Experimental prospects in rare (B-)decays

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Introduction

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

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

LHCb signal yields

channel	3fb^{-1}	Run 2	Upgrade (50fb^{-1})
$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$	2,400	9,000	80,000
$B^0 \to K^{*+}(K^0_{\rm S}\pi^+)\mu^+\mu^-$	160	600	5,500
$B^0 \to K^0_{\rm S}\mu^+\mu^-$	180	650	5,500
$B^+ \to K^+\mu^+\mu^-$	4,700	17,500	150,000
$\Lambda_b \to \Lambda\mu^+\mu^-$	370	1500	10,000
$B^+ \to \pi^+\mu^+\mu^-$	93	350	3,000
$B^0_s \to \mu^+\mu^-$	15	60	500
$B^0 \to K^{*0}e^+e^-$ (low q^2)	150	550	5,000
$B_s \to \phi\gamma$	4,000*	15,000	150,000

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

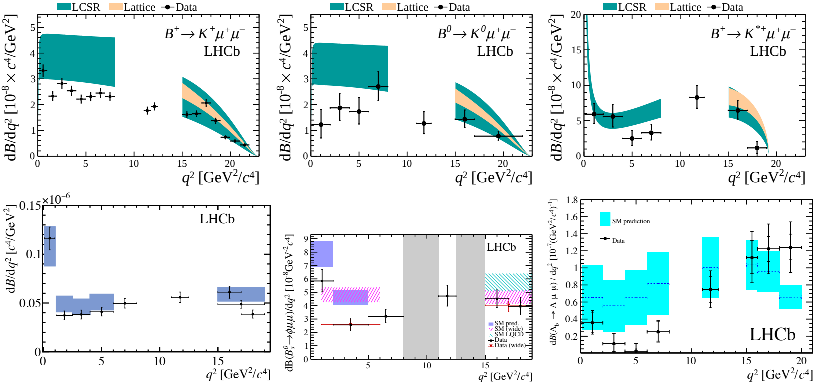
- Our measurements of $d\mathcal{B}/dq^2$ obtained by normalising rare yield to that of normalisation channel $B \to J/\psi K^*$
- For higher statistics decays, dominant uncertainty of integrated BF is the knowledge of $\mathcal{B}(B \to J/\psi K^*)$

  $\to$ 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

An intriguing set of results

1. Measurements of differential branching fractions of $B \to K^{(*)}\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$

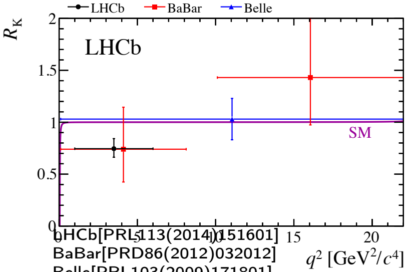
[JHEP06(2014)133], [JHEP07(2011)067], [1606.04731], [JHEP06(2015)115], [PLB725(2013)25]



An intriguing set of results

2. Tests of lepton universality between $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$

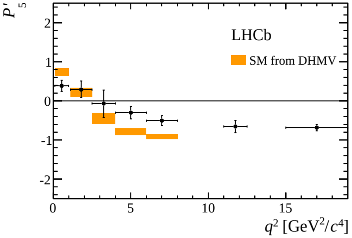
- Measure for $1 < q^2 < 6\,\text{GeV}^2/c^4$
  $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$
- Consistent with SM at $\sim 2.6\sigma$
- Consistent with decay rate measurements if new physics does not couple to electrons

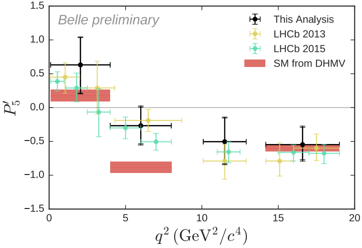


LHCb[PRL113(2014)151601]
BaBar[PRD86(2012)032012]
Belle[PRL103(2009)171801]

An intriguing set of results

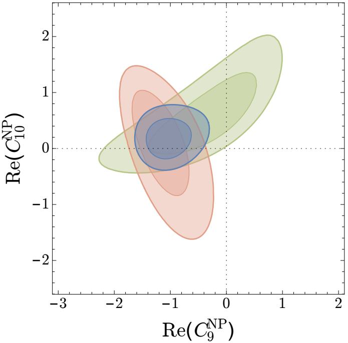
3. Angular analyses of $b \to s\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$





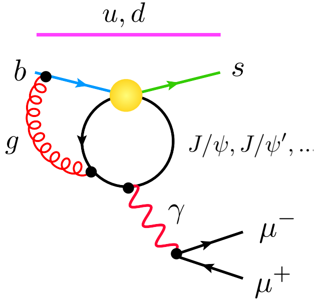
Interpretations

- Several attempts to interpret $b \to s\mu^+\mu^-$ and $b \to s\gamma$ data $\to$ Two views



Altmannshofer,Straub[1503.06199]

- Modified vector coupling $C_9^{NP} \neq 0$ at $\sim 4\sigma$
  $\to$ New vector Z', leptoquarks, vector-like confinement...
  Buttazzo et al [1604.03940], Bauer et al [PRL116,141802(2016)], Crivellin et al [PRL114,151801(2015)], Altmannshofer et al [PRD89(2014)095033]...



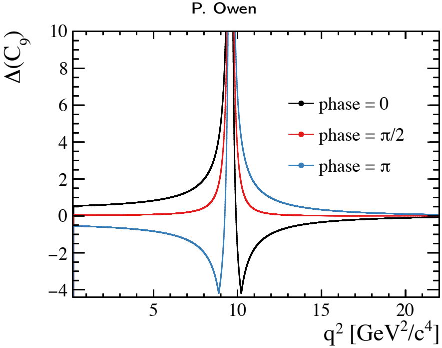
- Potential problem with our understanding of the contribution from $B \to X_{c\bar{c}}(\to \mu\mu)K$ Lyon,Zwicky [1406.0566], Altmannshofer,Straub[1503.06199], Ciuchini et al [1512.07157]...
  $\to$ Mimics vector-like new physics effects (corrections to C_9)

How can experiment help

Impact on C_9^{eff}

$$C_9^{eff} = C_9 + Y(q^2)$$

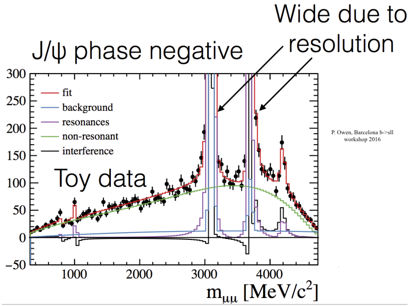
$\rightarrow Y(q^2)$ summarises contributions from $bs\bar{q}q$ operators



- At low q^2 main culprit is the J/ψ
  $\rightarrow$ Corrections to C_9^{eff} (ΔC_9) all the way down to $q^2 = 0$
  $\rightarrow$ **Effect strongly dependent on relative phase with penguin**

Measuring phase differences

- Measure relative phase between narrow resonances and penguin amplitudes
  → Model resonances as relativistic BWs multiplied by relative scale and phase Lyon et al. [1406.0566], Hiller et al. [1606.00775]
  → Use this model to replace $Y(q^2)$ in $C_9^{eff} = Y(q^2) + C_9$
  → $B \to K$ form factors constrainted to LCSR+Lattice predictions
  → Fit for phases and C_9 (and maybe C_{10})



- Fit dimuon spectrum in $B^+ \to K^+\mu^+\mu^-$
  → Expect precision of phase $\sim$ 0.1 rad (ambiguities over sign of phase)[Owen Barcelona workshop 2016]
- Work also ongoing for phases relative to each helicity amplitude of $B^0 \to K^{*0}\mu^+\mu^-$
  → Requires fit to q^2 and angular distribution to dissentangle amplitude components

Can $B \to D\bar{D}K$ help

- Measuring phase differences between charm and penguin relies on model including only resonant charm contributions below the J/ψ
  - Experimentally difficult to differentiate between non resonant charm and penguin
- However, above $\psi(3770)$ we know there should be a non-resonant $D\bar{D}$ component

$\to$ How large should the "virtual" $D\bar{D}$ contribution be below the J/ψ?

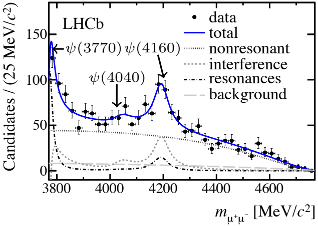
$\to$ Can we learn something from measuring the non-resonant component of $B \to D\bar{D}K$?

What about inclusive $B \to X\mu^+\mu^-$

- Are non-factorisable corrections under better control
- Would a measurement of dimuon spectrum at low recoil help?

  $\to$ Ideas also within LHCb on how to perform a fully inclusive $b \to X\mu^+\mu^-$

$B^+ \to K^+\mu^+\mu^-$ [PRL111,112003(2013)]

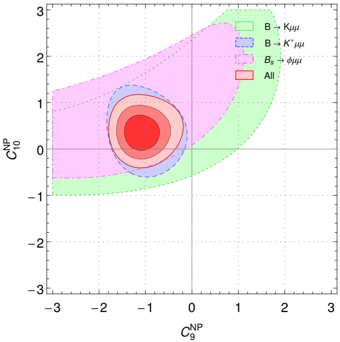


How to avoid charm?

- What about if new physics manifests itself also in C_{10}
  - ▷ Ideal case as do not suffer from effects of charm
- Alternatively: $B \to K\nu\bar{\nu}$

  $\to$ Does not suffer from charm effects

  $\to$ Belle2: Measure $\mathcal{B}(B \to K\nu\bar{\nu})$ at 30% precision (if at SM level)BelleII [1002.5012]
- Measurements of $b \to s\mu^+\mu^-$ provide powerful constraints on C_{10}



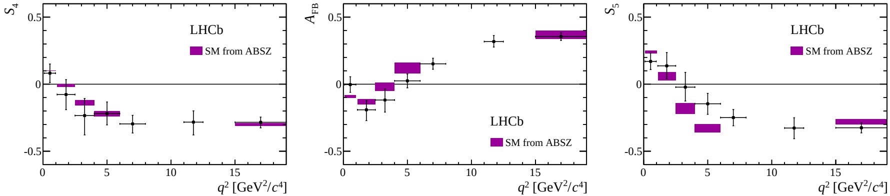
- $b \to s\mu^+\mu^-$ gives 25% precision in C_{10} [DHMV 1510.04329], [Quim priv. comm.]

  $\to$ most power from $B \to K^*\mu^+\mu^-$

New physics in axial-vector couplings cont'd

- Angular analysis measurements statistically limited dataset)
- Experimental uncertainty larger than theory uncertainty on angular observables
  - With Run 2 sample quadruple statistics

[JHEP02(2016)104]

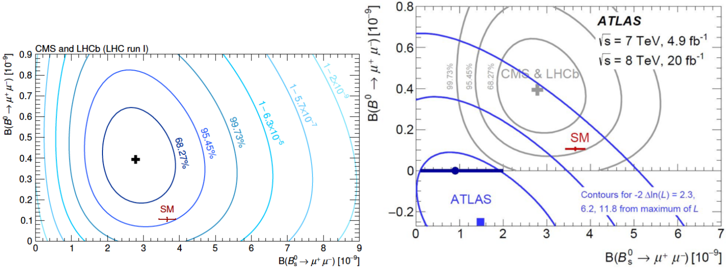


- Larger datasets also help unbinned methods

$B^0_{s,d} \to \mu^+\mu^-$

- LHCb, CMS and ATLAS performed measurements in Run 1
- Constrains on (pseudo) scalar and axial-vector couplings

Left: CMS+LHCb [Nature 522, 68, 2015], Right:ATLAS [1604.04263]

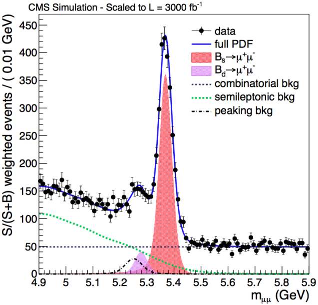


- Major effort to improve analysis techniques for Run 2
  - e.g LHCb: improve PID, isolations, mass descriptions of residual exclusive backgrounds

$B^0_{s,d} \to \mu^+\mu^-$ 2020 and beyond

- Two phases: Run 3 (2020-2023), Run 4 (2025-2029) (...)
- Crucial for detectors to maintain performance at higher inst. luminosities
  $\to$ Improved vertexing detectors (addition of pixel layer CMS, closer to beam LHCb)
  $\to$ Improved tracking (granularity, radiation hardness, reduce material)
  - ▷ Full tracking upgrade of CMS scheduled for 2nd phase

  $\to$ Improved trigger (track based triggers at L1 CMS/ATLAS, 40MHz readout LHCb)



- CMS : $N(B_s) = 2000$, $N(B_d) = 250$ @$3ab^{-1}$
  - ▷ less tracking material $\to$ improved mass resolution ($\times 1.6$ barrel muons)
- LHCb: Major effort to define plan beyond 50fb^{-1} of LHCb [info], $\frac{\mathcal{B}(B_s \to \mu^+\mu^-)}{\mathcal{B}(B_d \to \mu^+\mu^-)} \sim 10\%$ possible with $\geq 300\text{fb}^{-1}$

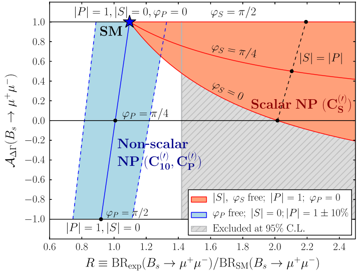
$B_s^0 \to \mu^+\mu^-$ Effective lifetime

- With the LHCb upgrade expect to measure effective lifetime ($\tau_{\mu\mu}$) of $B_s \to \mu^+\mu^-$ at $\sim 5\%$ precision.
- Can extract $A^{\Delta\Gamma}$
- Need 300fb^{-1} to fully exploit

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

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

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

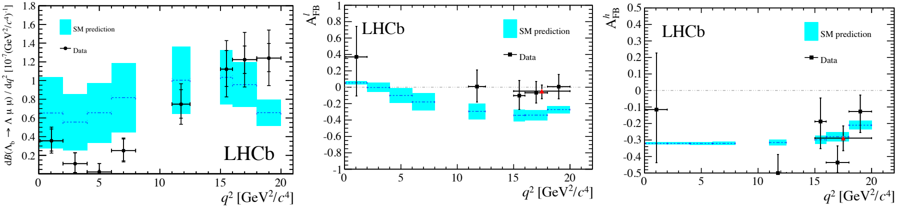


- With 15,000 $B_s \to \phi\mu^+\mu^-$ candidates expected with the LHCb upgrade, new observables become available in a tagged time-dependent analysis Descotes-Genon,Virto[JHEP 04 (2015) 045].

What about baryonic decays

- For example: Run 1: 370 $\Lambda_b \to \Lambda(\to p\pi)\mu^+\mu^-$ events

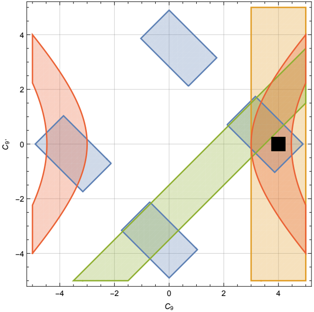
[PLB725(2013)25]



- Additional observables eg A^p_{FB} giving access to different combinations of Wilson coefficients

What about baryonic decays cont'd

vDyk, Meinel [1603.02974],[LHCb implications 2015]
(toy model low recoil)



F_L (common with $B \to K\mu^+\mu^-$)

A_{FB}^{ℓ} (common with $B \to K\mu^+\mu^-$)

$A_{FB}^{\ell p}$ (unique to $\Lambda_b \to \Lambda\mu^+\mu^-$ [not measured yet])

A_{FB}^{p} (unique to $\Lambda_b \to \Lambda\mu^+\mu^-$)

- With $\mathcal{O}(10^3)$ candidates after Run 2, full angular analysis of $\Lambda_b \to \Lambda\mu^+\mu^-$ can access more observables
- Ongoing work on $\Lambda_b \to \Lambda^*(\to pK)\mu^+\mu^-$ BF measurement, CP asymmetry measurements etc

Radiative decays

Photon polarisation

- Photon in $b \to s\gamma$ transitions is almost purely left-handed in the SM
- Multiple approaches to provide a precision measurements of the photon polarisation
  - ▷ Sensitive to combinations of $C_7/C_7^{'}$

$\to$ Measurement of time-dependent CP asymmetry in $B \to K_S\pi^0\gamma$
BaBar [PRD78(2008)071102], Belle [PRD74(2006)111104]

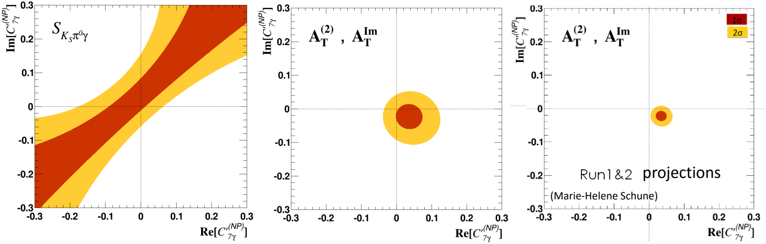
$\to$ Measurement of polarisation parameter in $B \to K\pi\pi\gamma$
Gronau et al. [PRL88(2002)051802], LHCb [PRL112,161801(2014)]

$\to$ Angular analysis of $B^0 \to K^{*0}e^+e^-$ at low q^2 (contribution from $C_{9,10}$ are small) Becirevic et al. [JHEP08(2012)090], Camalich, Jaeger [PRD93,014028], LHCb [JHEP04(2015)064]

Constraints on $C_7^{(\prime)}$

- Angular $B^0 \to K^{*0}ee$ measurements currently provide best constraints to C_7'

Left: $A_{CP}(t)\ K_S\pi^{\mathbf{0}}\gamma$, Middle: K^*ee angular Run 1, Right: K^*ee angular Run 2 projections



($C_{\mathbf{7}}^{NP} = 0$) Borsato thesis [CERN-THESIS-2015-219]

- Expected constraints from K^*ee after Run 2
  - Also measure full set of observables
- Note $A_{CP}(t)K_S\pi^0\gamma$ precision improves by $\sim \times 7$ with BelleII

Photon polarisation through $B_s \to \phi\gamma$

- LHCb has ~ 4000 $B_s \to \phi\gamma$ events in Run 1
  $\to$ Enables untagged measurement of the time dependent decay rate

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

  $A^{\Delta\Gamma} \sim \frac{|\mathcal{A}(B_s\to\phi\gamma_L)|}{|\mathcal{A}(B_s\to\phi\gamma_R)|} cos\phi_s$

  $A^{\Delta\Gamma}(SM) = 0.047 \pm 0.025 \pm 0.015_{\alpha_s}$ Muheim et al. [PLB664(08)174]

  $\to$ Requires good understanding of the detection efficiency as a function decay time

  $\to$ Use $B^0 \to K^{*0}\gamma$ data to constrain the efficiency
- Result expected soon using Run 1 data
- With Run 2 data 20,000 $B_s \to \phi\gamma$
  - Expected stat. precision on $A^{\Delta\Gamma} \sim 0.13$ (for SM like $A^{\Delta\Gamma}$) (syst. unc. similar to stat. unc.)A. Oyanguren [Barcelona Workshop 2016]
  - With flavour tagging $\to \sim 1000$ candidates, measure additional observables (a la $B^0 \to K_S\pi^0\gamma$)

Lepton Non-Universality and Flavour Violation

LNU and LFV with rare B-decays

- Mild tension in $R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$ consistent with $b \to s\mu^+\mu^-$ anomalies if new physics couples only to muons and not electrons
  - Rich program to measure R_{K^*}, R_ϕ, R_{Λ^*}, R_{angular}
- Coupled with 4σ tension in $R(D^*)$, $R(D)$ plane
  $\rightarrow$ Strong hints of lepton non universality in both tree-level and loop-level transitions
  $\rightarrow$ Can generate lepton flavour violating effects Glashow et al.[PRL114,091801(2015)]
- Current limit $\mathcal{B}(B \to K\mu\tau) < 4.8 \times 10^{-5}$@90% CL Babar [PRD86,012004(2012)]
- Models predict particular enhancements in $B \to K\mu\tau$ final states
  $\rightarrow \mathcal{B}(B^+ \to K\mu\tau) \sim 10^{-8} - 10^{-6}$ Hiller et al. [1503.01084], Glashow et al. [PRL114,091801(2015)], Feruglio et al.[1606.00524]
- Ongoing work within LHCb, $\leq \mathcal{O}(10^{-6})$ achievable with Run 2 data

LNU and LFV with rare B-decays cont'd

- These models also can predict enhacments to $b \to s\tau\tau$ amplitudes
  $\to$ up to $\times 5\mathcal{B}$(SM) Greljo et al. [JHEP1507(2015)142]
  e.g $\mathcal{B}(B \to K\tau\tau) \sim \mathcal{O}(10^{-6})$

- Latest limit by BaBar BaBar [1605.09637]
  $\to \mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$@90% CL
- Ongoing work for LHCb ($\mathcal{B}(B^0 \to K^{*0}(\to K^+\pi^-)\tau^+\tau^-)$
  - $K^{*0} \to K^+\pi^-$ gives B^0 decay vertex

- Also ongoing for LHCb $B_s \to \tau^+\tau^-$
  - Both τs decay in flight$\to$ cannot reconstruct B_s vertex
  - Use 3-prong τ decays to help reconstruct (approximate) decay topology
  - Sensitive to $\mathcal{B}(B_s \to \tau^+\tau^-) \sim \mathcal{O}(10^{-3})$...

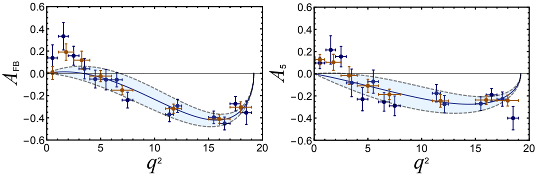
Related measurements

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

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.

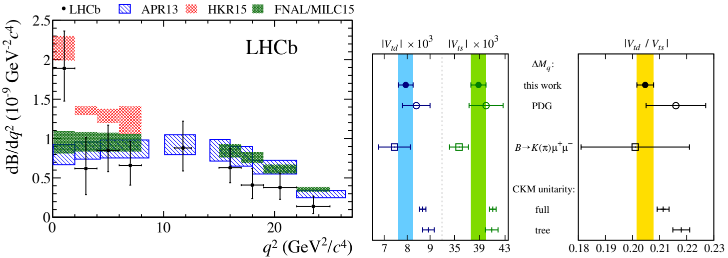


$b \to d\mu^+\mu^-$ measurements

- 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]
- Run 2 $\to$ experimental uncertainty halved, more modes available

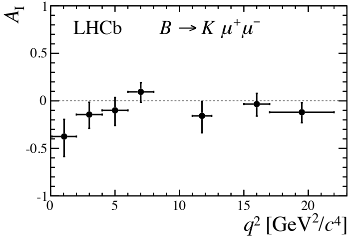
[JHEP10(2015)034] FNAL/MILC[1602.03560], FNAL/MILC[PRD93,034005(2016]

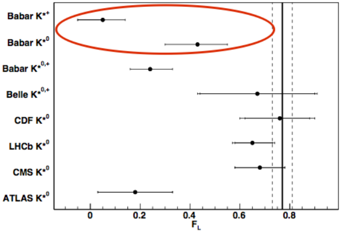


Isospin asymmetry

- 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 (?)

Summary

- Run 1 of the LHC introduced precision era in rare B-decay measurements
- Many measurements and plans under way:

$\rightarrow$ Clarify the impact of $c\bar{c}$ and other resonances in $B^0 \rightarrow K^{*0}\mu^+\mu^-$ observables

$\rightarrow$ Fully exploit sensitivity of $b \rightarrow s\ell\ell$ to $C_{10}^{(\prime)}$

$\rightarrow$ Baryonic decays provide additional powerful constraints

$\rightarrow$ Suite of photon polarisation measurements to constrain new physics in $C_7^{(\prime)}$

$\rightarrow$ Understand LNU hints in R_K both by searching in related modes as well as looking for LFV

$\rightarrow$ Towards Run 2 and beyond + Belle2

Backup

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]
$d\mathcal{B}/dq^2$ $B^0 \to K^{*0}\mu^+\mu^-$	3	[1606.04731]
$d\mathcal{B}/dq^2$ $B_s^0 \to \phi\mu^+\mu^-$	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)]
$\mathcal{B}(B^0 \to K^{*0}e^+e^-)$	3	[JHEP05(2013)159]
$\mathcal{B}(B^+ \to K^+e^+e^-)$	3	[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]