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Probing the Standard Model with $B \to K^{(*)} l^+ l^-$ decays at LHCb

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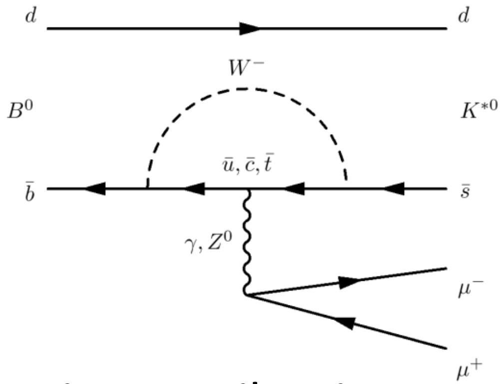
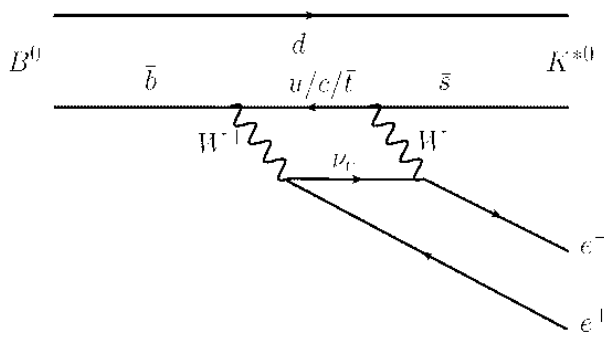
On behalf of the LHCb collaboration

Brookhaven Forum 2015, 7th-9th Oct.





Effective Hamiltonian can be expressed via Operator Product Expansion (OPE) in terms of operators O and calculable Wilson coefficients C.

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tq}^{*} V_{tb} \sum_{i=1} C_i^{(\prime)}(\mu) O_i^{(\prime)}(\mu) + \sum_i \frac{C_i^{NP}}{\Lambda^2} O_i^{NP}$$

$i = 1,2$	Tree
$i = 3-6,8$	Gluon Penguin
$i = 7$	Photon Penguin
$i = 9$	EW Penguin (axial)
$i = 10$	EW Penguin (vector)
$i = S$	Scalar Penguin
$i = P$	Pseudoscalar Penguin

New Physics (NP) can enter via new particles in loops

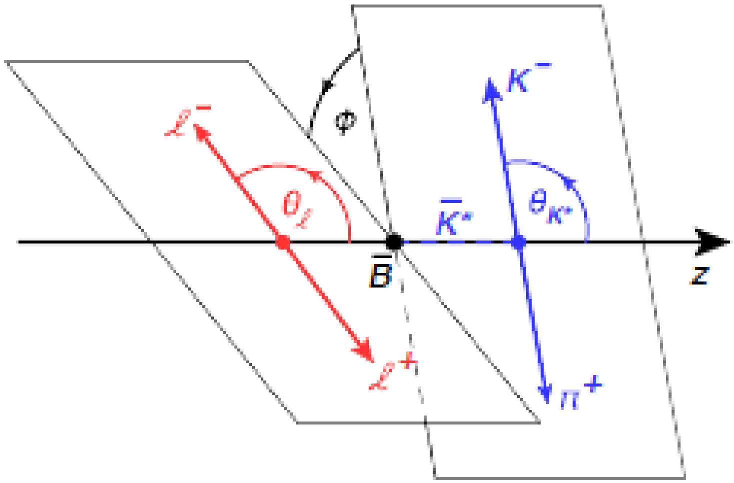
- Potentially modifies magnitude and phase of SM C_i
- Potentially introduces new couplings C^{NP}.
- Potentially different couplings to the leptons.

Look for changes in branching fractions, angular distributions, and lepton universality.

Results are based on 3 fb^{-1} (~1 fb^{-1} @ 7 GeV and ~2 fb^{-1} @ 8 GeV)

Full Angular Analysis of $B^0 \to K^{*0}\mu^+\mu^-$

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^3(\Gamma+\bar{\Gamma})}{d\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].$$



θ_k between K^+ & B^0 in K^* rest frame.
θ_l between $l^+(l^-)$ & $B(\bar{B})$ in l^+l^- rest frame.
ϕ between the di-lepton and $K\pi$ plane in B rest frame.

F_L, Longitudinal Polarization.

A_{FB}, Forward-Backward di-lepton asymmetry.

$P'_{4,5,6,8} = S_{4,5,7,8} / \sqrt{F_L(1-F_L)}$ [JHEP 01 (2013) 048]

SM theoretical predictions exist for F_L, A_{FB}, P', $S_{3,4,5}$ as a function of q^2. Other S_i are expected to be ~zero in the SM.

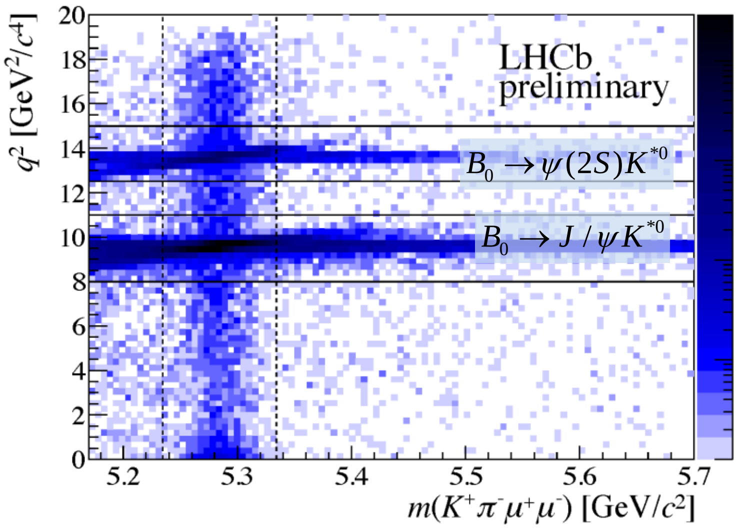
Full Angular Analysis of $B^0 \to K^{*0}\mu^+\mu^-$

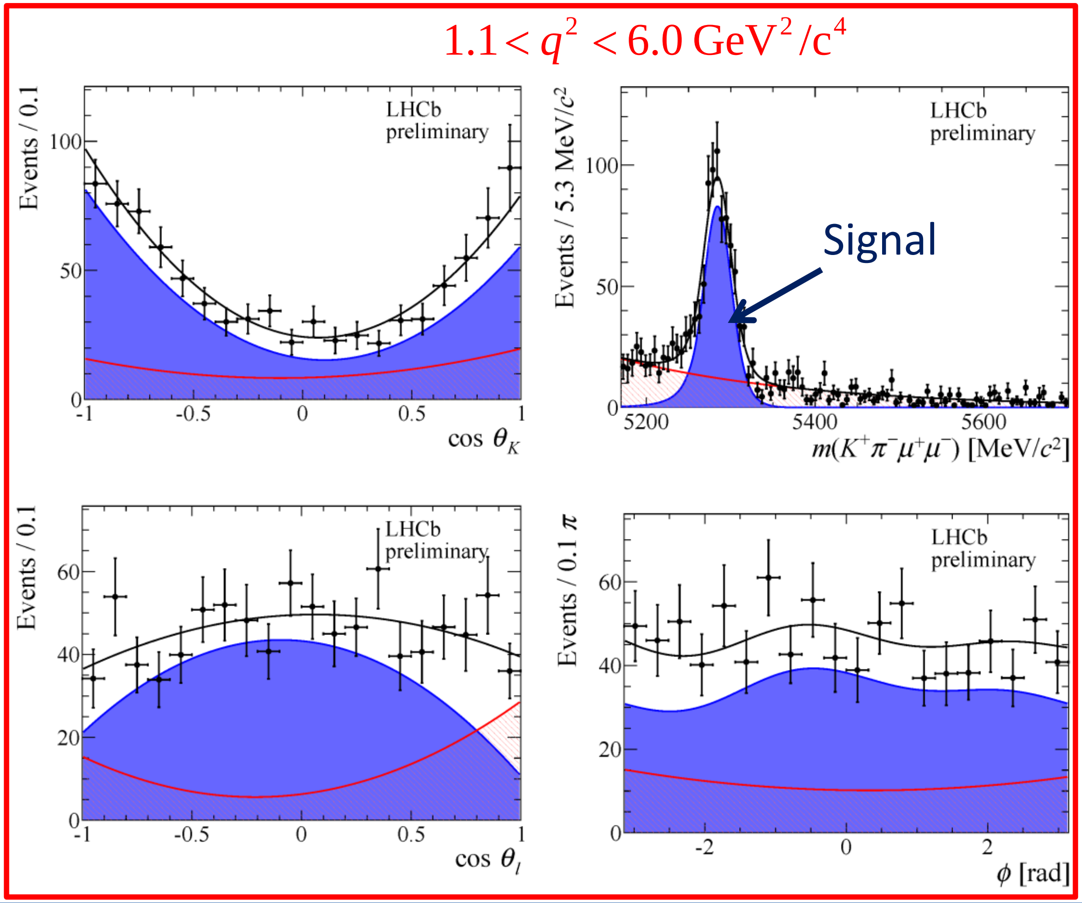
LHCb-CONF-2015-002

Require $795.9 < m(K^+\pi^-) < 995.9$ MeV/c^2 and $0.1 < q^2 < 19$ GeV^2/c^4.

But need to account for S-wave from $K^+\pi^-$ final state via fits to $m(K^+\pi^-)$.

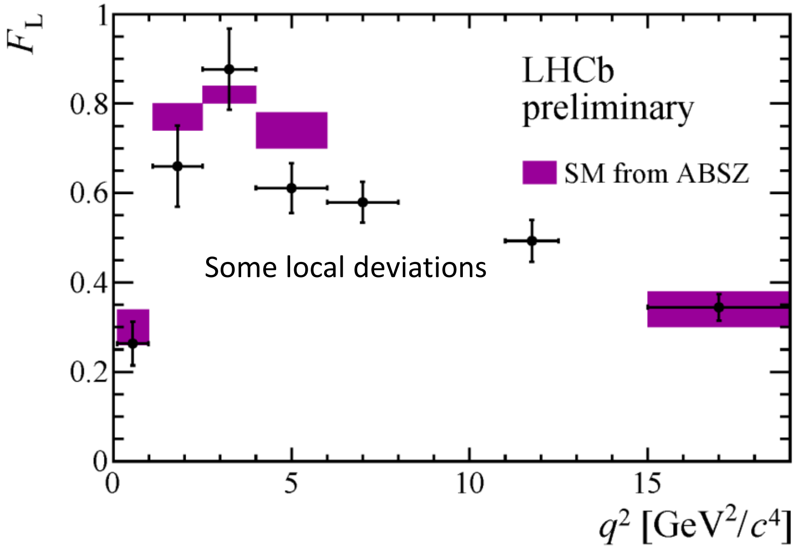
Maximum likelihood (ML) fit in q^2 bins to $\cos\theta_k$, $\cos\theta_l$, φ, $m(K^+\pi^-\mu^+\mu^-)$, $m(K^+\pi^-)$.

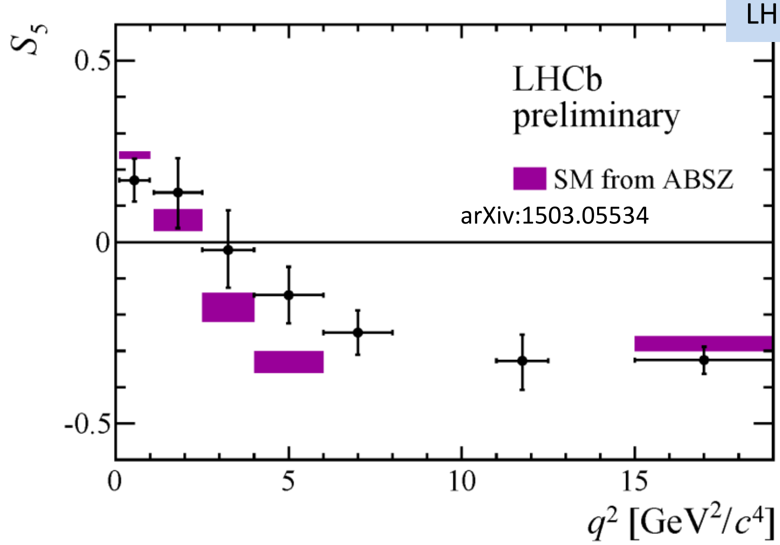


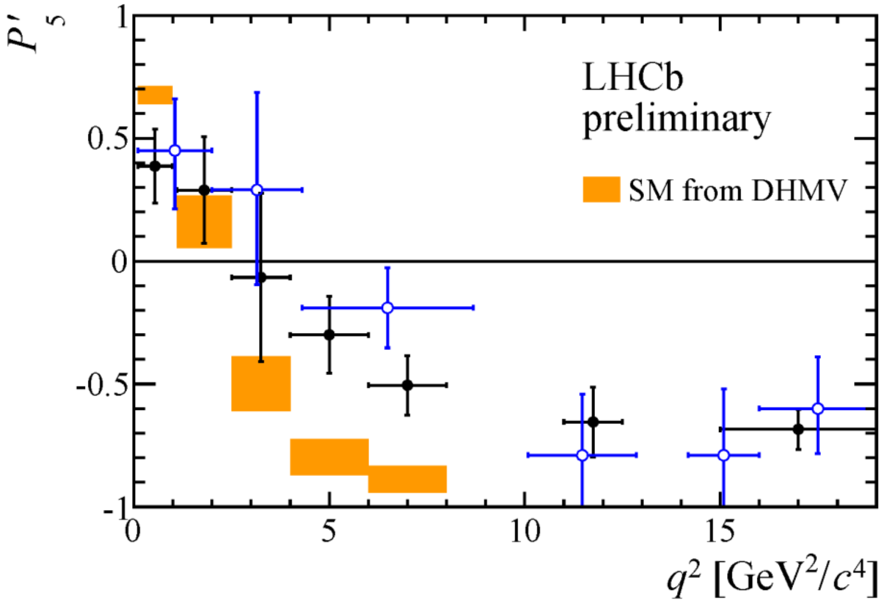


Full Angular Analysis of $B^0 \to K^{*0}\mu^+\mu^-$

LHCb-CONF-2015-002



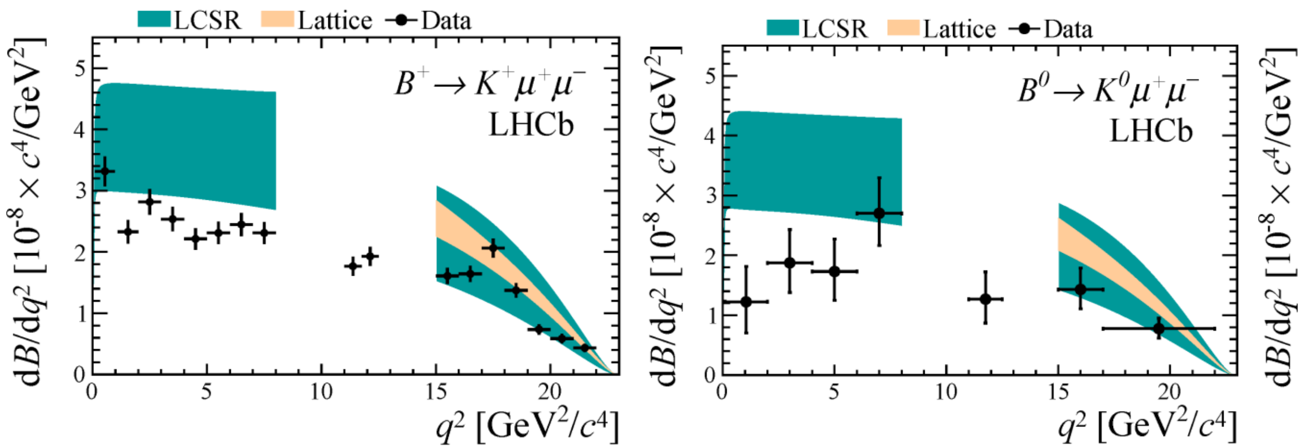




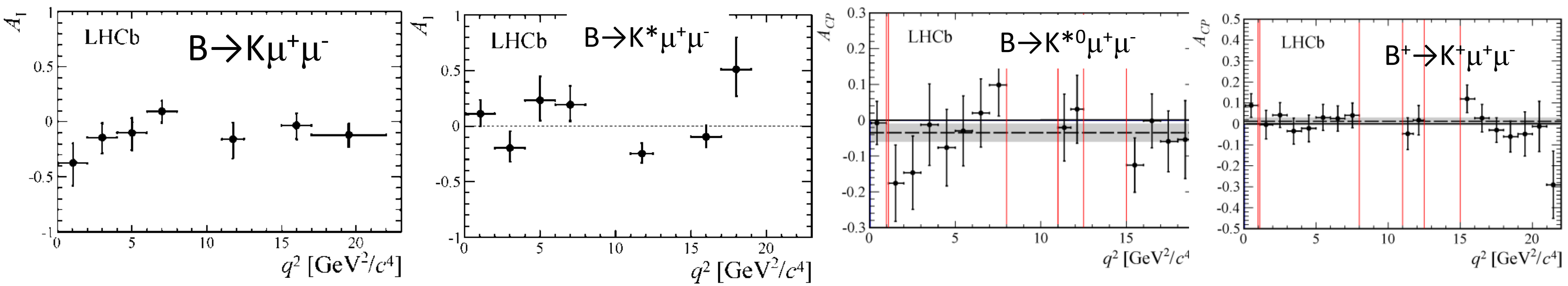
Black – this result with SM prediction
Orange - SM prediction JHEP 1412 (2014) 129)
Blue - earlier LHCb 1fb^{-1} PRL 111 (2013) 191801).

New data agrees with 2013 result.
Tension in P_5' confirmed.
[4.0-6.0] and [6.0-8.0] GeV^2/c^4 bins both 2.9σ.
The combined deviation is 3.7σ.
Other coefficients C compatible with SM.

JHEP 06 (2014) 133; JHEP 09 (2014) 177



Branching fractions seem to be consistently lower than SM predictions

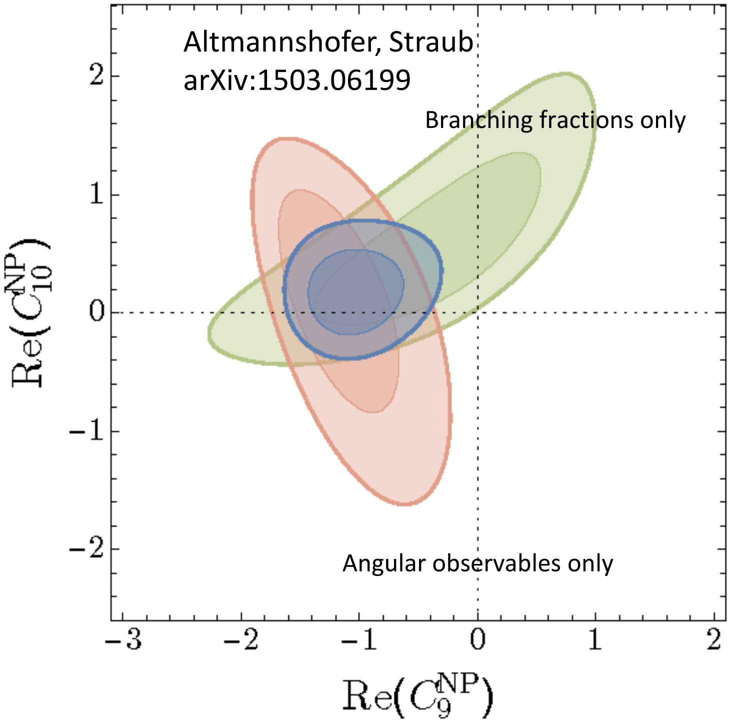


Isospin Asymmetries A_I and CP Asymmetries A_{CP} are in agreement with SM

Interpreting the results

Example of a global fit to multiple measurements from many experiments with coefficients allowed to float one by one.

Coeff.	best fit	1σ	2σ	$\sqrt{\chi^2_{\text{b.f.}} - \chi^2_{\text{SM}}}$	p [%]
C_7^{NP}	-0.04	$[-0.07, -0.01]$	$[-0.10, 0.02]$	1.42	2.4
C_7'	0.01	$[-0.04, 0.07]$	$[-0.10, 0.12]$	0.24	1.8
C_9^{NP}	-1.07	$[-1.32, -0.81]$	$[-1.54, -0.53]$	3.70	11.3
C_9'	0.21	$[-0.04, 0.46]$	$[-0.29, 0.70]$	0.84	2.0
C_{10}^{NP}	0.50	$[0.24, 0.78]$	$[-0.01, 1.08]$	1.97	3.2
C_{10}'	-0.16	$[-0.34, 0.02]$	$[-0.52, 0.21]$	0.87	2.0
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.22	$[-0.44, 0.03]$	$[-0.64, 0.33]$	0.89	2.0
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.53	$[-0.71, -0.35]$	$[-0.91, -0.18]$	3.13	7.1
$C_9' = C_{10}'$	-0.10	$[-0.36, 0.17]$	$[-0.64, 0.43]$	0.36	1.8
$C_9' = -C_{10}'$	0.11	$[-0.01, 0.22]$	$[-0.12, 0.33]$	0.93	2.0



Angular analysis of $B \to K^{*0} e^+ e^-$

JHEP 04 (2015) 064

- Can go to lower effective q^2 than $K^{*0}\mu^+\mu^-$: 0.002 – 1.12 GeV^2/c^4
- Some NP models predict significant right-handed photons.

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\tilde{\phi}} = \frac{9}{16\pi}\Bigg[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \left(\frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K - F_{\mathrm{L}}\cos^2\theta_K\right)\cos 2\theta_\ell + \frac{1}{2}(1-F_{\mathrm{L}})A_{\mathrm{T}}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\tilde{\phi} + (1-F_{\mathrm{L}})A_{\mathrm{T}}^{\mathrm{Re}}\sin^2\theta_K\cos\theta_\ell + \frac{1}{2}(1-F_{\mathrm{L}})A_{\mathrm{T}}^{\mathrm{Im}}\sin^2\theta_K\sin^2\theta_\ell\sin 2\tilde{\phi}\Bigg]. \quad (1.1)$$

$$\tilde{\phi} = \phi + \pi \text{ if } \phi < 0$$

$$F_{\mathrm{L}} = \frac{|A_0|^2}{|A_0|^2+|A_{||}|^2+|A_\perp|^2}$$

$$A_{\mathrm{T}}^{(2)} = \frac{|A_\perp|^2-|A_{||}|^2}{|A_\perp|^2+|A_{||}|^2}$$

$$A_{\mathrm{T}}^{\mathrm{Re}} = \frac{2\mathcal{R}e(A_{||L}A_{\perp L}^* + A_{||R}A_{\perp R}^*)}{|A_{||}|^2+|A_\perp|^2}$$

$$A_{\mathrm{T}}^{\mathrm{Im}} = \frac{2\mathcal{I}m(A_{||L}A_{\perp L}^* + A_{||R}A_{\perp R}^*)}{|A_{||}|^2+|A_\perp|^2},$$

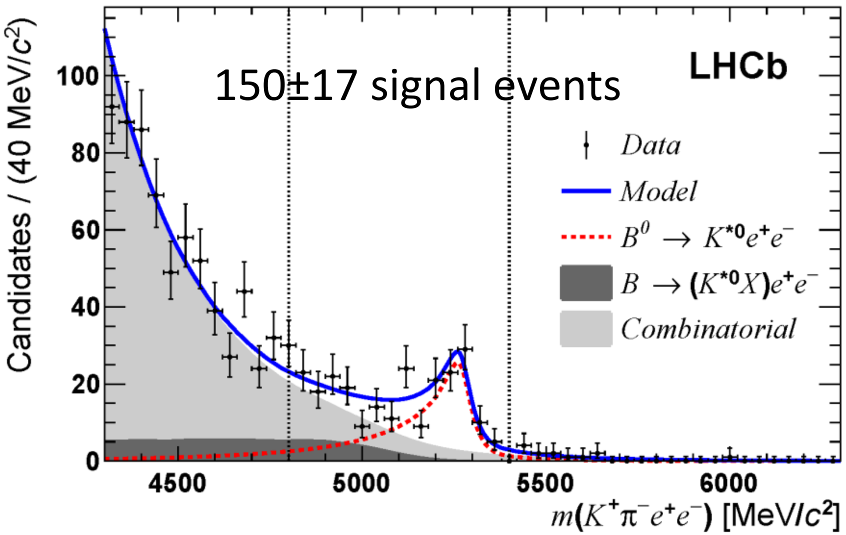
- F_L expected to be small
- A_T sensitive to C_7' (right-handed photon):

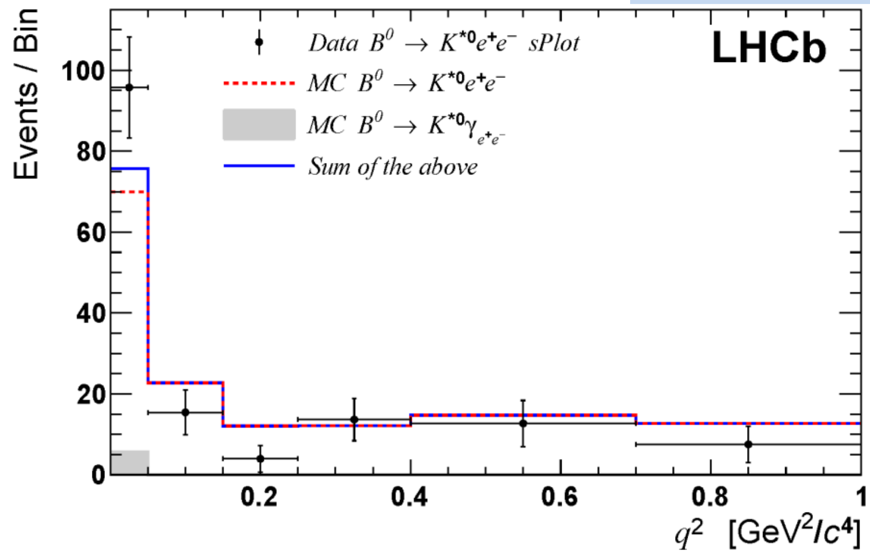
$$A_T^{(2)}(q^2 \to 0) = \frac{2\Re e(C_7 C_7'^*)}{|C_7|^2+|C_7'|^2},\ A_T^{\mathrm{Im}}(q^2 \to 0) = \frac{2\Im m(C_7 C_7'^*)}{|C_7|^2+|C_7'|^2},\ A_T^{\mathrm{Re}} = \frac{4A_{FB}}{3(1-F_L)}$$

- Extract F_L, $A_T^{(2)}$, $A_T^{(Im)}$, and $A_T^{(Re)}$ in q^2 range [0.002,1.12] GeV^2 from ML fit to ($\cos\theta_k$, $\cos\theta_l$, $\tilde{\phi}$, $m(K^+\pi^-e^+e^-)$).

Angular analysis of $B \to K^{*0} e^+ e^-$

JHEP 04 (2015) 064



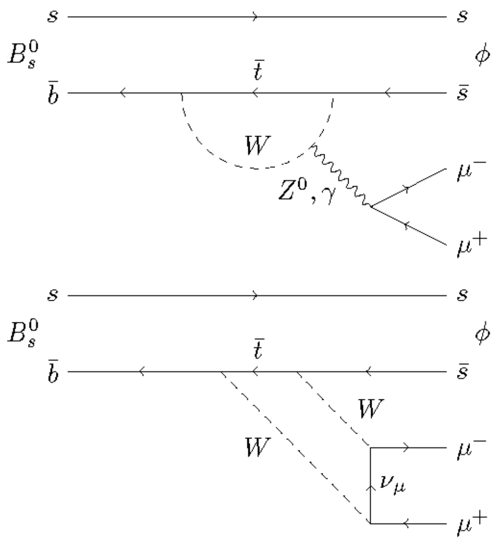


Observable	Measured	SM Prediction
F_L	$+0.16 \pm 0.06 \pm 0.03$	$+0.10^{+0.11}_{-0.05}$
$A_T^{(2)}$	$-0.23 \pm 0.23 \pm 0.05$	$+0.03^{+0.05}_{-0.04}$
A_T^{Re}	$+0.10 \pm 0.18 \pm 0.05$	$-0.15^{+0.04}_{-0.03}$
A_T^{Im}	$+0.14 \pm 0.22 \pm 0.05$	$(-0.2 \pm 1.2) \times 10^{-4}$

Consistent with SM predictions (Jaeger et al. JHEP 05 (2013) 043)

Angular Analysis and dB/dq^2 of $B_s \to \phi\mu^+\mu^-$

JHEP 09 (2015) 179

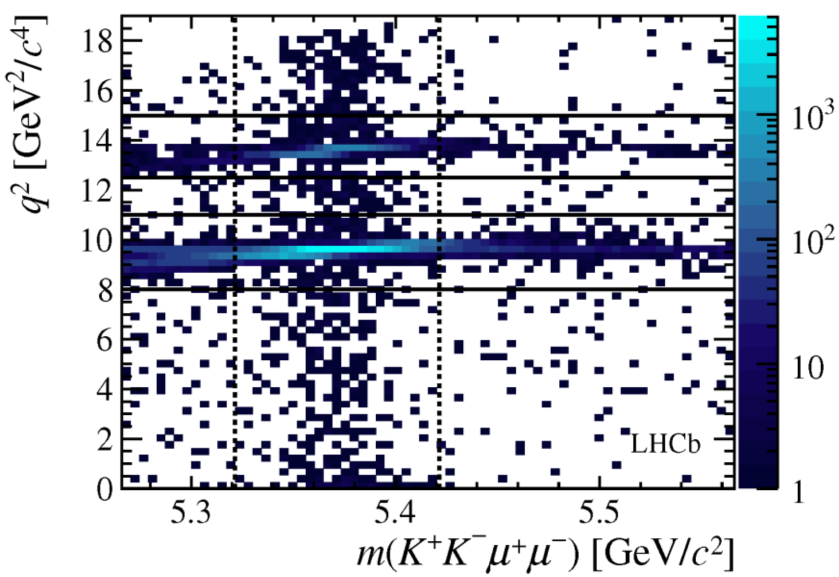


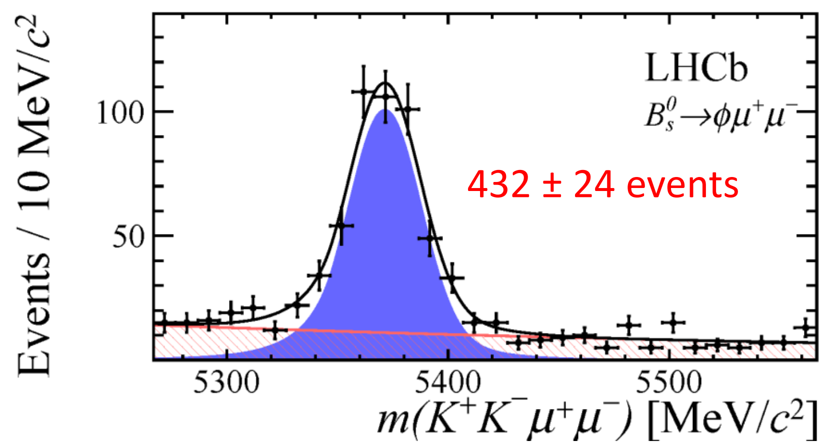
$$
\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\Phi} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\rm L})\sin^2\theta_K + F_{\rm L}\cos^2\theta_K
+ \tfrac{1}{4}(1-F_{\rm L})\sin^2\theta_K\cos 2\theta_l - F_{\rm L}\cos^2\theta_K\cos 2\theta_l
+ S_3\sin^2\theta_K\sin^2\theta_l\cos 2\Phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\Phi
+ A_5\sin 2\theta_K\sin\theta_l\cos\Phi + A_6\sin^2\theta_K\cos\theta_l
+ S_7\sin 2\theta_K\sin\theta_l\sin\Phi + A_8\sin 2\theta_K\sin 2\theta_l\sin\Phi
+ A_9\sin^2\theta_K\sin^2\theta_l\sin 2\Phi\Big].
$$

$\phi \to K^+K^-$ not flavor specific:

$F_L, S_{3,4,7}$: CP averaged

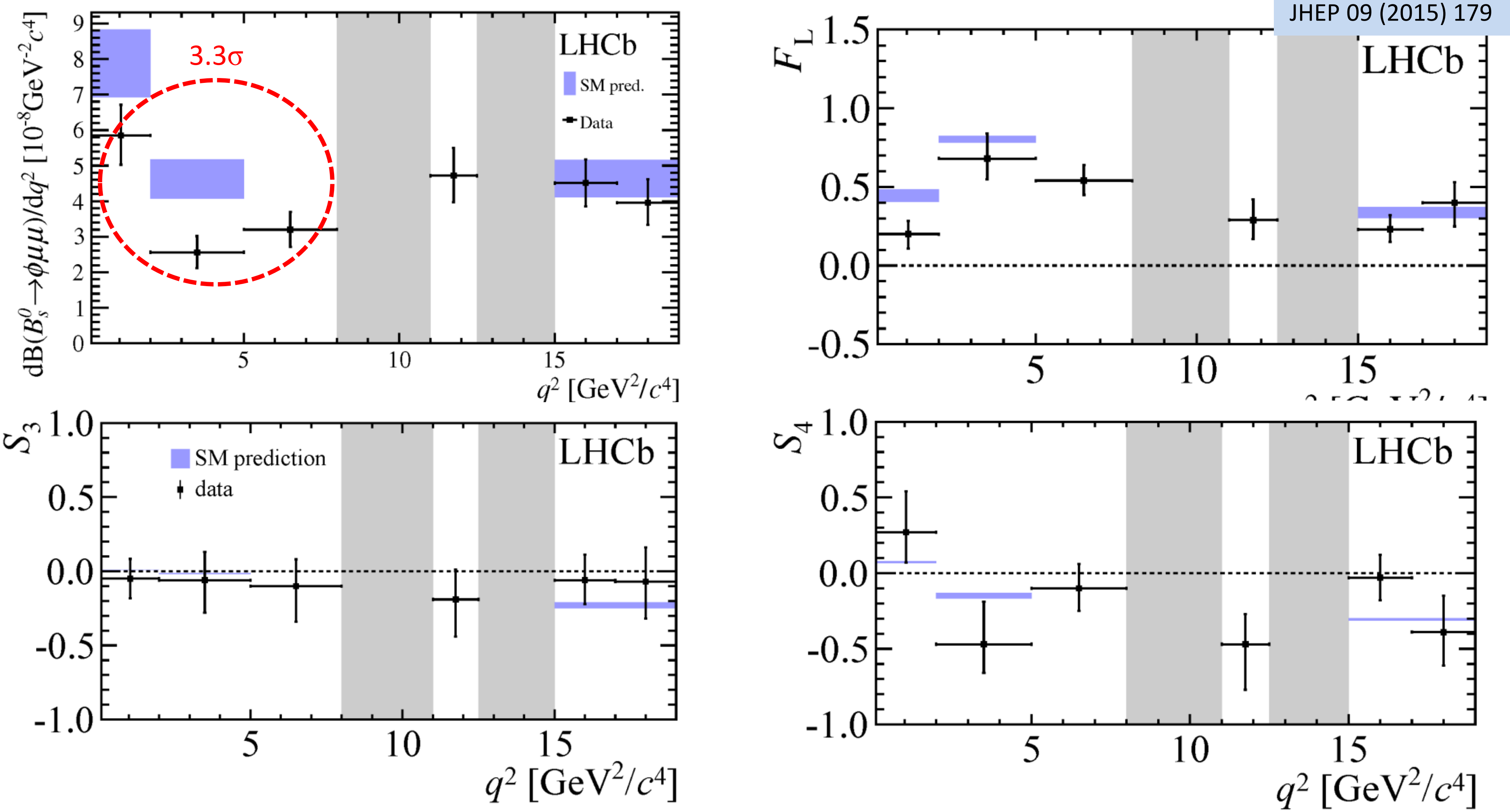
$A_{5,6,8,9}$: CP asymmetries





Angular Analysis of $B_s \to \phi\mu^+\mu^-$

JHEP 09 (2015) 179



dB/dq^2 disagrees with SM at low q^2 by 3.3σ

F_L, S_3, S_4 agree with SM predictions.

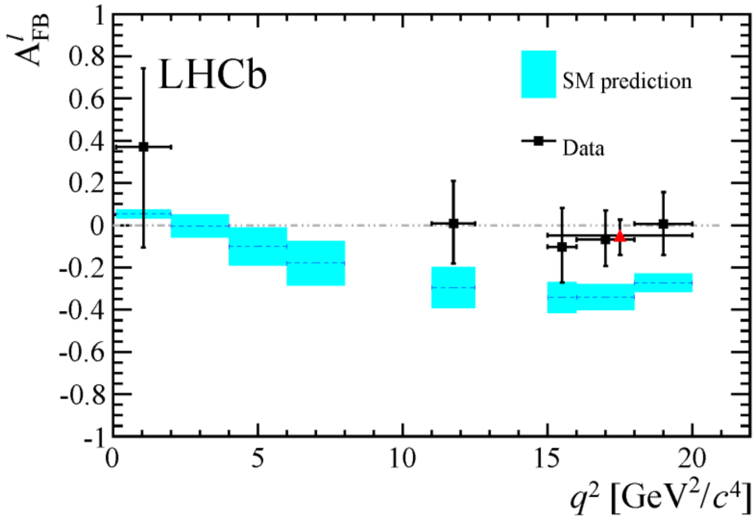
No SM predictions for other S_i and A_i. If assume SM values near zero, then measurements agree with SM.

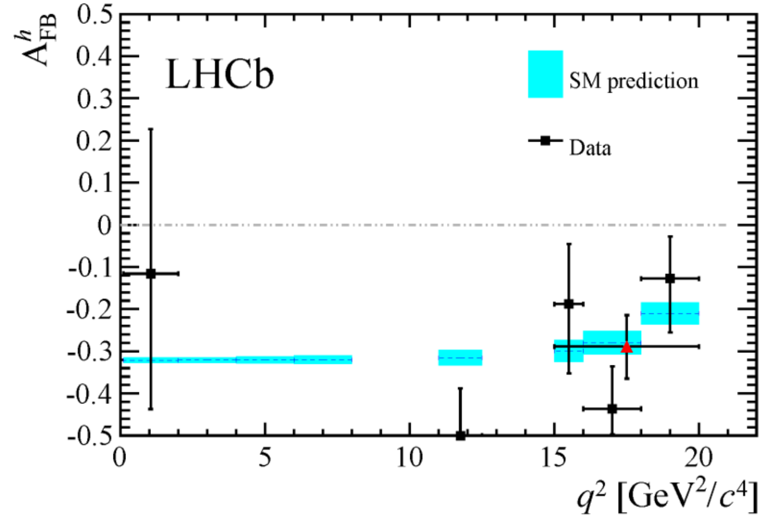
$\Lambda^0_b \to \Lambda\mu^+\mu^-$

JHEP 06 (2015) 115

Similar to $B \to K^* l^+ l^-$ but in baryonic mode

Can also look at Forward-Backward asymmetry of the hadron system, A^h_{FB}.



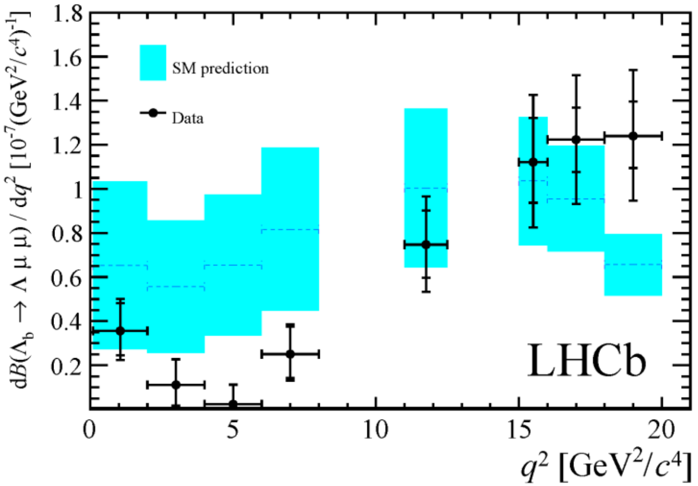


In range $15 < q^2 < 20\ \mathrm{GeV}^2/c^4$:

$$\frac{dB(\Lambda^0_b \to \Lambda\mu^+\mu^-)}{dq^2} = \left(1.18^{+0.09}_{-0.08} \pm 0.03 \pm 0.27\right) \times 10^{-7} (\mathrm{GeV}^2/c^4)^{-1}$$

$$A^l_{FB} = -0.05 \pm 0.09 \pm 0.03$$

$$A^h_{FB} = -0.29 \pm 0.07 \pm 0.03$$



Results are compatible with SM in high $q^2 > 15\ \mathrm{GeV}^2/c^4$

Results are below SM predictions in low q^2 region

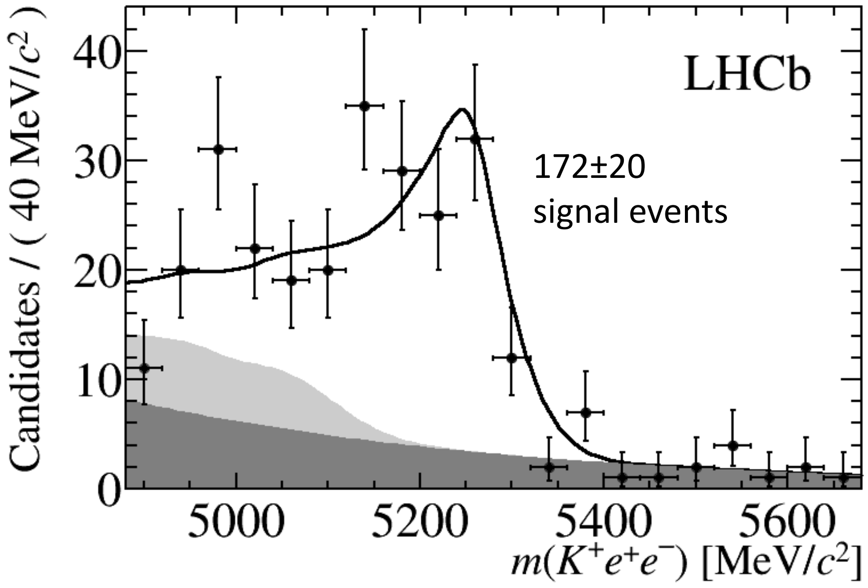
PRL 113, 151601 (2014)

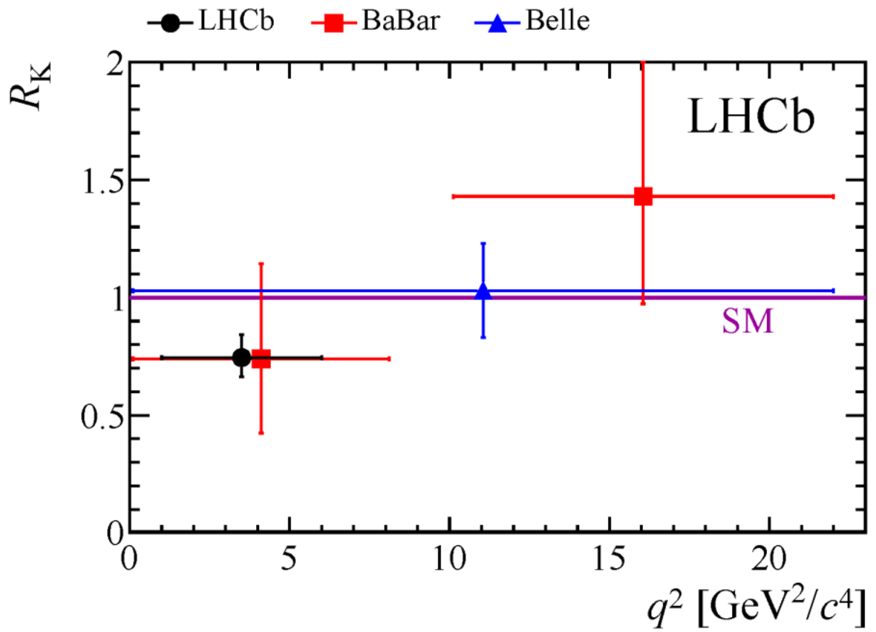
Theoretical uncertainties in branching fraction mostly cancel in ratios.

SM prediction $R_K \approx 1.0 \pm (0.001\text{-}0.01)$ depending on corrections.

Extract yields from ML fit to $m(K^+l^+l^-)$ spectrum

Use range $1.0 < q^2 < 6.0$ GeV^2 as theoretical uncertainties lowest here and for comparison with other experiments.



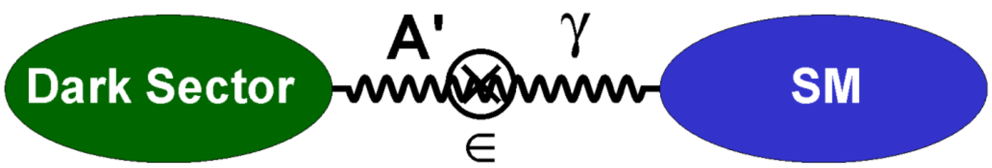


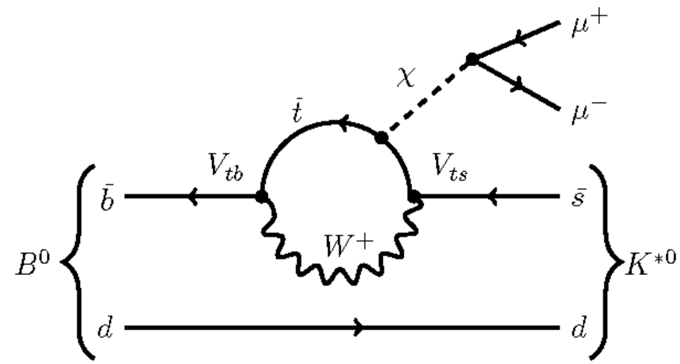
$$R_K = \frac{B(B^+ \to K^+ \mu^+ \mu^-)}{B(B^+ \to K^+ e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

Ratio is 2.6σ from SM prediction.

Hidden-Sector Bosons in $B \to K^{*0}\mu^+\mu^-$ decays

- With little evidence for ~1 TeV scale NP, increased interest in hidden-sector models.
- Postulate a dark matter particle A' interacting feebly with neutral SM particles (H,Z,γ,ν) via mixing of the hidden-sector and SM field with a coupling ε.
- The models have the potential to explain e.g. inflation, baryon asymmetries, suppressed strong-CP, …

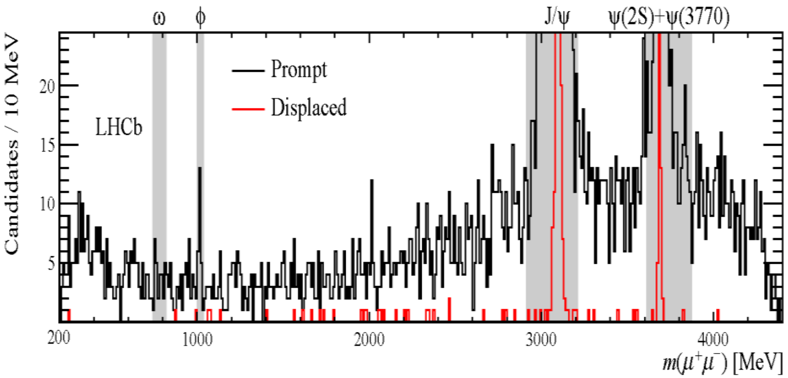


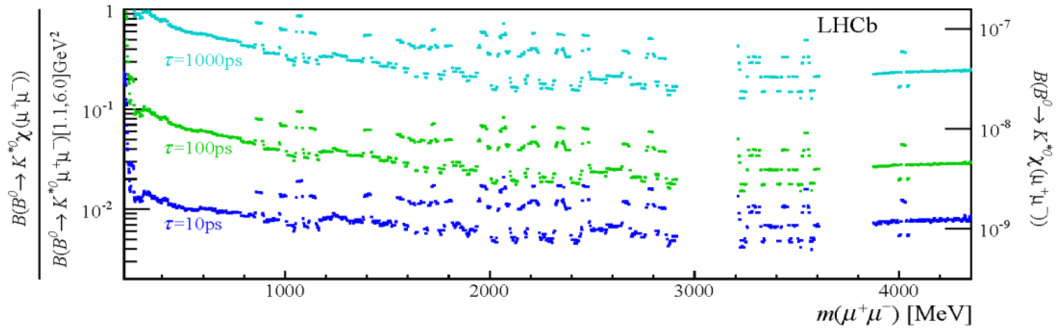


- LHCb has looked for $B^0 \to K^{*0}\chi$ ($\chi \to \mu^+\mu^-$) allowing for different χ lifetimes (lifetime resolution better than 1 ps).
- Normalise branching fraction to prompt $B^0 \to K^{*0}\mu^+\mu^-$ in range $1.1 < m^2(\mu^+\mu^-) < 6.0$ GeV^2/c^4.

Hidden-Sector Bosons in $B \to K^{*0}\mu^+\mu^-$ decays

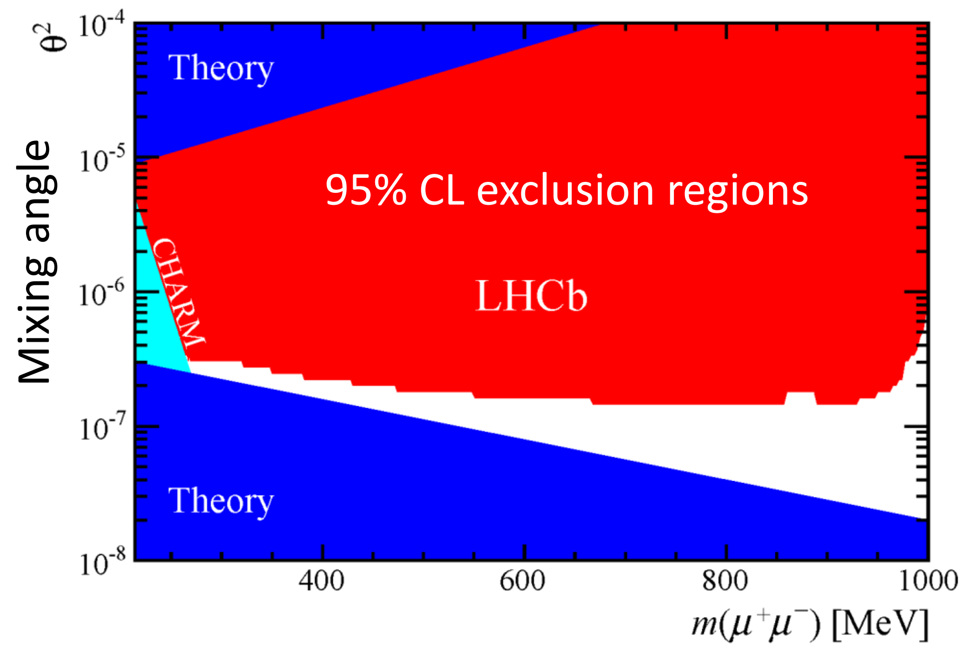
arXiv:1508.04094





Example of constraint on a particular inflaton model with sterile neutrino:

F. Bezrukov and D. Gorbunov, PLB 736 (2014) 494.



Conclusion

Latest LHCb 3 fb^{-1} results are confirming earlier 1 fb^{-1} observations.

Rare $b \rightarrow s$ decays are proving to be intriguing:

- 2-3σ deviations from SM in some $B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular observables.
- Some deviations in dB/dq^2 for $B \rightarrow Kl^+l^-$ decays.
- 2.6σ deviation in Lepton Universality in $B^+ \rightarrow K^+l^+l^-$ decays.

Results from other experiments, e.g. Belle and BaBar, point in the same direction.

Models that incorporate new physics, e.g. Z' with mass O(10 TeV), are having some success in explaining deviations.

LHCb is taking more data at higher energy and can expect to continue to improve on precision.