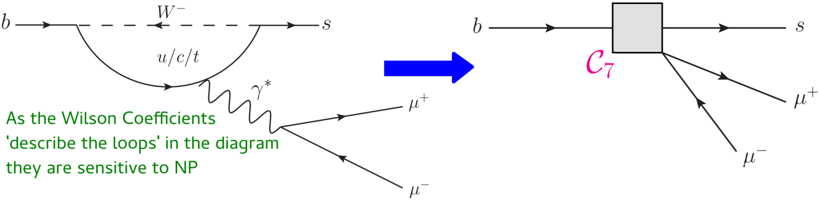
Wilson coefficients



An example of a well-known effective theory



Contributing loops factorised out to give effective couplings, parameterised by the Wilson Coefficients

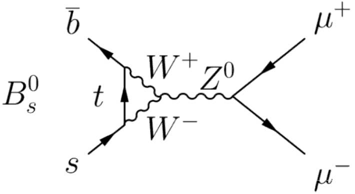


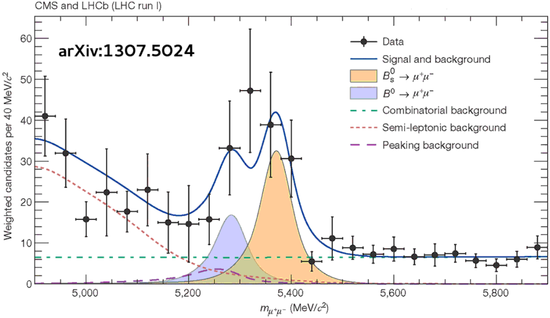
As the Wilson Coefficients 'describe the loops' in the diagram they are sensitive to NP

$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ $[\mathcal{C}_{10}, \mathcal{C}_s, \mathcal{C}_p]$

LHCb and CMS data combined:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.8^{+1.6}_{-1.4}) \times 10^{-10}$$





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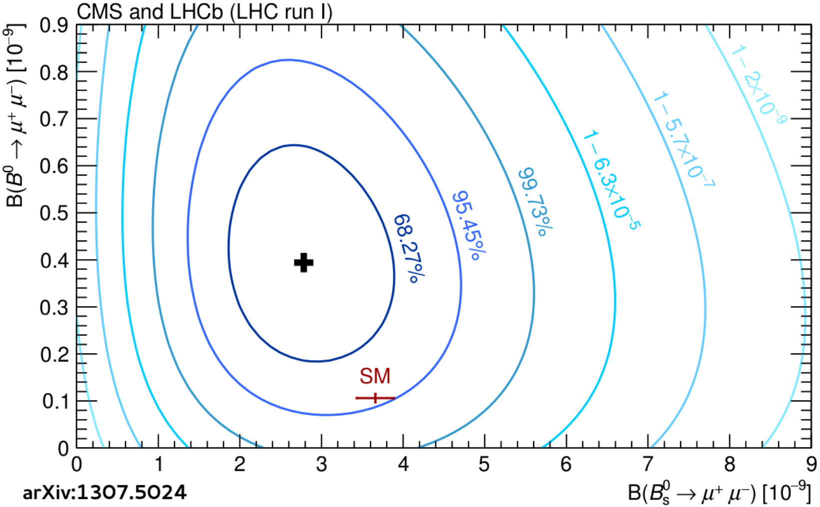
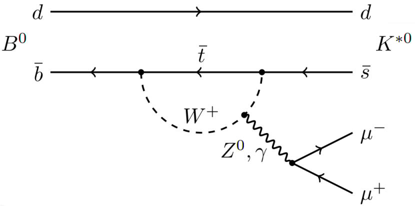
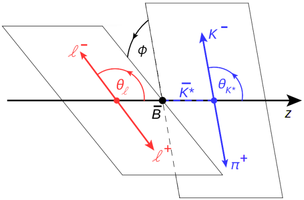


$B^0 \to K^{*0} [\to K^+\pi^-]\mu^+\mu^-$ angular analysis $[\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}]$

Angular decay fully described by the dilepton mass (q^2) and the angles $\cos(\theta)_{ll}$ $\cos(\theta)_k$ and ϕ:





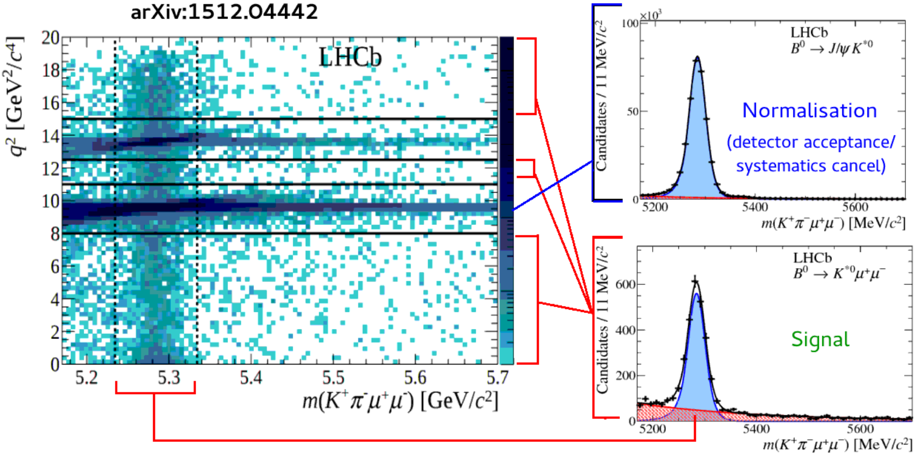
Decay rate as a function of q^2

Angular observables related to the Wilson Coefficients

$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi} \sum_i I_i(q^2) f_i(\vec{\Omega})$$

Spherical harmonics

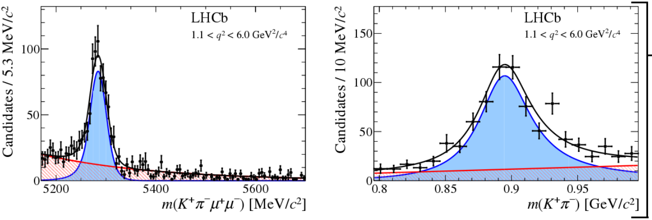
$B^0 \to K^{*0} [\to K^+\pi^-]\mu^+\mu^-$ angular analysis: Results



Use $B^0 \to K^{*0} J/\psi$ as control channel.

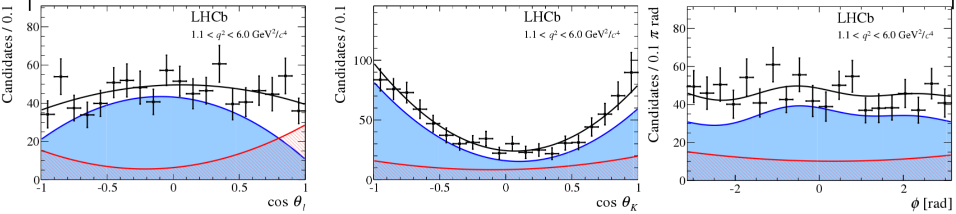
$B^0 \to K^{*0} [\to K^+\pi^-]\mu^+\mu^-$ angular analysis: Results

arXiv:1512.04442

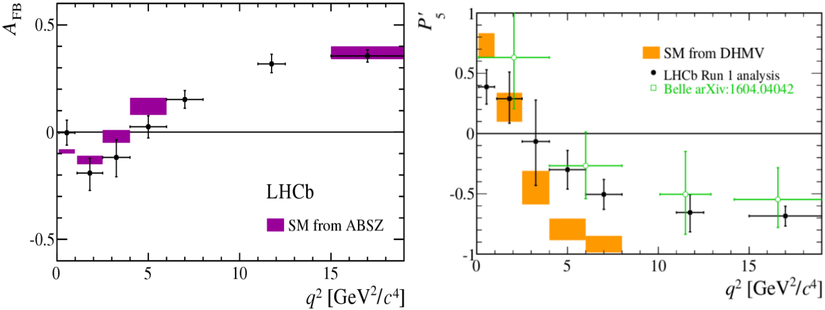


Simultaneous mass fits

1D projections of angles from 3D fit



$B^0 \to K^{*0} [\to K^+\pi^-]\mu^+\mu^-$ angular analysis: Results



Form factor free observables

Can construct ratios of angular observables where form-factors cancel, giving clean theoretical predictions:

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

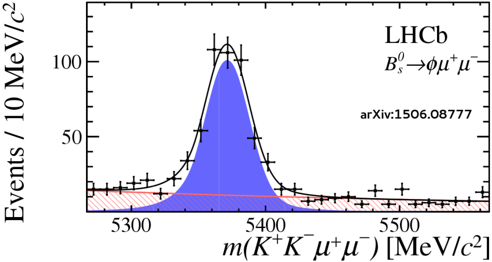
$\boldsymbol{P'_5}$ **plot**: Bins 4/5 = local SM tension of 2.8 and 3.0σ. Global tension= 3.4σ, assuming tension due to shift in Wilson coeff. $\mathcal{R}e(C_9)$

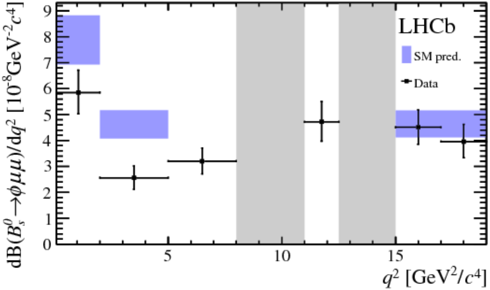
$B_s^0 \to \phi[\to K^+K^-]\mu^+\mu^-$ $[\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}]$

Equivalent process of $B^0 \to K^{*0}\mu^+\mu^-$ for B_s^0 mesons.

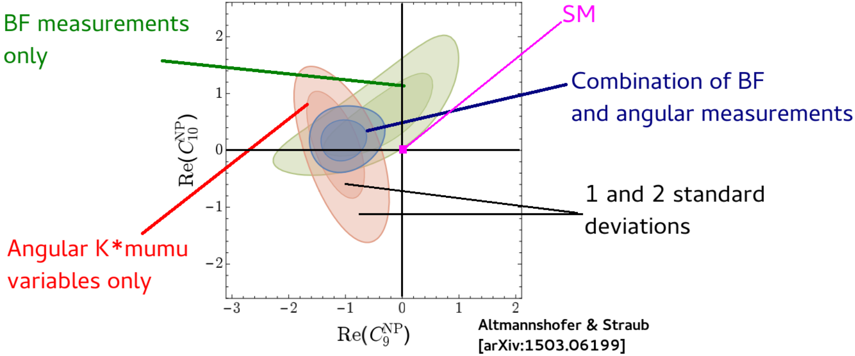
Angular variables consistent with the SM. P_5' cannot be measured as $B_s^0 \to \phi\mu^+\mu^-$ not self-tagging.

In bin $1< q^2 <6$ GeV/c^2 the data is 3.3σ from the SM prediction.





Global fits



An example of a fit to many results from $b \to s\ell\ell$ transitions.
3-4σ tension with SM observed in the $\mathcal{C}_9$ Wilson coefficient.

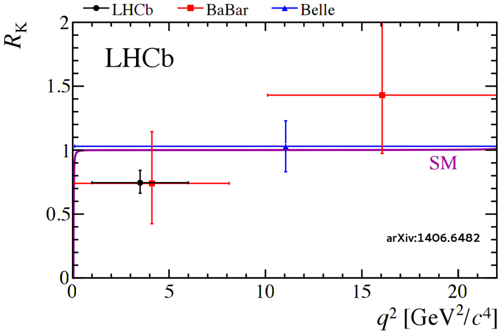
$B^+ \to K^+ \mu^+ \mu^-$ and $B^+ \to K^+ e^+ e^-$ decays

Lepton universality

The quantity:

$$R_k = \frac{\int \Gamma(B^+ \to K^+ \mu^+ \mu^-)/dq^2 . dq^2}{\int \Gamma(B^+ \to K^+ e^+ e^-)/dq^2 . dq^2}$$

differs from unity only due to phase space.



Theoretically clean as matrix elements cancel.

$$R_K = 0.745^{+0.090+0.036}_{-0.074-0.036} \implies 2.6\,\sigma \text{ from SM}$$

Experimentally challenging due to electrons.

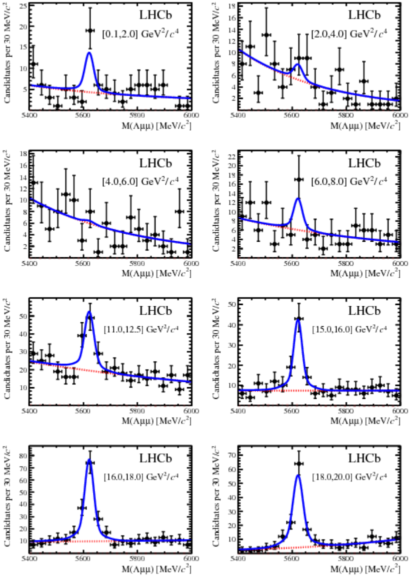
Deficit of $b \to s \mu^+ \mu^-$ transitions, tension in same direction as measurements previously discussed

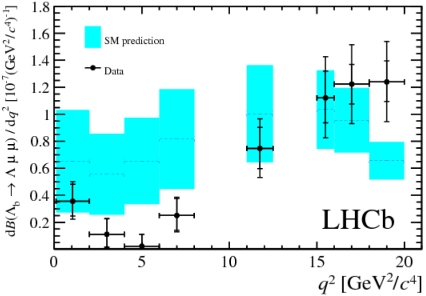
Conclusions

- Flavour observables in rare decays allow for NP searches and can place many strong constraints on NP models.
- Some tensions with the SM observed, particular within $b \to s\ell\ell$ transitions.
- Many rare decay analyses performed with LHC Run 1 data and many more results to come using the Run 1 and first Run 2 datasets.

Back-up slides

$\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-$ differential branching fraction





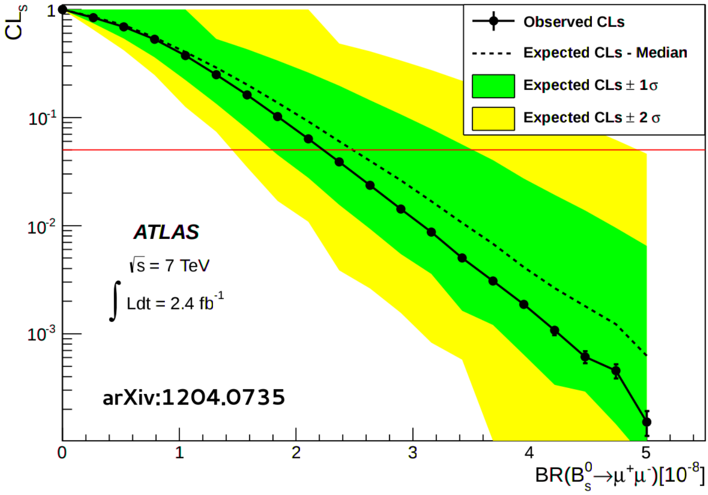
b→ sℓℓ transition in the baryon sector

Global fits $b \to s\ell\ell$ decays

Decays included
in fit in *Altmannshofer et al.* with tension $> 1.9\,\sigma$ in a Wilson Coefficient.

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

$B_s^0 \to \mu^+\mu^-$ results from Atlas



NP models: contribution to C_9 arXiv:1308.1501

Z' models

- Z' models involve tree-level exchange of a heavy neutral boson (Z') with a flavour-changing $b \to s$ coupling.
- Z' models allow for significant contributions to the C_9 vector coefficient which could accommodate tensions in $b \to s\ell\ell$ measurements.
- Best fit values for C_9 global fits and constraints from B_s meson mixing favour a light Z' with mass of order $1\,\mathrm{TeV}$. To avoid constraints from di-lepton searches, the Z' coupling to SM fermions must be $\sim$ an order of magnitude less than those of the SM Z.

NP models: contribution to C_9 arXiv:1308.1501

Models with partial composites

- Most well-motivated to contribute to C_7 coefficients, contributions could be large enough to significantly reduce tension in C_9 coefficient.
- To contribute C_9 would require several cancellations in the V-A coefficient C_{10} and properties of muons would be strongly dependent on chirality.

MSSM

- Contributions to C_9 from Z penguins, charged Higgs (box and loops), Higgsinos (box and loops) all negligible.
- MSSM can affect C_7 which could soften tensions.