Rare Beauty and Charm Decays at LHCb

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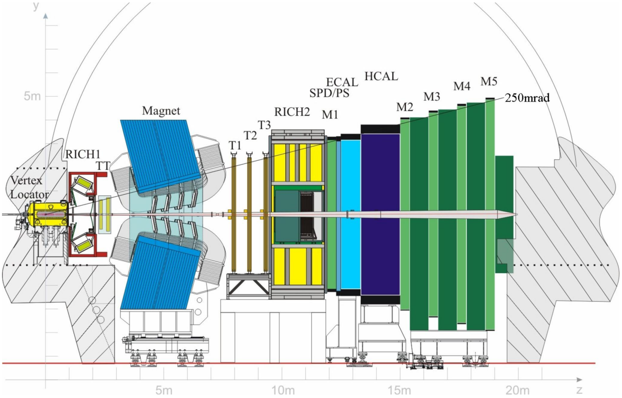
Outline

- Branching fraction measurements
  - $\mathrm{B}_s^0 \to \phi\mu^+\mu^-$ differential branching fraction measurement
  - $B^+ \to \pi^+\mu^+\mu^-$ branching fraction measurement
- Branching fraction limits
  - $B \to \mu^+\mu^-\mu^+\mu^-$ branching fraction limits
  - $B \to \mu^+\mu^-$ branching fraction limits
  - $D^0 \to \mu^+\mu^-$ branching fraction limits

The LHCb Detector

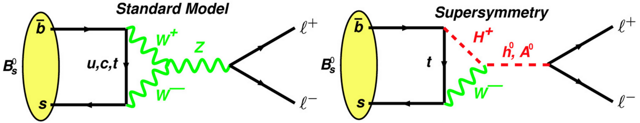
- LHCb is a forward detector ($2 < \eta < 5$) designed to study heavy flavour physics



- LHCb has excellent vertex and momentum resolution, PID and μ-ID ...
- Each of these are critical for studies of heavy flavour physics

Rare Decays at LHCb

- LHCb is searching for physics beyond the Standard Model (SM) by studying rare B and D meson decays
- The rare decays discussed here are Flavour Changing Neutral Current processes
  - These are mediated by loop diagrams in the SM
- New physics particles can make significant contributions to these diagrams



- New physics contributions can affect:
  - The Lorentz structure, accessible through angular analysis
  - The total amplitude, accessible through branching fraction measurement

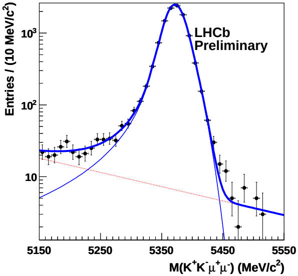
- Indirect searches at LHCb are complimentary to direct searches at the GPDs

$B_s^0 \to \phi\mu^+\mu^-$ differential branching fraction measurement
LHCB-CONF-2012-003

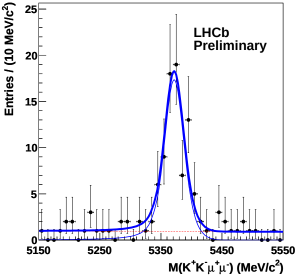
$B_s^0 \to \phi\mu^+\mu^-$ differential branching fraction

- Branching fraction of $B_s^0 \to \phi\mu^+\mu^-$ sensitive to new physics contributions
- Extract as ratio with $B_s^0 \to J/\psi\,\phi$ events to cancel systematic effects
- LHCb($1.0\ \text{fb}^{-1}$) : $B_s^0 \to \phi\mu^+\mu^-$: 77 ± 10 signal events

$B_s^0 \to J/\psi\,\phi$



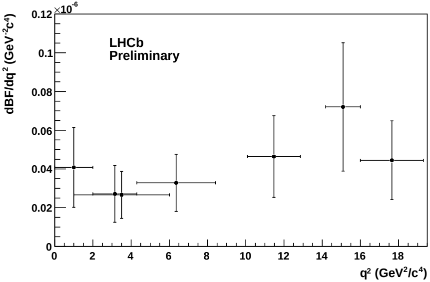
$B_s^0 \to \phi\mu^+\mu^-$



- $\frac{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi\,\phi)} = 0.558 \pm 0.070(\text{stat}) \pm 0.043(\text{syst}) \pm 0.006(\mathcal{B})) \times 10^{-3}$

$B_s^0 \to \phi\mu^+\mu^-$ differential branching fraction

- Using PDG value for $\mathcal{B}(B_s^0 \to J/\psi\,\phi) = (1.4 \pm 0.5) \times 10^{-3}$ can calculate:
- $\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (0.78 \pm 0.10(\text{stat}) \pm 0.06(\text{syst}) \pm 0.28(\mathcal{B})) \times 10^{-6}$
- Can also extract the branching fraction in bins of $q^2 = m^2_{\mu^+\mu^-}\ \text{GeV}^2/c^4$ plus the theoretically interesting region $1 < q^2 < 6\,\text{GeV}^2/c^4$



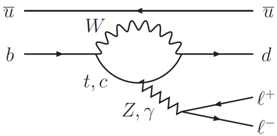
- The most precise measurement to-date and is consistent with the SM expectation [1]

First observation of $B^+ \to \pi^+\mu^+\mu^-$

LHCb-CONF-2012-006

First observation of $B^+ \to \pi^+\mu^+\mu^-$

- The $B^+ \to \pi^+\mu^+\mu^-$ decay is a $b \to d\ell\ell$ transition



  - In the SM the branching fraction is $\sim$ 25x smaller than analogous $B^+ \to K^+\mu^+\mu^-$ ($b \to s\ell\ell$) transition but it can be enhanced in new physics models
  - This decay can be used for measurement of $\frac{V_{td}}{V_{ts}}$ from penguin diagrams

- The SM prediction is $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = 1.96 \pm 0.21 \times 10^{-8}$ [2]
- Current limit set by BELLE at $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) < 6.9 \times 10^{-8}$ at 90% C.L. [3]

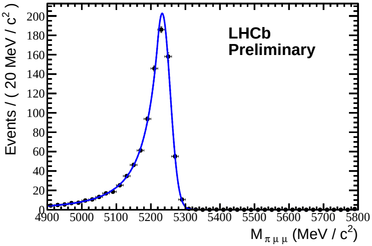
First observation of $B^+ \to \pi^+\mu^+\mu^-$

- A major background comes from mis-identified $B^+ \to K^+\mu^+\mu^-$ decays
- A critical analysis issue is separating these two decays
  - The $K - \pi$ separation provided by the LHCb RICH detectors is crucial

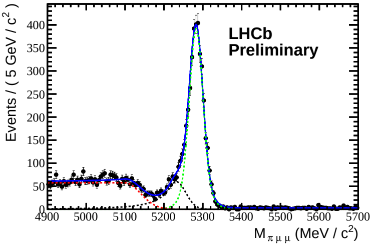
- Simultaneous fit in data of
  - $B^+ \to J/\psi K^+$, for the $B^+ \to \pi^+\mu^+\mu^-$ line shape
  - Mis-ID $B^+ \to J/\psi K^+$, for the shape of residual $B^+ \to K^+\mu^+\mu^-$ events (left)
  - $B^+ \to \pi^+\mu^+\mu^-$, for the signal yield (next slide!)

- Fit method validated on $B^+ \to J/\psi \pi^+$ events (right)

$B^+ \to J/\psi K^+$ with $m_K \to m_\pi$



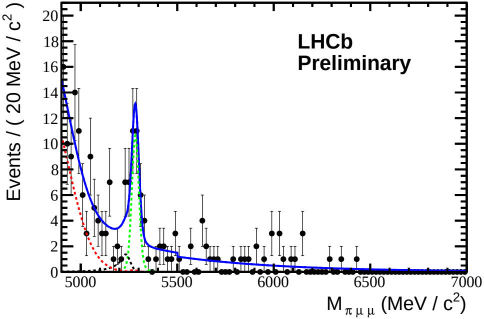
$B^+ \to J/\psi \pi^+$



First observation of $B^+ \to \pi^+\mu^+\mu^-$

- This is the first observation of a $b \to d\ell\ell$ transition
- LHCb(1.0 fb^{-1}) : $B^+ \to \pi^+\mu^+\mu^-$: $25.3^{+6.7}_{-6.4}$ events, a 5.2σ excess above background
- The measurement is consistent with the SM prediction

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



- $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (2.4 \pm 0.6(stat) \pm 0.2(syst)) \times 10^{-8}$ [preliminary]
- The rarest B decay ever observed

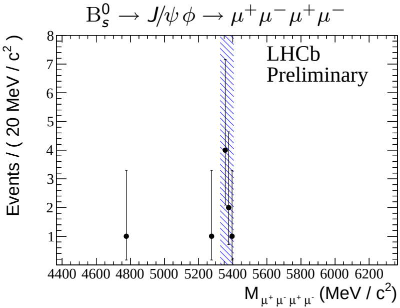
Search for $B \to \mu^+\mu^-\mu^+\mu^-$

LHCb-CONF-2012-010

Search for $B \to \mu^+\mu^-\mu^+\mu^-$

- No search for $B \to \mu^+\mu^-\mu^+\mu^-$ performed until now
- Can be mediated by decay to new physics S,P particles where both decay $\to \mu^+\mu^-$
- Evidence for P particle at hyperCP experiment with $m_P \approx 214\,\mathrm{MeV}$ [4]

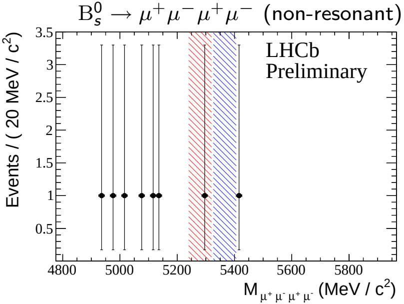
- Expect 4μ final state in the SM from $\mathrm{B}_s^0 \to J/\psi\,\phi$ 'resonant' decays
  - where $J/\psi \to \mu^+\mu^-$ and $\phi \to \mu^+\mu^-$
  - from the PDG: $\mathcal{B}(\mathrm{B}_s^0 \to J/\psi\,\phi \to 4\mu) = (2.38 \pm 0.87) \times 10^{-8}$ [5]



- The non-resonant SM prediction is $< 10^{-10}$ [6]

Search for $B \to \mu^+\mu^-\mu^+\mu^-$

- Now excluding J/ψ and ϕ resonant decays ...



- Observed number of non-resonant events consistent with background expectation
- Branching fraction limits set using $\mathrm{CL_S}$ method and phase-space model:

$$\left.\begin{array}{l}\mathcal{B}(B_s^0 \to \mu^+\mu^-\mu^+\mu^-) < 1.3 \times 10^{-8} \\ \mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 5.4 \times 10^{-9}\end{array}\right\} \text{ at 95\% C.L. [preliminary]}$$

- These measurements are consistent with SM predictions
- Worlds first limits on $B \to \mu^+\mu^-\mu^+\mu^-$

The Search for $B \to \mu^+\mu^-$ and $D^0 \to \mu^+\mu^-$

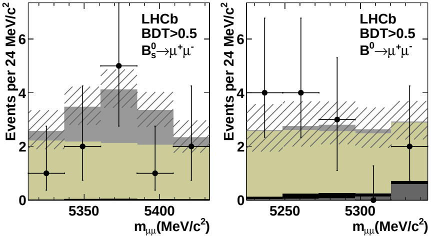
LHCb-PAPER-2012-007

LHCB-CONF-2012-005

The Search for $B \to \mu^+\mu^-$ and $D^0 \to \mu^+\mu^-$

- World best limits on $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$
- The branching fractions are sensitive to contributions from new scalar particles
  - New limits constrain e.g. the SUSY parameter space at high $\tan\beta$
- SM prediction $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ [7]
- SM prediction $\mathcal{B}(B^0 \to \mu^+\mu^-) = (0.10 \pm 0.01) \times 10^{-9}$ [8]

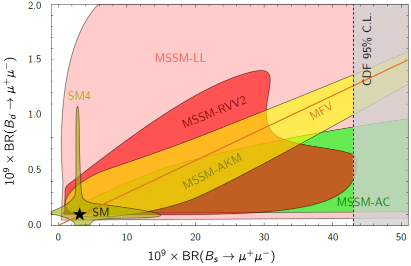
mode	limit	at 95% C.L.
$B_s^0 \to \mu^+\mu^-$	expected bg+SM	7.2×10^{-9}
	expected bg only	3.4×10^{-9}
	observed	4.5×10^{-9}
$B^0 \to \mu^+\mu^-$	expected	1.13×10^{-9}
	observed	1.03×10^{-9}



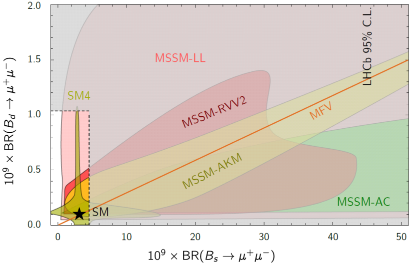
- Worlds best limit on $D^0 \to \mu^+\mu^-$ decay:
  - $\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.3 \times 10^{-8}$ at 95% C.L. [preliminary]
- An order of magnitude improvement from previous experiments [9] and consistent with the SM prediction [10]

SUSY limits from B and D decays

Status of limits pre-LHC



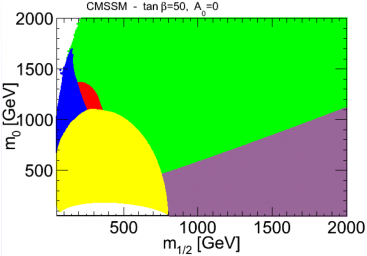
Current LHCb limits



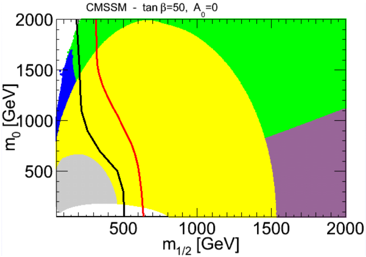
Plots from D. Straub. [link]

SUSY limits from B and D decays

Flavour physics limits (EPS)



Current flavour physics limits



Allowed
No LSP
$\mathcal{B}(\bar{B} \to X_s\gamma)$
$\mathcal{B}(B \to \tau\nu)$
$\mathcal{B}(\mathrm{B}_s^0 \to \mu^+\mu^-)$
$\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-)$
(line) CMS exclusion limit with 1.1 fb data
(line) CMS exclusion limit with 4.4 fb data

Plots from N. Mahmoudi. [link]

Summary

- $\mathrm{B}_s^0 \to \phi\mu^+\mu^-$ Worlds most precise differential branching fraction measurement
  - LHCB-CONF-2012-003
- $B^+ \to \pi^+\mu^+\mu^-$ Worlds most precise branching fraction measurement [First observation!]
  - LHCb-CONF-2012-006
- $B \to \mu^+\mu^-\mu^+\mu^-$ Worlds first branching fraction limits
  - LHCb-CONF-2012-010
- $B \to \mu^+\mu^-$ Worlds best branching fraction limits
  - LHCb-PAPER-2012-007
- $D^0 \to \mu^+\mu^-$ Worlds best branching fraction limit [Order of magnitude improvement!]
  - LHCB-CONF-2012-005

References I

[1] C. Geng and C. Liu, *Study of $B_s \to (\eta, \eta', \phi)\ell\bar{\ell}$ decays*, J. Phys. G **G29** (2003) 1103, arXiv:hep-ph/0303246.

[2] S. Hai-Zhen, L. Lin-Xia, and L. Gong-Ru, *New physics effects on rare decays $B^+ \to \pi^+\ell^+\ell^-$, $\rho^+\ell^+\ell^-$ in a top quark two-higgs-doublet model*, Communications in Theoretical Physics **50** (2008) 696.

[3] Belle Collaboration, J.-T. Wei *et al.*, *Search for $B \to \pi\ell^+\ell^-$ Decays at Belle*, Phys. Rev. **D78** (2008) 011101, arXiv:0804.3656.

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[5] Particle Data Group, K. Nakamura et al., *Review of particle physics*, J. Phys. **G37** (2010) 075021, and 2011 partial update for the 2012 edition.

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[7] A. J. Buras, M. V. Carlucci, S. Gori, and G. Isidori, *Higgs-mediated FCNCs: Natural Flavour Conservation vs. Minimal Flavour Violation*, JHEP **10** (2010) 009, arXiv:1005.5310.

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[9] Belle Collaboration, M. Petric *et al.*, *Search for leptonic decays of D^0 mesons*, Phys. Rev. **D81** (2010) 091102, arXiv:1003.2345.

[10] G. Buchalla, A. J. Buras, and M. E. Lautenbacher, *Weak decays beyond leading logarithms*, Rev. Mod. Phys. **68** (1996) 1125, arXiv:hep-ph/9512380.

$\mathrm{B}^0 \to K^{*0}\mu^+\mu^-$

$$\frac{1}{\Gamma}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}\,\mathrm{d}q^2} = \frac{9}{16\pi}\Big[\, F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) \;+$$

$$F_L\cos^2\theta_K(2\cos^2\theta_\ell - 1) \;+$$

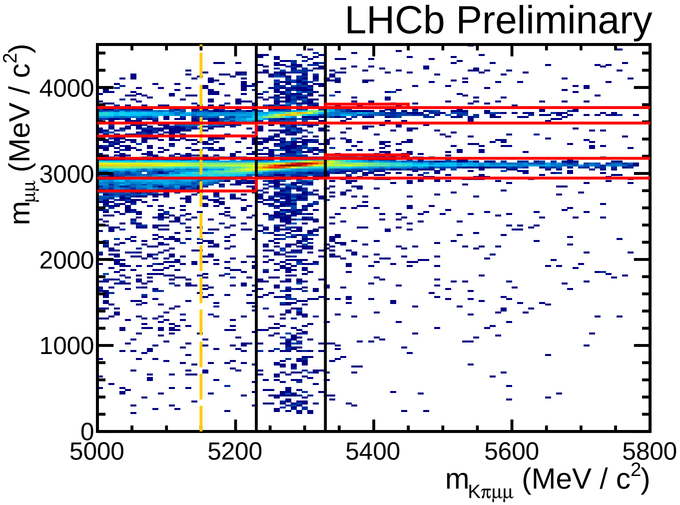
$$\frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) \;+$$

$$S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} \;+$$

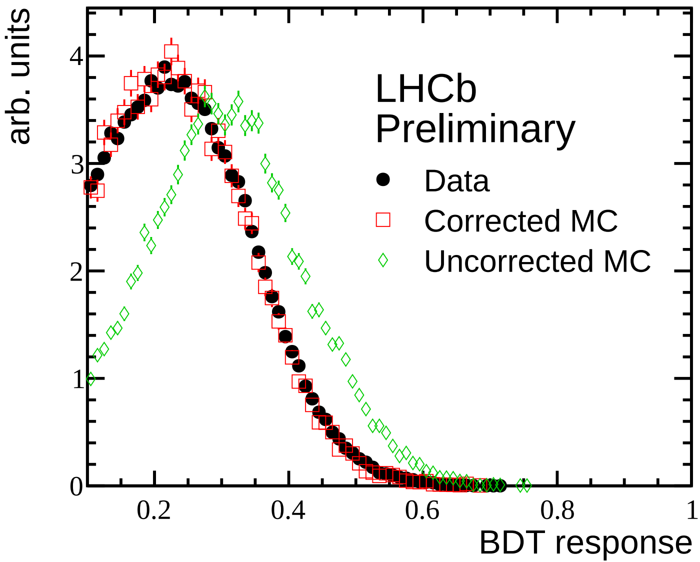
$$\frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell \;+$$

$$A_{Im}(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi}\,\Big]$$

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



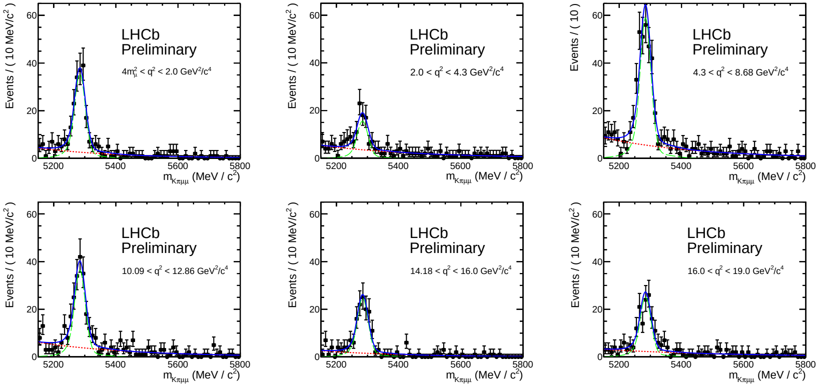
LHCb Preliminary
$m_{\mu\mu}$ (MeV / c^2)
4000
3000
2000
1000
0
5000
5200
5400
5600
5800
$m_{K\pi\mu\mu}$ (MeV / c^2)



arb. units
4
3
2
1
0
0.2
0.4
0.6
0.8
1
BDT response
LHCb
Preliminary
Data
Corrected MC
Uncorrected MC

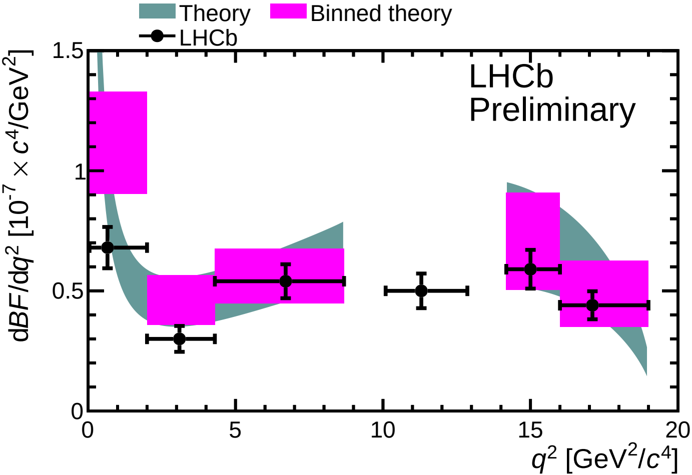
q^2 (GeV^2/c^4) range	Signal Yield	Background Yield
$4m_\mu^2 < q^2 < 2.00$	162.4 ± 14.2	27.7 ± 3.8
$2.00 < q^2 < 4.30$	71.4 ± 10.7	37.1 ± 4.1
$4.30 < q^2 < 8.68$	270.5 ± 18.8	58.8 ± 5.5
$10.09 < q^2 < 12.90$	167.0 ± 14.9	41.7 ± 4.5
$14.18 < q^2 < 16.00$	113.0 ± 11.7	17.1 ± 3.0
$16.00 < q^2 < 19.00$	115.0 ± 12.4	23.9 ± 3.6
$1.00 < q^2 < 6.00$	195.2 ± 16.9	75.8 ± 6.0
$4m_\mu^2 < q^2 < 19.00$	900.0 ± 34.4	206.2 ± 10.3

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



LHCb
Preliminary
$4m_\mu^2 < q^2 < 2.0$ GeV^2/c^4
$2.0 < q^2 < 4.3$ GeV^2/c^4
$4.3 < q^2 < 8.68$ GeV^2/c^4
$10.09 < q^2 < 12.86$ GeV^2/c^4
$14.18 < q^2 < 16.0$ GeV^2/c^4
$16.0 < q^2 < 19.0$ GeV^2/c^4
Events / (10 MeV/c^2)
Events / (10)
$m_{K\pi\mu\mu}$ (MeV / c^2)
0
20
40
60
5200
5400
5600
5800

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


Theory
Binned theory
LHCb
LHCb
Preliminary
1.5
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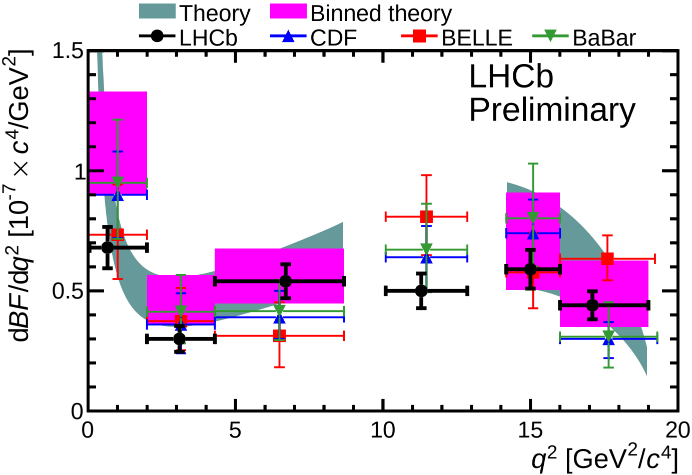
dBF/dq^2 [$10^{-7} \times c^4$/GeV^2]
q^2 [GeV^2/c^4]

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


Theory
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LHCb
CDF
BELLE
BaBar
LHCb
Preliminary
dBF/dq^2 [$10^{-7} \times c^4$/GeV^2]
q^2 [GeV^2/c^4]
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0.5
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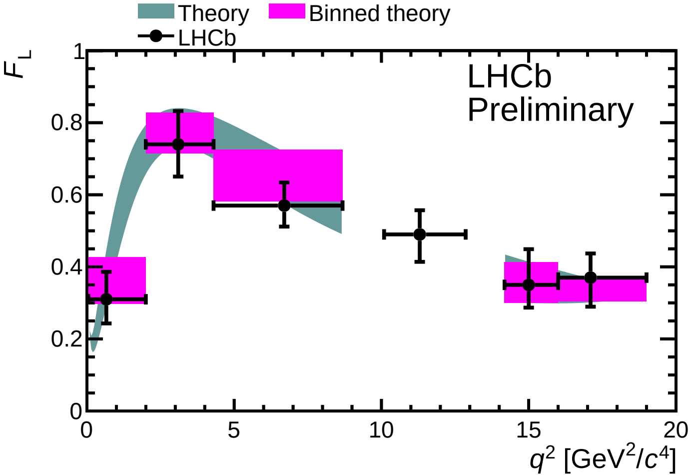
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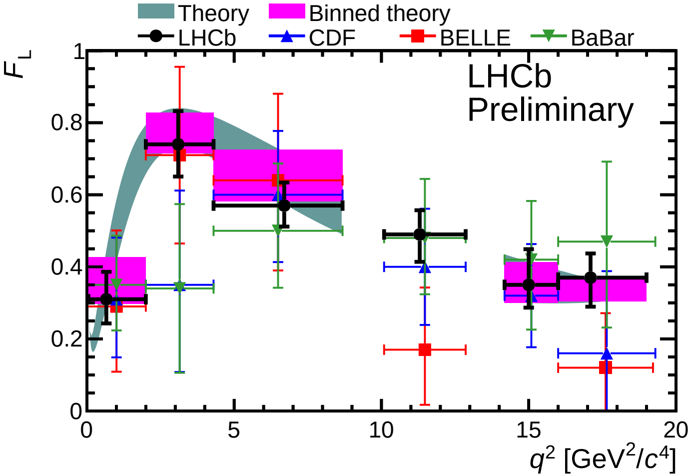
q^2 [GeV^2/c^4]

$B^0 \to K^{*0}\mu^+\mu^-$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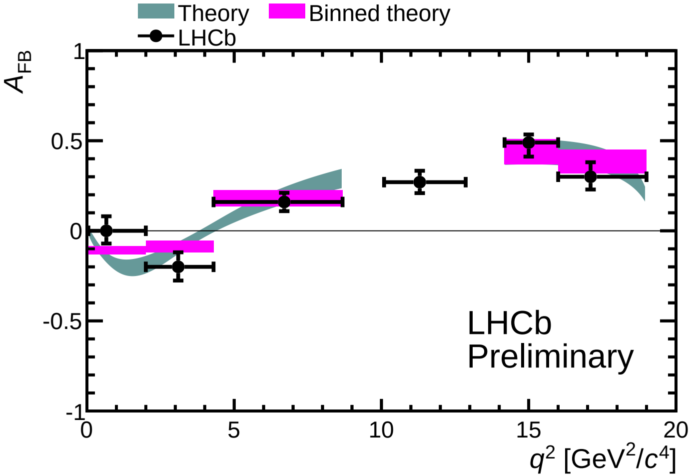
q^2 [GeV^2/c^4]

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


Theory
Binned theory
LHCb
A_{FB}
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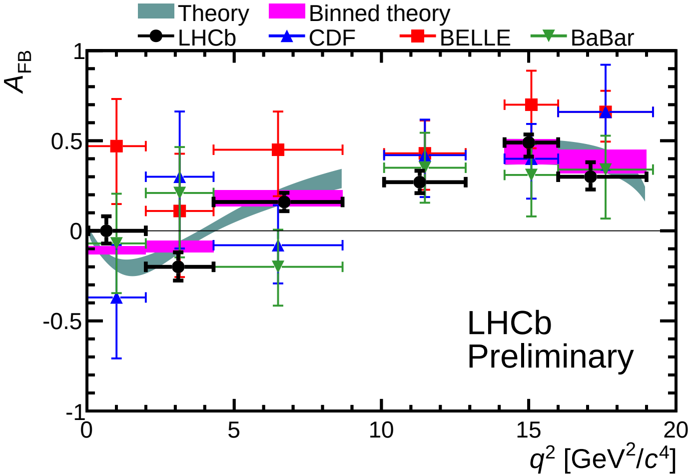
q^2 [GeV^2/c^4]
LHCb
Preliminary

$B^0 \to K^{*0}\mu^+\mu^-$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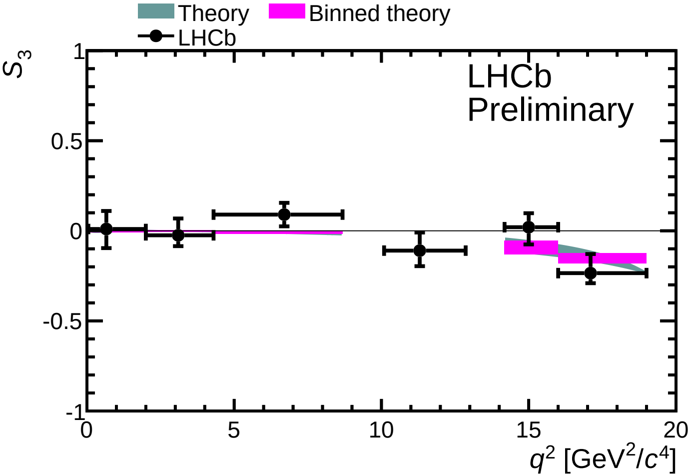
q^2 [GeV^2/c^4]
LHCb
Preliminary

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



Theory
Binned theory
LHCb
S_3
LHCb
Preliminary
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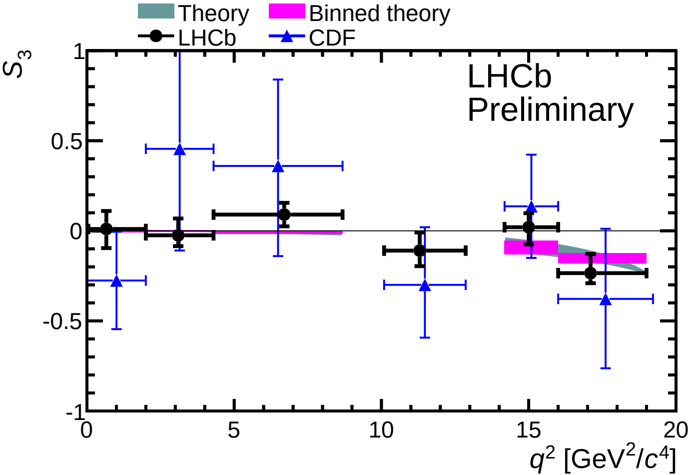
20
q^2 [GeV^2/c^4]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CDF
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LHCb
Preliminary
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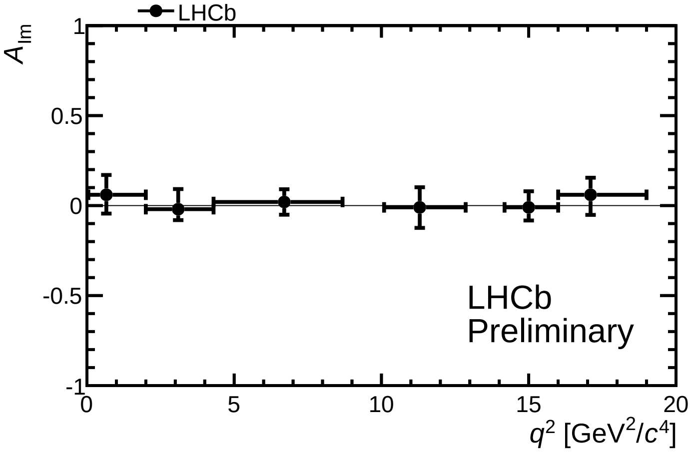
20
q^2 [GeV^2/c^4]


LHCb
$A_{\rm Im}$
1
0.5
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-0.5
-1
0
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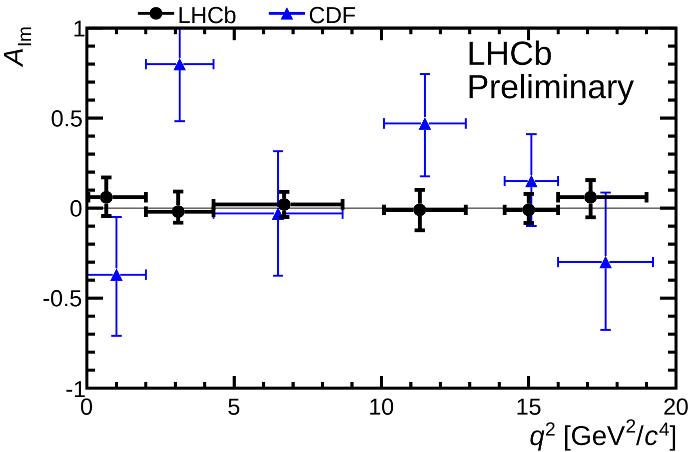
q^2 [GeV^2/c^4]
LHCb
Preliminary

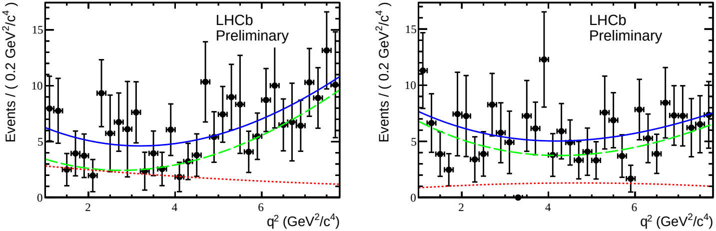

LHCb
CDF
A_{Im}
1
0.5
0
-0.5
-1
LHCb
Preliminary
0
5
10
15
20
q^2 [GeV^2/c^4]

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

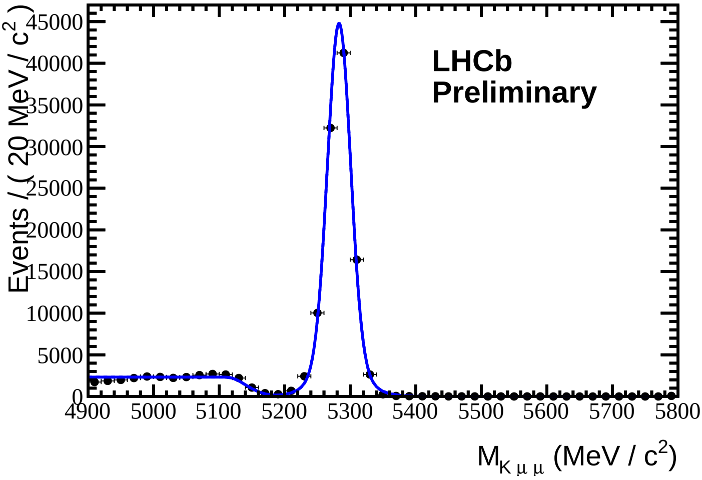
q^2 range (GeV^2/c^4)	dBF/dq^2 ($\times 10^{-7}$ $GeV^{-2}c^4$)	A_{FB}	F_L
$4m_\mu^2 < q^2 < 2.00$	$0.68 \pm 0.07 \pm 0.05$	$0.00^{+0.08}_{-0.07}{}^{+0.01}_{-0.01}$	$0.31^{+0.07}_{-0.06}{}^{+0.03}_{-0.03}$
$2.00 < q^2 < 4.30$	$0.30 \pm 0.05 \pm 0.02$	$-0.20^{+0.08}_{-0.07}{}^{+0.01}_{-0.03}$	$0.74^{+0.09}_{-0.08}{}^{+0.02}_{-0.04}$
$4.30 < q^2 < 8.68$	$0.54 \pm 0.05 \pm 0.05$	$0.16^{+0.05}_{-0.05}{}^{+0.01}_{-0.01}$	$0.57^{+0.05}_{-0.05}{}^{+0.04}_{-0.03}$
$10.09 < q^2 < 12.89$	$0.50 \pm 0.06 \pm 0.04$	$0.27^{+0.06}_{-0.06}{}^{+0.02}_{-0.01}$	$0.49^{+0.06}_{-0.07}{}^{+0.03}_{-0.03}$
$14.18 < q^2 < 16.00$	$0.59 \pm 0.07 \pm 0.04$	$0.49^{+0.04}_{-0.06}{}^{+0.02}_{-0.05}$	$0.35^{+0.07}_{-0.06}{}^{+0.07}_{-0.02}$
$16.00 < q^2 < 19.00$	$0.44 \pm 0.05 \pm 0.03$	$0.30^{+0.07}_{-0.07}{}^{+0.04}_{-0.01}$	$0.37^{+0.06}_{-0.07}{}^{+0.03}_{-0.04}$
$1.00 < q^2 < 6.00$	$0.42 \pm 0.04 \pm 0.04$	$-0.18^{+0.06}_{-0.06}{}^{+0.01}_{-0.02}$	$0.66^{+0.06}_{-0.06}{}^{+0.04}_{-0.03}$

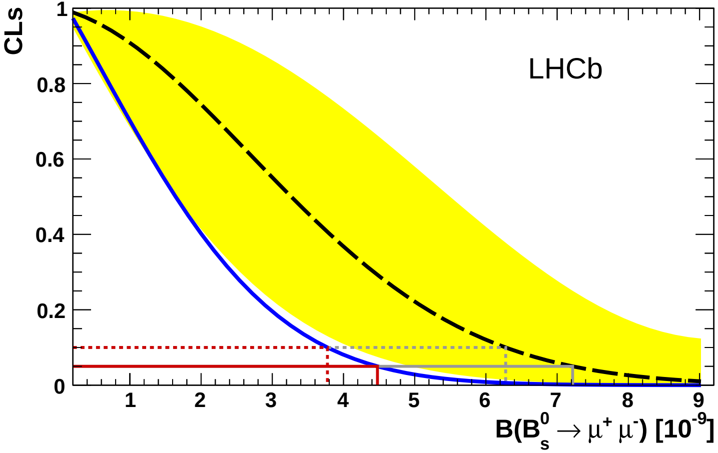
q^2 range (GeV^2/c^4)	A_{IM}	$2S_3$
$4m_\mu^2 < q^2 < 2.00$	$0.06^{+0.11}_{-0.10}{}^{+0.00}_{-0.03}$	$0.02^{+0.20}_{-0.21}{}^{+0.00}_{-0.03}$
$2.00 < q^2 < 4.30$	$-0.02^{+0.10}_{-0.06}{}^{+0.05}_{-0.01}$	$-0.05^{+0.18}_{-0.12}{}^{+0.05}_{-0.01}$
$4.30 < q^2 < 8.68$	$0.02^{+0.07}_{-0.07}{}^{+0.01}_{-0.01}$	$0.18^{+0.13}_{-0.13}{}^{+0.01}_{-0.01}$
$10.09 < q^2 < 12.89$	$-0.01^{+0.11}_{-0.11}{}^{+0.02}_{-0.03}$	$-0.22^{+0.20}_{-0.17}{}^{+0.02}_{-0.03}$
$14.18 < q^2 < 16.00$	$-0.01^{+0.08}_{-0.07}{}^{+0.04}_{-0.02}$	$0.04^{+0.15}_{-0.19}{}^{+0.04}_{-0.02}$
$16.00 < q^2 < 19.00$	$0.06^{+0.09}_{-0.10}{}^{+0.03}_{-0.05}$	$-0.47^{+0.21}_{-0.10}{}^{+0.03}_{-0.05}$
$1.00 < q^2 < 6.00$	$0.07^{+0.07}_{-0.07}{}^{+0.02}_{-0.01}$	$0.10^{+0.15}_{-0.16}{}^{+0.02}_{-0.01}$

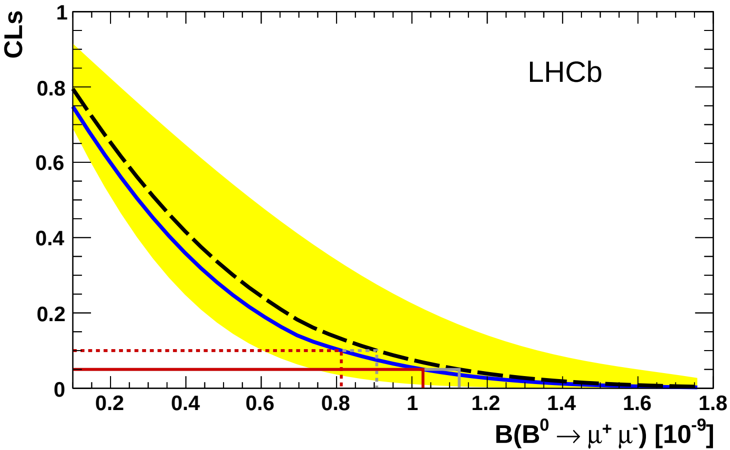
$B^0 \to K^{*0}\mu^+\mu^-$



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


LHCb
Preliminary
Events / (20 MeV / c^2)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
4900
5000
5100
5200
5300
5400
5500
5600
5700
5800
$M_{K\,\mu\,\mu}$ (MeV / c^2)


CLs
1
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
7
8
9
LHCb
B(B$_s^0$ → μ$^+$ μ$^-$) [10^{-9}]


CLs
1
0.8
0.6
0.4
0.2
0
LHCb
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
B(B^0 → μ$^+$ μ$^-$) [10^{-9}]