Future $b \to s(d)\mu^+\mu^-$ measurements at LHCb

Konstantinos A. Petridis
on behalf of the LHCb collaboration

University of Bristol

April 18, 2016

Introduction

- Run 1 of the LHC provided us with a rich set of results
  $\rightarrow$ Precision era for rare decays

- Selective set of plans and thoughts with Run 2 data and beyond involving $b \rightarrow s(d)\mu^+\mu^-$ modes

How are we doing?

channel	$\mathcal{L}^{int}$ (fb^{-1})	Publication
$d\mathcal{B}/dq^2\ B \to K^{*+}\mu^+\mu^-$	3	[JHEP06(2014)133]
$d\mathcal{B}/dq^2\ B \to K^0\mu^+\mu^-$	3	[JHEP06(2014)133]
$d\mathcal{B}/dq^2\ B \to K^+\mu^+\mu^-$	3	[JHEP06(2014)133]
$d\mathcal{B}/dq^2\ B^0 \to K^{*0}\mu^+\mu^-$	1	[JHEP08(2013)131]
$d\mathcal{B}/dq^2\ B_s^0 \to \phi\mu^+\mu^-$	3	[JHEP09(2015)179]
$\mathcal{B}(B^+ \to \phi K\mu^+\mu^-)$	3	[JHEP10(2014)064]
$d\mathcal{B}/dq^2\ B^+ \to K^+\pi^-\pi^+\mu^+\mu^-$	3	[JHEP10(2014)064]
$d\mathcal{B}/dq^2\ \Lambda_b \to \Lambda\mu^+\mu^-$	3	[JHEP06(2015)115]
$d\mathcal{B}/dq^2\ B^+ \to \pi^+\mu^+\mu^-$	3	[JHEP10(2015)034]
$\mathcal{B}(B_{s,d} \to \mu^+\mu^-)$	3	[Nature522(2015)68]
$\mathcal{B}(B^0 \to \pi^+\pi^-\mu^+\mu^-)$	3	[PLB743(2015)]
$\mathcal{B}(B^0 \to K^{*0}e^+e^-)$	1	[JHEP05(2013)159]
$\mathcal{B}(B^+ \to K^+e^+e^-)$	1	[PRL113(2014)151601]
$A_I\ B \to K^{(*)}\mu^+\mu^-$	3	[JHEP06(2014)133]
$A_{CP}\ B^+ \to K^+\mu^+\mu^-$	3	[JHEP09(2014)177]
$A_{CP}\ B^0 \to K^{*0}\mu^+\mu^-$	3	[JHEP09(2014)177]
$A_{CP}\ B^+ \to \pi^+\mu^+\mu^-$	3	[JHEP10(2015)034]
Angular $B^+ \to K^+\mu^+\mu^-$	3	[JHEP05(2014)082]
Angular $B^0 \to K^0\mu^+\mu^-$	3	[JHEP05(2014)082]
Angular $B^0 \to K^{*0}\mu^+\mu^-$	3	[JHEP02(2016)104]
Angular $B_s^0 \to \phi\mu^+\mu^-$	3	[JHEP09(2015)179]
Angular $\Lambda_b \to \Lambda\mu^+\mu^-$	3	[JHEP06(2015)115]

How are we doing?

channel	3fb^{-1}	Run 2	Upgrade (50fb^{-1})
$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$	2,400	9,000	80,000
$B^0 \to K^{*+}(K^0_S\pi^+)\mu^+\mu^-$	160	600	5,500
$B^0 \to K^0_S\mu^+\mu^-$	180	650	5,500
$B^+ \to K^+\mu^+\mu^-$	4700	17,500	150,000
$B^+ \to \pi^+\mu^+\mu^-$	93	350	3,000
$B^0_s \to \mu^+\mu^-$	15	60	500
$B^0 \to K^{*0}e^+e^-$	150	550	5,000

Naively scaling with luminosity and linear scaling of $\sigma_{b\bar{b}}$ with $\sqrt{s}$. Extrapolated yields rounded to the nearest 50/500

- Our measurements of $d\mathcal{B}/dq^2$ obtained by normalising rare yield to that of normalisation channel $B \to J/\psi K^*$
- For higher statistics decays, dominant uncertainty of integrated BF is the knowledge of $\mathcal{B}(B \to J/\psi K^*)$

  $\to$ More $b \to s\ell\ell$ decays in Run 1 than $B \to J/\psi K^*$ of B-factories!
- With the LHCb upgrade even "tough" modes will be sufficiently populated

A word on normalisation channel

- Moving forward, uncertainty of $\mathcal{B}(B \to J/\psi K^*)$ comparable to statistical uncertainty of $d\mathcal{B}/dq^2$ per bin
- Does not make sense to normalise to J/ψ

  $\to$ Measure relative to semileptonic $b \to c$ decay?

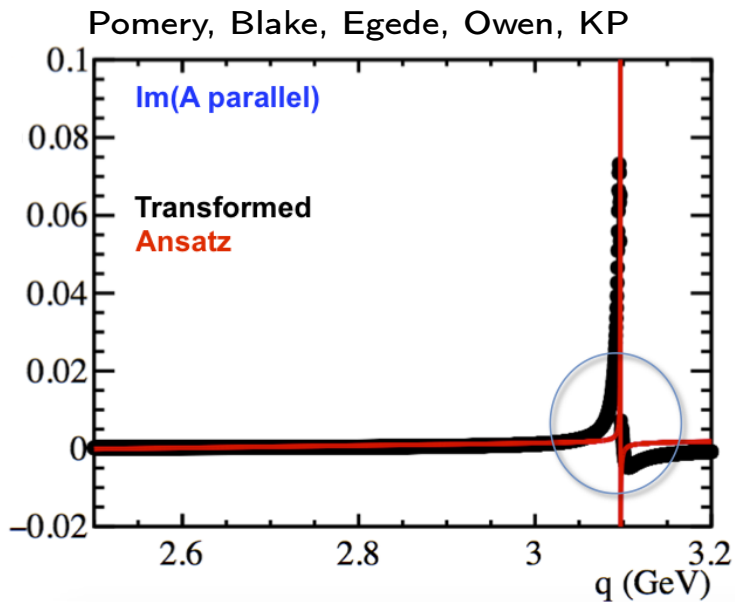
  $\to$ Experimentally ok assuming systematic uncertainties due to differences in decay topologies are small

$B^0 \to K^{*0}\mu^+\mu^-$ and (charm) resonances

Can we help constrain the contribution of resonances at low and high q^2?

- Introduce a relativistic Breit-Wigner with relative phase ($\chi_{0,\parallel,\perp}$) and magnitude ($\eta_{0,\parallel,\perp}$) to each transversity penguin amplitude (similar to $B^+ \to K^+\mu^+\mu^-$)
  - Same phase and mag for left- and right-handed amplitudes
- Different contributions to each amplitude requires an angular analysis to disentangle contributions
- Fit for the angular and q^2 distribution including resonance regions to determine $\chi_{0,\parallel,\perp}$ and $\eta_{0,\parallel,\perp}$

- Amplitude fit requires transformation to basis to remove redundant degrees of freedom
- Simple q^2 dependent ansatz+Breit-Wigners to describe amplitudes in transformed basis not possible



$B^0 \to K^{*0}\mu^+\mu^-$ and (charm) resonances cont'd

Follow approach described by Patrick for $B^+ \to K^+\mu^+\mu^-$ Subject to the same assumptions regarding line shape, charm threshold, other effects

- Introduce relativistic Breit-Wigner to each $C_9^{\rm eff}$ term of each transversity amplitude with relative phase and magnitude $\chi_{0,\parallel,\perp}$,$\eta_{0,\parallel,\perp}$ (common for L and R)
- Fit for the angular and q^2 distribution across full q^2 range, to determine $\chi_{0,\parallel,\perp}$ and $\eta_{0,\parallel,\perp}$
  - Relations between amplitudes explicitly encoded $\to$ no redundant information

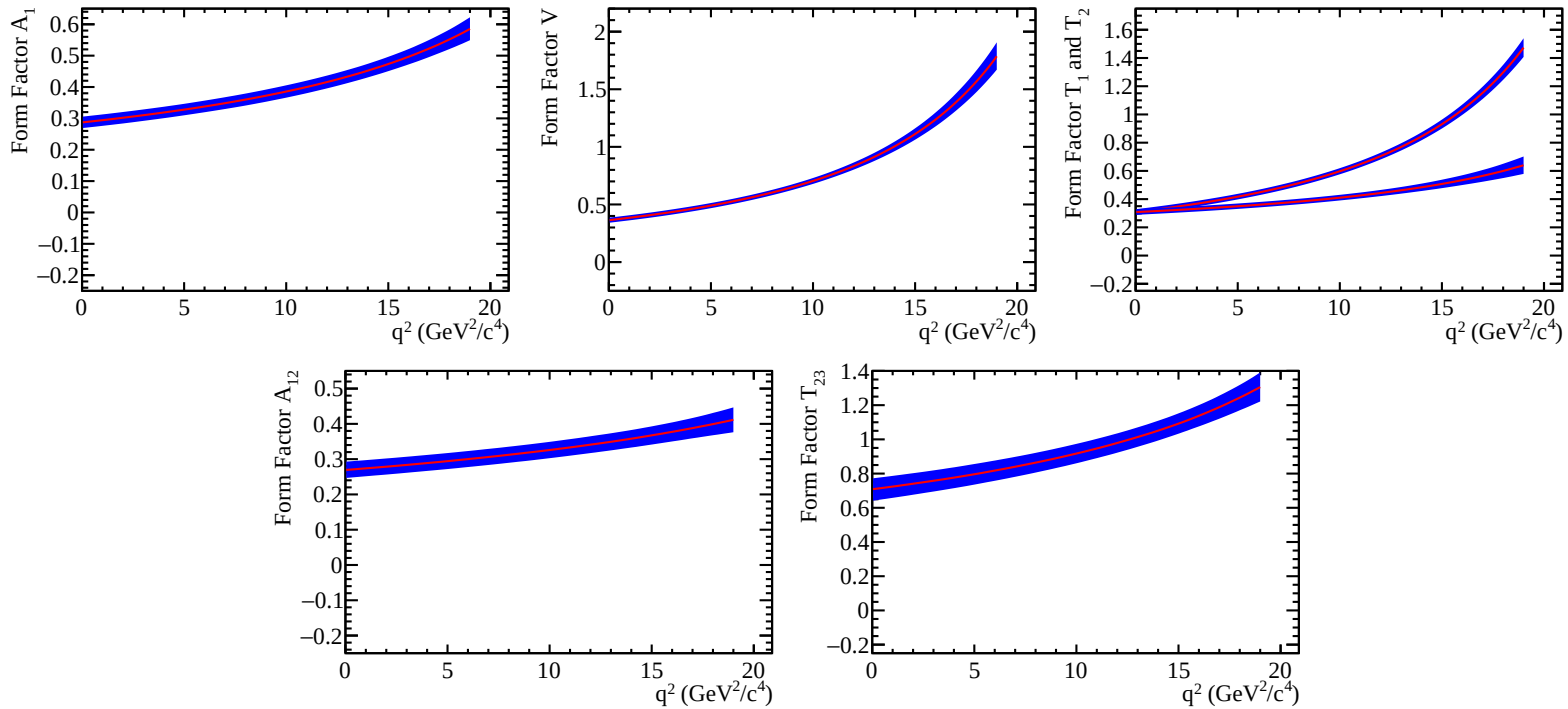
$$A_\perp^{L(R)} = N\sqrt{2\lambda}\left\{\left[(\mathbf{C_9^{eff}} + \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} + \mathbf{C_{10}^{\prime eff}})\right]\frac{\mathbf{V(q^2)}}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} + \mathbf{C_7^{\prime eff}})\mathbf{T_1(q^2)}\right\}$$

$$A_\parallel^{L(R)} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}})\right]\frac{\mathbf{A_1(q^2)}}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} - \mathbf{C_7^{\prime eff}})\mathbf{T_2(q^2)}\right\}$$

$$A_0^{L(R)} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}})\right]\left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})\mathbf{A_1(q^2)} - \lambda\frac{\mathbf{A_2(q^2)}}{m_B + m_{K^*}}\right]\right.$$
$$\left. + 2m_b(\mathbf{C_7^{eff}} - \mathbf{C_7^{\prime eff}})\left[(m_B^2 + 3m_{K^*} - q^2)\mathbf{T_2(q^2)} - \frac{\lambda}{m_B^2 - m_{K^*}^2}\mathbf{T_3(q^2)}\right]\right\}$$

Theoretical and experimental inputs

- Range of q^2 we fit depends on available statistics and number of resonances we can include
- Where possible, constrain overall rate of each resonance to PDG branching fractions
- Can constrain form factors using the covariance matrix provided in BSZ[1503.05534]



- Depending on sensitivity and fit stability could also measure some Wilson coefficients

What can we say with current information

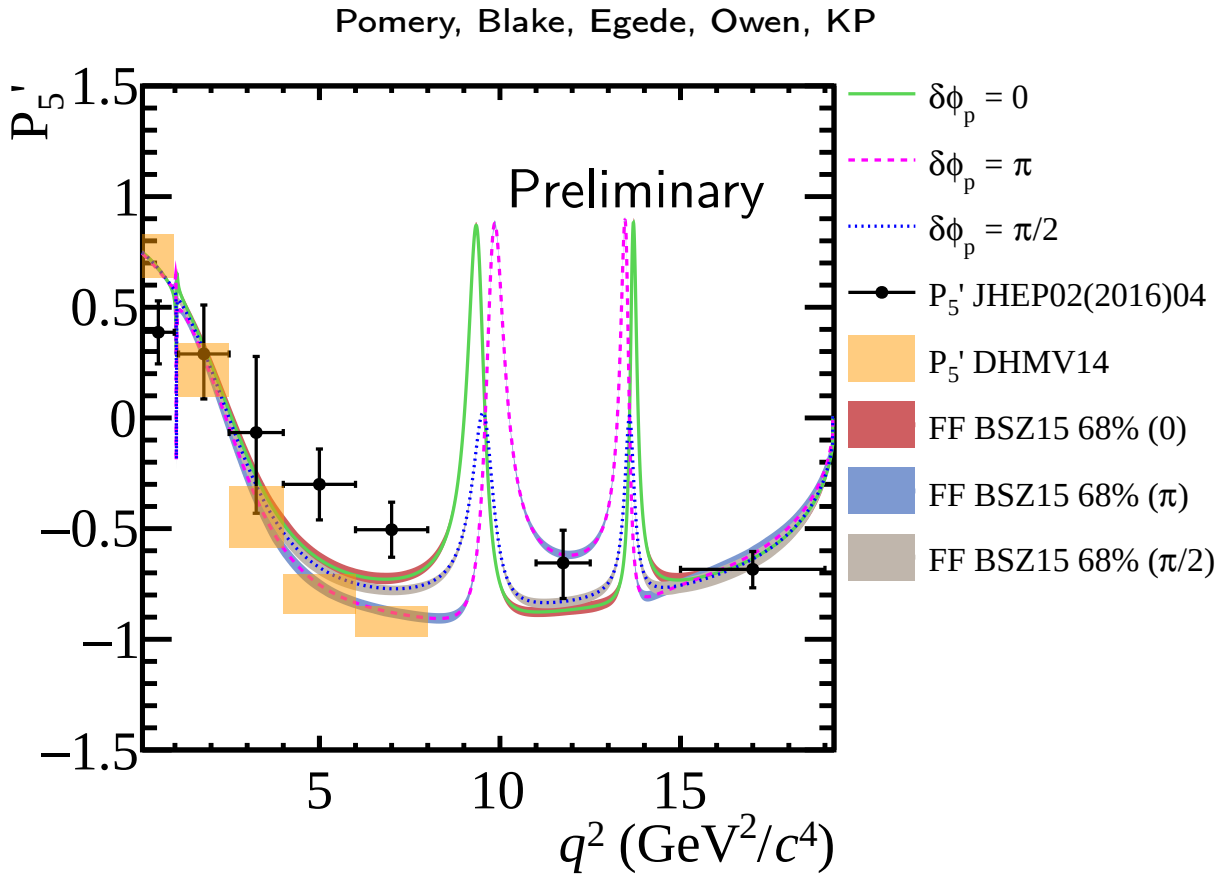
- Angular analyses of $B^0 \to J/\psi K^{*0}$, $B^0 \to \psi(2S)K^{*0}$ and $B^0 \to \phi K^{*0}$ determine relative magnitudes and phases between transversity amplitudes of the decay LHCb[PRD88,052002(2013)], Belle[PRD88,074026(2013)], LHCb[JHEP1405(2014)069] e.g
  - $|A_\perp^{J/\psi}|^2 = 0.20 \pm 0.01$, $|A_\parallel^{J/\psi}|^2 = 0.23 \pm 0.01$, $\delta_\perp^{J/\psi} = 2.94 \pm 0.03$, $\delta_\parallel^{J/\psi} = -2.94 \pm 0.04$,
- Combined with branching fraction measurements from PDG, we can estimate $\chi_{0,\parallel,\perp}$ and $\eta_{0,\parallel,\perp}$ up to a single overall phase difference with the penguin mode ($\delta\phi_p$) for each resonance
- The naive assumption is made that the effect of the penguin contribution within the resonant regions has a small effect on the relative magnitude and phases of the resonant amplitudes

What can we say with current information cont'd

Naively...

- Putting all the theory and experimental information together
- Setting Wilson coefficients to SM and varying FFs within uncertainties
- Ignoring detector resolution effects

- $c\bar{c}$ could explain part of the effect
- Uncertainties of experimental inputs do not change picture
- Potential information in peak positions (need resolution effect)



$\rightarrow$ Worth perform fit to data to extract relative mag's and phases

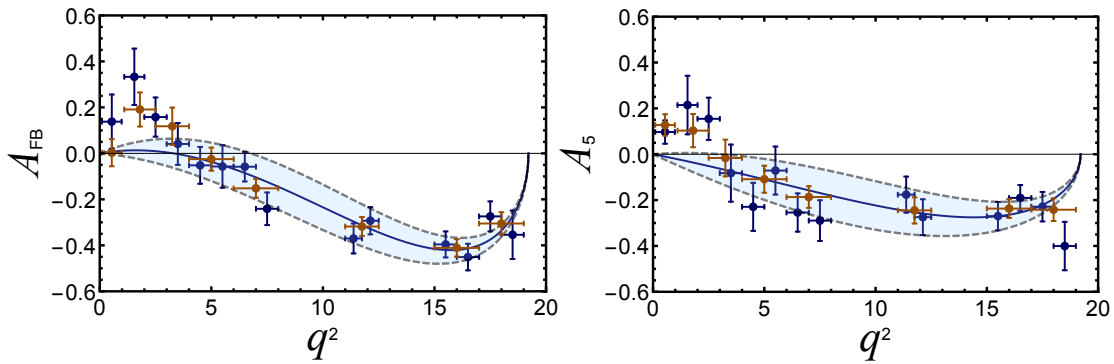
$B^0 \to K^{*0}\mu^+\mu^-$ near kinematic endpoint

- Determining q^2 dependent amplitudes was difficult with Run 1 dataset
- Could not guarantee statistical coverage for all amplitudes/observables
  $\to$ Only subset provided
- With Run 2, back on the table (I know Quim wants at least P_5' continuous in q^2)

What else could we do?

- Observables near kinematic endpoint Hiller, Zwicky [JHEP03(2014)042] and Sinha et al [1603.04355]

- Fit angles and q^2 accounting for variation of phasespace with $m_{K\pi}$
- Resonances at high q^2 will make this fit difficult, could also try finely binned measurements.

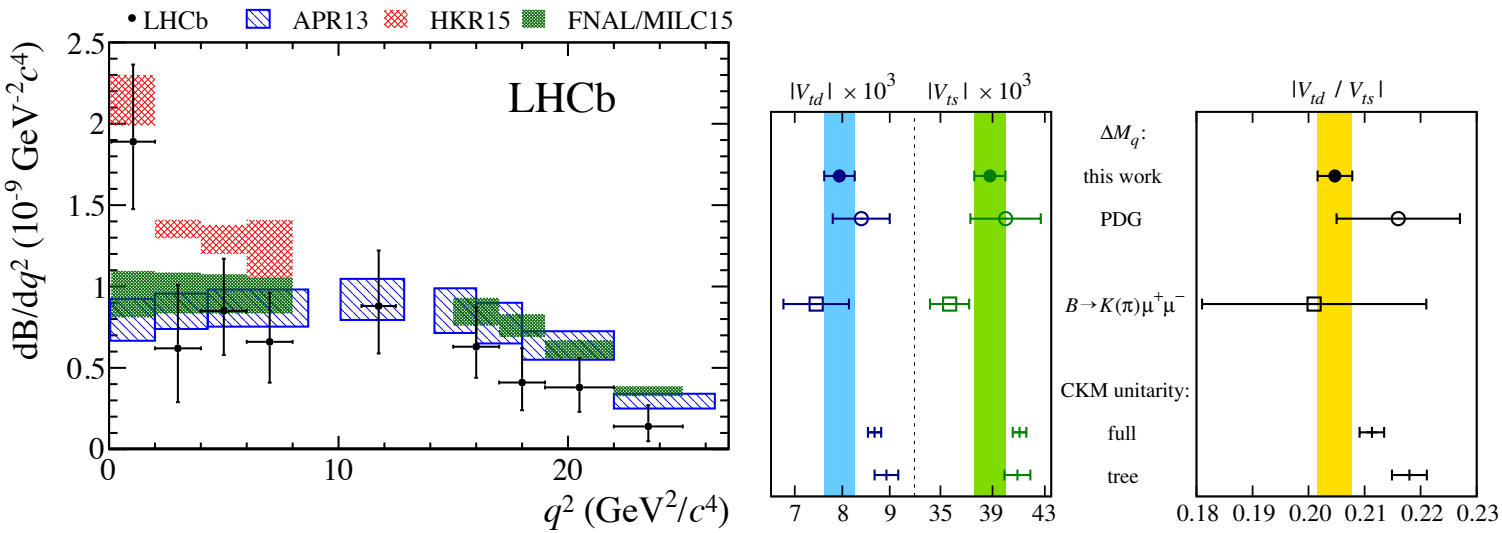


$b \to d\mu^+\mu^-$ measurements

- Run 2 and Upgrade will give access to precision measurements in $b \to d\mu^+\mu^-$ decays (including modes with π^0s)
- Very relevant if tensions persist $\to$ test MFV nature of new physics
- Latest lattice results enable further precision tests of CKM paradigm
  Buras,Blanke[1602.04020], FNAL/MILC[1602.03560]

- Current measurement from penguin decays of $|V_{td}/V_{ts}| = 0.201 \pm 0.020$
  FNAL/MILC[PRD93,034005(2016)]
- Uncertainty dominated by statistical uncertainty of experiment
- Run 2 $\to$ experimental uncertainty halved

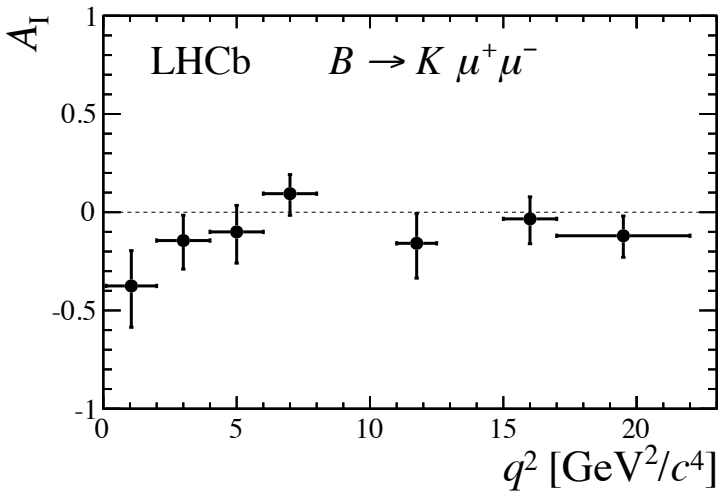
[JHEP10(2015)034] FNAL/MILC[1602.03560], FNAL/MILC[PRD93,034005(2016)]

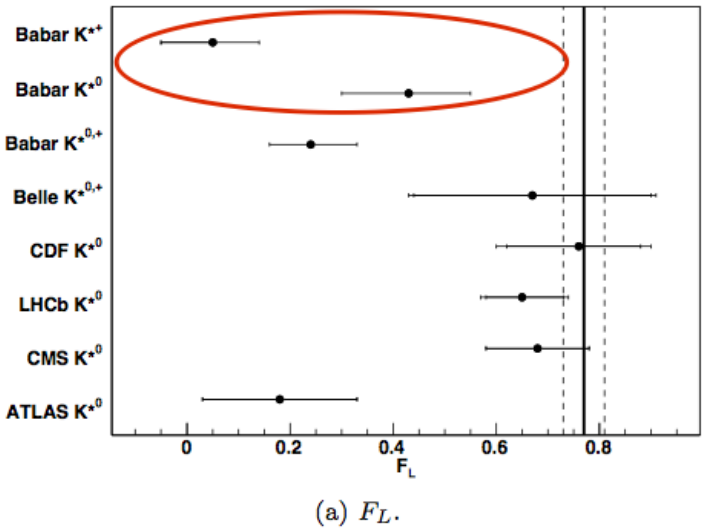


Isospin asymmetry

- Excitement of A_I in $B \to K\mu^+\mu^-$, diminished with the Run 1 measurement $\to$ p-value to $A_I = 0$ hypothesis: 11% (test based on constant distribution of A_I with q^2) for $B \to K\mu^+\mu^-$

Left: [JHEP06(2014)133], Right: BaBar [PRD93,052015(2016)]





(a) F_L.

- Even so, A_I in $B \to K\mu^+\mu^-$ still seems negative
- Hint of tension in F_L between $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$
- Worth revisiting particularly in light of other anomalies (?)

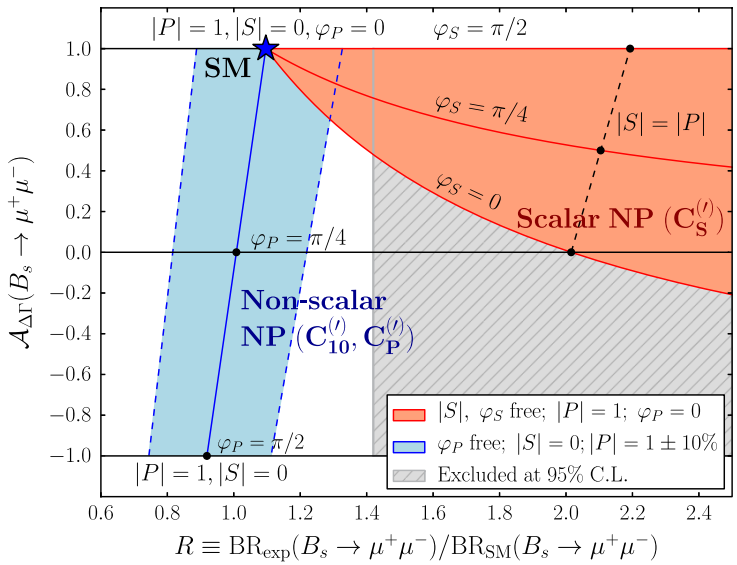
Effective lifetime

- With the LHCb upgrade expect to measure effective lifetime ($\tau_{\mu\mu}$) of $B_s \to \mu^+\mu^-$ at $\sim 5\%$ precision.

$$\Gamma(B_s + \overline{B}_s)(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - A^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right)\right]$$

- $A^{\Delta\Gamma}$ sensitive to new physics even if $\mathcal{B}(B_s \to \mu^+\mu^-)$ compatible with SM

De Bruyn et al [PRL109,041801(2012)]



- With 15,000 $B_s \to \phi\mu^+\mu^-$ candidates expected with the LHCb upgrade, new observables become available in a tagged time-dependent analysis
Descotes-Genon,Virto[JHEP 04 (2015) 045].

Conclusions

- Run 1 of LHCb introduced precision era in $b \to s\mu^+\mu^-$ measurements
- Ideas to help clarify the impact of $c\bar{c}$ and other resonances in $B^0 \to K^{*0}\mu^+\mu^-$ observables
- Did not mention, however measurements involving rare baryon decays also underway
- Run 2 and beyond will enable precision measurements in $b \to d\mu^+\mu^-$ and $B_{s,d} \to \mu^+\mu^-$