An overview of anomalies in rare B decays

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Helmholtz alliance, Physics at the Tetrascale 2017

What this talk will cover

- General introduction into rare B decays
- An overview of the types of measurements being performed in the sector:

  $B_s^0(B^0) \to \mu^+\mu^-$ (PRL 118 (2017) 191801)
  $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis (JHEP 02 (2016) 104, ATLAS-CONF-2017-023, PRL 118 (2017), arXiv:1710.02846)
  $B_s^0 \to \phi\mu^+\mu^-$ angular analysis (JHEP 09 (2015) 179)
  $B^0 \to K^+\mu^+\mu^-$ (EPJC 77 (2017) 16, JHEP 06 (2014) 133)
  R_{K*0} (JHEP 08 (2017) 055)
  R_K (PRL 113 (2014) 151601)
- Focus on anomalous results and global fits.

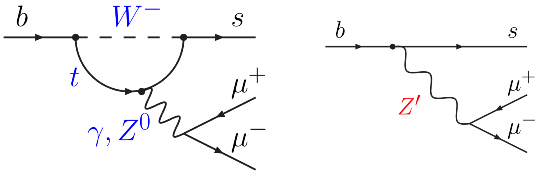
Disclaimer: Majority of these results are going to be LHCb results.

Rare B decays: indirect searches

✓ Measurable deviations from the SM caused by interference of "off-shell" NP particles, so sensitive to heavier particles $\sim$ 100 TeV (arXiv:1408.0728)

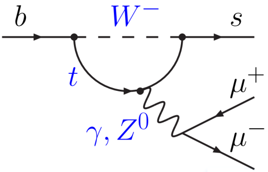
× Must always be certain that a deviation from the SM predictions is not due to an error in the SM predictions, e.g. QCD effects.

So far no direct discovery of new physics at LHC and there is an increasing interest in indirect searches

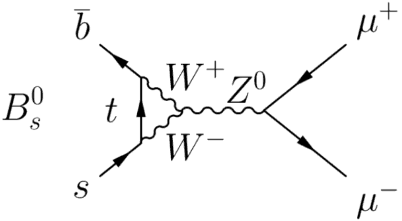


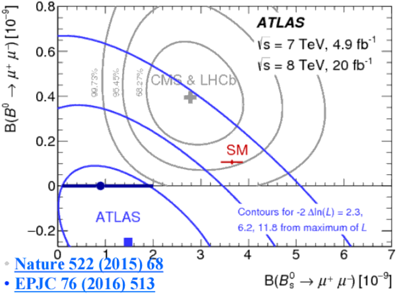
Why rare B decays?

- Flavour Changing Neutral Currents (FCNC) as appear in $b \to s\ell\ell$ transitions are forbidden at tree level $\implies$ suppressed decays in the SM maybe be more sensitive to new physics (NP) effects.
- Presence of loops allows for the appearance of virtual NP particles
- Particularly sensitive to NP models that favour third generation.



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





- Nature 522 (2015) 68
- EPJC 76 (2016) 513

- Occur at loop-level and helicity suppressed
- Very precise SM predictions:

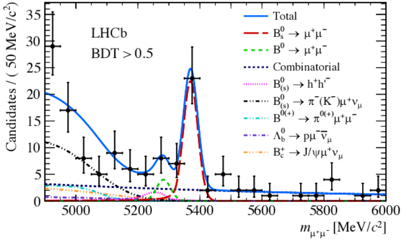
  $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

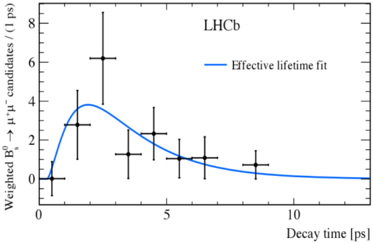
  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$
- Combined fit to Run-1 data by CMS and LHCb :

  First observation of $B_s^0 \to \mu^+\mu^-$ (6.2σ, SM at 1.2 σ)

  First evidence of $B^0 \to \mu^+\mu^-$ (3.0σ, SM at 2.2 σ)

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





PRL 118 (2017) 191801

- Analysis recently updated with just LHCb data (Run 1 (3 fb^{-1}) and 2 (1.4 fb^{-1}))

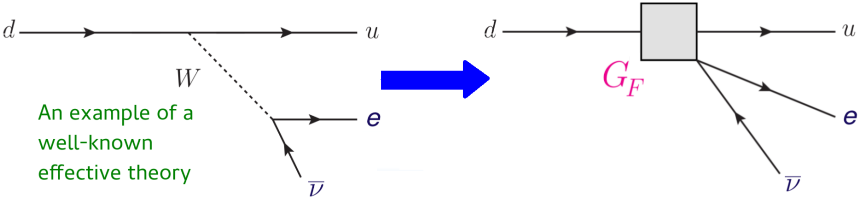
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6) \pm 0.3 \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} @95\% CL \; (1.2\sigma) \text{ excess.}$$

- Effective lifetime measured

$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05\text{ps}$$

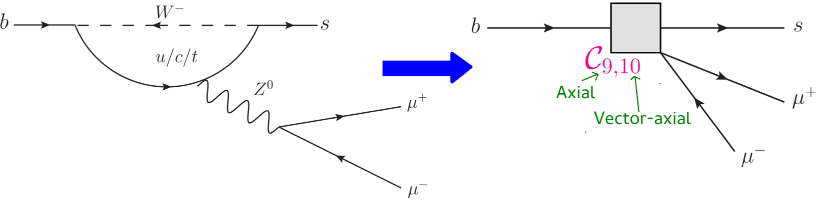
Aside: a recap of Wilson Coefficients

- Allows model independent description of heavy flavour decays using effective theories.
- Well known effective theory: Fermi's constant, G_F:



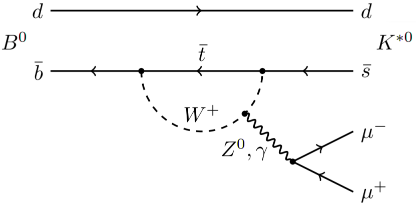
Effective theories in b decays

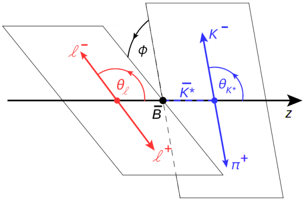
- Contributing loops factorised out to give effective couplings, parameterised by the Wilson Coefficients.
- As Wilson Coefficients "describe the loops" in the diagram they are sensitive to NP.
- There are various Wilson coefficients, for $b \to s\mu\mu$: C_9(A) and C_{10}(V-A).



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





$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K + \boxed{F_{\mathrm{L}}}\cos^2\theta_K + \tfrac{1}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K\cos 2\theta_\ell$$

$$-\boxed{F_{\mathrm{L}}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$

$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + P_5'\sqrt{F_L(1-F_L)}\sin 2\theta_K\sin\theta_\ell\cos\phi$$

$$+\tfrac{4}{3}\boxed{A_{\mathrm{FB}}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$

$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

Fraction of longitudanal polaristion of the K*

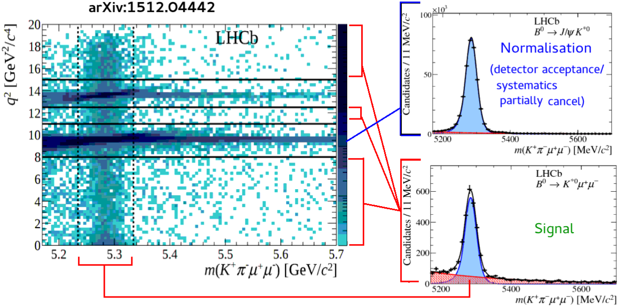
Forward-backward asymmetry of the dilepton system

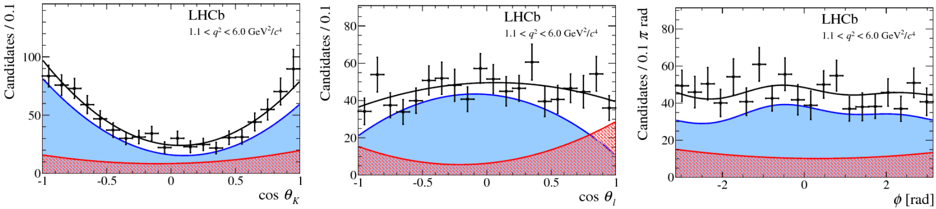
All angular coefficients depend on Wilson coefficients and hadronic form factors

3D fit to all three angles (in q^2 bins), exploiting the correlations between the S_i, F_L and A_{FB} terms to obtain their respective values.

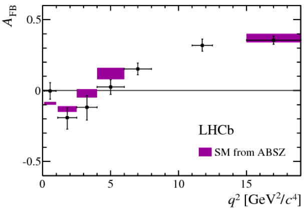
$B^0 \to K^{*0} [\to K^+\pi^-]\mu^+\mu^-$ angular analysis: Results

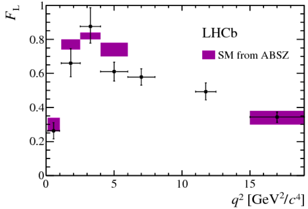
arXiv:1512.04442





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





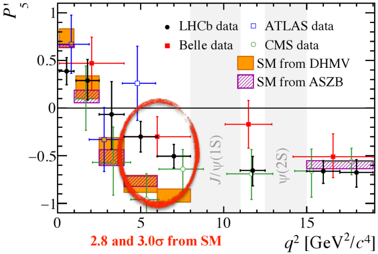
Generally good agreement with SM predictions

Form factor free observables

Can construct ratios of angular observables where form-factors cancel at leading order:

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

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. $\mathcal{R}e(C_9)$ (LHCb only)



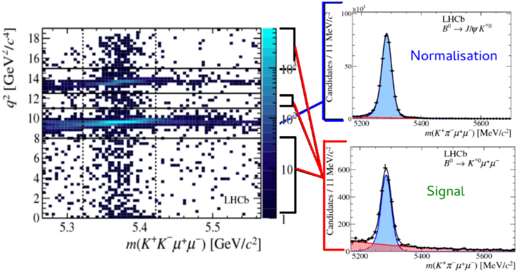
- JHEP 02 (2016) 104
- ATLAS-CONF-2017-023
- PRL 118 (2017)
- arXiv:1710.02846

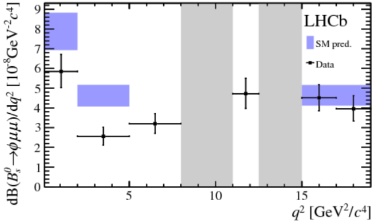
$B_s^0 \to \phi[\to K^+K^-]\mu^+\mu^-$ $[\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}]$

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

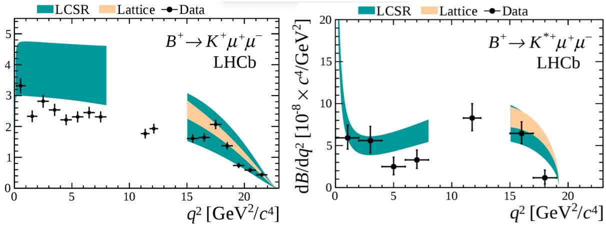
Angular variables consistent with the SM. P_5' cannot be measured as $B_s^0 \to \phi\mu^+\mu^-$ not self-tagging.

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





$B^+ \to K^+\mu^+\mu^-$ branching fraction



- Branching fraction measured whilst analysing the isospin asymmetry in $B \to K^{(*)}\mu^+\mu^-$ decays.
- Isospin consistent with SM but deficit seen in $B \to K\mu^+\mu^-$ branching fractions.

Lepton universality measurements

Test lepton universality by measuring ratio of $\frac{H_b \to H\ell\ell}{H_b \to H\ell'\ell'}$

Lepton universality

The quantity:

$$R_H = \frac{\int d\blacksquare(H_b \to H\mu^+\mu^-)/dq^2.q^2}{\int d\blacksquare(H_b \to He^+e^-)/dq^2.q^2}$$

differs from unity only due to phase space.

Theoretically clean as matrix elements cancel.

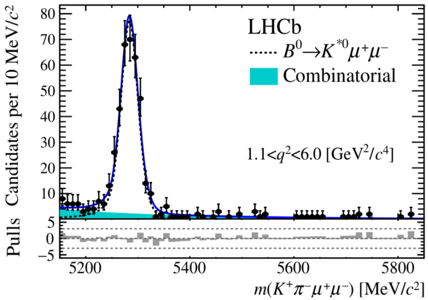
Challenge of measuring electrons.

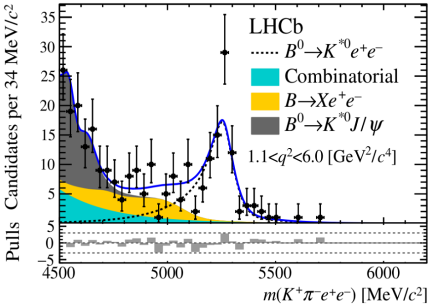
$B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}\, e^+e^-$ decays

Measure as double ratio:

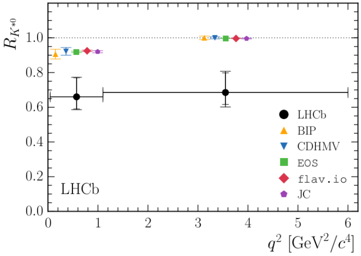
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi\,(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi\,(e^+e^-))},$$

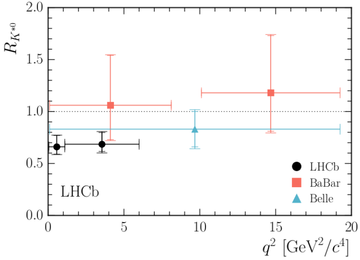
For given q^2 bin, left: $B^0 \to K^{*0}\mu^+\mu^-$ events, right: $B^0 \to K^{*0}\, e^+e^-$ events





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



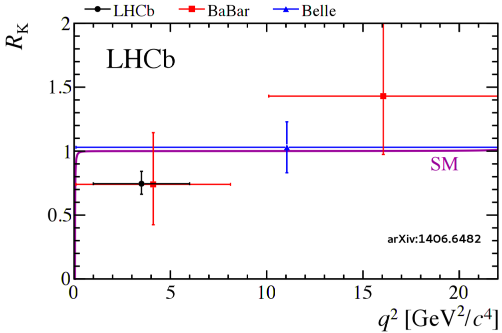


$$R_{K^{*0}} = \begin{cases} 0.660\,^{+\,0.110}_{-\,0.070}\,(\text{stat}) \pm 0.028\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4\,, \\ 0.685\,^{+\,0.113}_{-\,0.069}\,(\text{stat}) \pm 0.047\,(\text{syst}) & \text{for } 1.1 \quad\; < q^2 < 6.0\ \text{GeV}^2/c^4\,. \end{cases}$$

$$\begin{cases} 2.1 - 2.3\sigma & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4\,, \\ 2.4 - 2.5\sigma & \text{for } 1.1 \quad\; < q^2 < 6.0\ \text{GeV}^2/c^4\,, \end{cases}$$

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

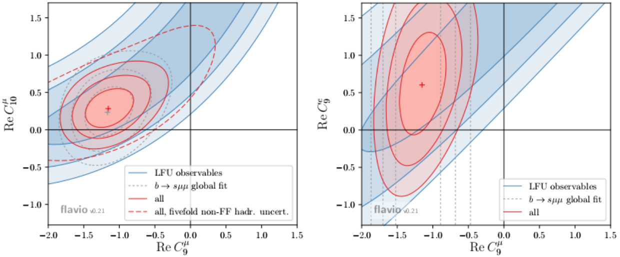
As for $R_{K^{*0}}$, however only one bin in q^2 is used.



$R_K = 0.745^{+0.090+0.036}_{-0.074-0.036} \Longrightarrow$ 2.6 σ from SM.

Global fits

Fits favour $\sim 4\,\sigma$ deviation in C_9^μ



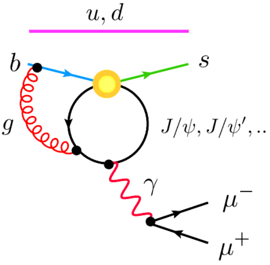
arXiv:1704.05435

Coeff.	best fit	1σ	2σ	pull
C_9^μ	-1.59	$[-2.15, -1.13]$	$[-2.90, -0.73]$	4.2σ
C_{10}^μ	$+1.23$	$[+0.90, +1.60]$	$[+0.60, +2.04]$	4.3σ
C_9^e	$+1.58$	$[+1.17, +2.03]$	$[+0.79, +2.53]$	4.4σ
C_{10}^e	-1.30	$[-1.68, -0.95]$	$[-2.12, -0.64]$	4.4σ
$C_9^\mu = -C_{10}^\mu$	-0.64	$[-0.81, -0.48]$	$[-1.00, -0.32]$	4.2σ
$C_9^e = -C_{10}^e$	$+0.78$	$[+0.56, +1.02]$	$[+0.37, +1.31]$	4.3σ
$C_9'^\mu$	-0.00	$[-0.26, +0.25]$	$[-0.52, +0.51]$	0.0σ
$C_{10}'^\mu$	$+0.02$	$[-0.22, +0.26]$	$[-0.45, +0.49]$	0.1σ
$C_9'^e$	$+0.01$	$[-0.27, +0.31]$	$[-0.55, +0.62]$	0.0σ
$C_{10}'^e$	-0.03	$[-0.28, +0.22]$	$[-0.55, +0.46]$	0.1σ

Pull assuming NP is one coefficient

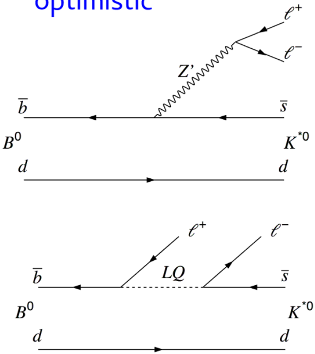
What could be causing this anomaly?

pessimistic



long distance SM effects

optimistic



short distance NP effects

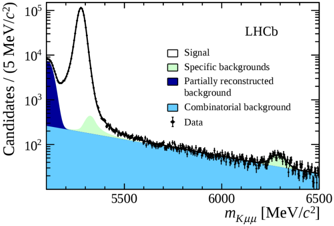
Data driven measurements of short and long distance interference

- Due to the difficulty of modelling Charmonium resonances, the J/ψ and $\psi(2S)$ are generally removed from data when looking at just the short-distance contributions.
- Vector resonances producing dimuon pairs could mimic a contribution to C_9 allowing C_9 to be expressed as

$$C_{9\mathrm{eff}} = C_9 + Y(q^2)$$

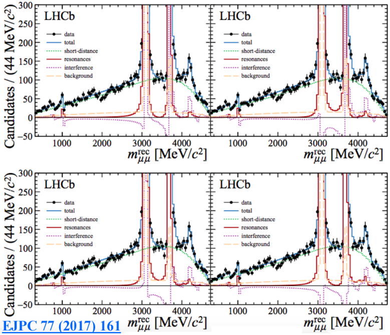
- Possible that the deficiency in muons could be due to destructive interference from such Charmonium resonances.

Data driven measurements of short and long distance interference



- Data driven approach $\rightarrow$ fit data over all q^2 to extract long and short distance components
- Allow a measurement of $\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)$ without interpolation of q^2.
- Express $Y(q^2)$ in terms of the sum of the magnitude and phases of the vector meson resonances $(\rho, \omega, \phi, J/\psi, \psi(2S), \psi(X)) \implies$ model these contributions as a sum of Breit Wigners with individual width and phase.

Data driven measurements of short and long distance interference



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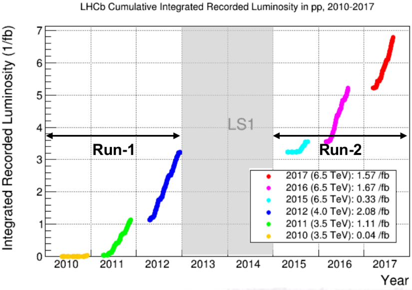
- Four solutions fit data well reflecting the unknown sign of the J/ψ and $\psi(2S)$ phases (NB resolution dominants these resonances widths)
- The phases that are measured suggest a small contribution to the short-distance component in the dimuon mass regions far from the J/ψ and $\psi(2S)$ masses, given the assumptions made in model.

Conclusions and outlook

- Number of anomalies in $b \to s\ell\ell$ transitions, consistent with a deficit in the muon channel
- Could be theoretical limitations or new physics
- More data necessary to further qualify this, as well as development in theory
- Advent of Belle 2 and further runs at the LHC will yield interesting results



Back-up slides

Isospin in $B \to K\mu^+\mu^-$ decays

Definition of asymmetry:

To maximise sensitivity, observables can be constructed from ratios or asymmetries where the leading form factor uncertainties cancel. The CP-averaged isospin asymmetry (A_{I}) is such an observable. It is defined as

$$\begin{aligned} A_{\mathrm{I}} &= \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)} \\ &= \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - (\tau_0/\tau_+) \cdot \mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + (\tau_0/\tau_+) \cdot \mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}, \end{aligned} \tag{1}$$

where $\Gamma(f)$ and $\mathcal{B}(f)$ are the partial width and branching fraction of the $B \to f$ decay and τ_0/τ_+ is the ratio of the lifetimes of the B^0 and B^+ mesons[1]. The decays in the isospin ratio differ only by the charge of the light (spectator) quark in the B meson. The SM prediction for A_{I} is $\mathcal{O}(1\%)$ in the dimuon mass squared, q^2, region below the J/ψ resonance [3–5]. There is no precise prediction for A_{I} for the q^2 region above the J/ψ resonance, but it is expected to be even smaller than at low q^2 [5]. As q^2 approaches zero,