Rare decays at LHCb

Lake Louise Winter Institute - February 7-13 2016

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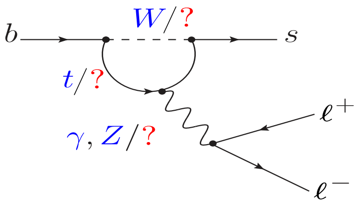
On behalf of the LHCb collaboration

Rare decays as probes for BSM physics

- New particles may appear in loops of rare FCNC decays, affecting **branching ratios** and **angular distributions**;
- these particles wouldn't need to be produced on mass shell in such diagrams $\Rightarrow$ access to very **large masses**.



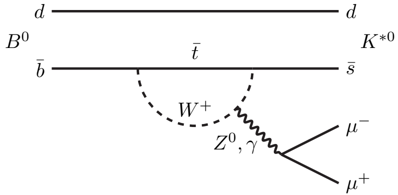
FCNC effective hamiltonian described as operator product expansion, $\mathcal{C}_i$ being the Wilson coefficients, that encode the short-distance physics, and O_i the corresponding operators.

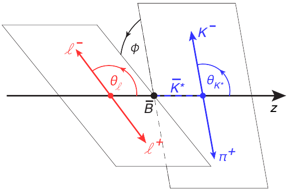
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left-handed part}} + \underbrace{\mathcal{C}_i'(\mu)\mathcal{O}_i'(\mu)}_{\substack{\text{right-handed part}\\ \text{suppressed in SM}}}]$$

i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

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

[LHCb, arXiv:1512.04442]





- Decay described by q^2 (i.e. $m^2_{\mu\mu}$) and three helicity angles $\vec{\Omega} = (\theta_l, \theta_K, \phi)$:

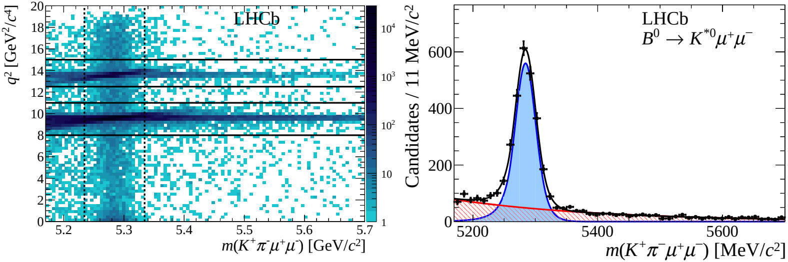
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$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

F_L, A_{FB}, and S_i depend on $\mathcal{C}_7$, $\mathcal{C}_9$ and $\mathcal{C}_{10}$ and hadronic form factors

- Additional observables, for which the leading form factor uncertainties cancel, e.g.: $P'_5 = S_5/\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}$;
- S-wave pollution is also taken into account $\Rightarrow$ one more observable.

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

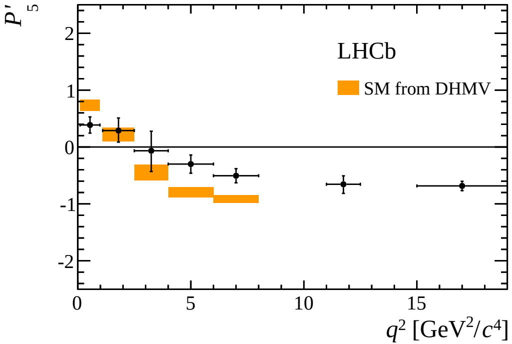
[LHCb, arXiv:1512.04442]



- Veto of $B^0 \to J/\psi K^{*0}$ and $B^0 \to \psi(2S)K^{*0}$;
- signal mass model obtained from high statistics $B^0 \to J/\psi K^{*0}$;
- events are then binned in eight q^2 intervals.

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

[LHCb, arXiv:1512.04442]

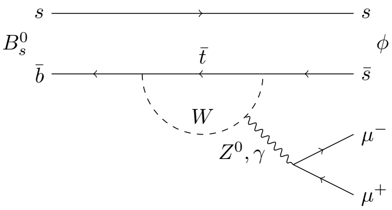


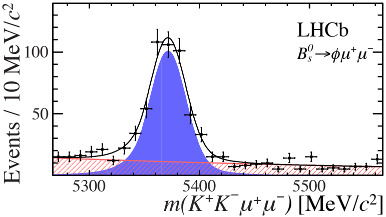
- Tension seen in P'_5 (and S_5):
  $2.8\,\sigma$ deviation in $[4,6]GeV^2/c^4$ and $3\,\sigma$ in $[6,8]GeV^2/c^4$ q^2 intervals.
- compatible with $1\ fb^{-1}$ analysis [PRL 111, 191801 (2013)];
- corresponds to a $3.4\,\sigma$ shift of $\mathcal{R}e(\mathcal{C}_9)$ w.r.t. SM...
- ...or just hadronic effect?

DHMV = S. Descotes-Genon, L. Hofer, J. Matias, and J. Virto, JHEP 12 (2014) 125

$B_s^0 \to \Phi[\to K^+K^-]\mu^+\mu^-$

[LHCb, JHEP 09 (2015) 179]

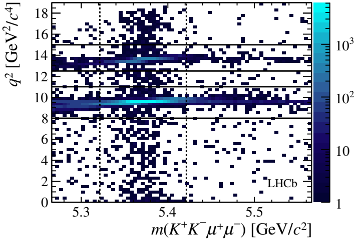


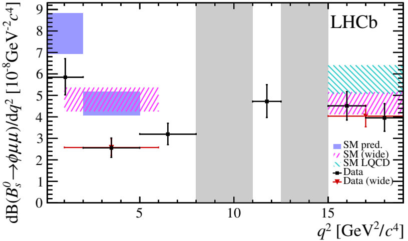


- $\mathcal{B}$ measured as a function of q^2;
- $f_s/f_d \simeq 1/4$ but ϕ is narrow, allowing clean selection; furthermore, low contamination from S-wave K^+K^-;
- $K^+K^-\mu^+\mu^-$ final state is not flavour-specific $\Rightarrow$ reduced number of angular observables: F_L, $S_{3,4,7}$, $A_{5,6,8,9}$.

$B_s^0 \to \Phi[\to K^+K^-]\mu^+\mu^-$

[LHCb, JHEP 09 (2015) 179]





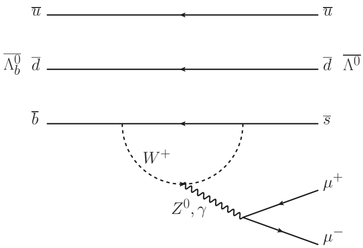
- $B_s^0 \to \psi(2S)\phi$ and $B_s^0 \to J/\psi\phi$ (control mode) vetoed;
- $\mathcal{B}$ more than 3σ below SM in $1 < q^2 < 6 GeV^2/c^4$;
- total $\mathcal{B}$: $\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (7.97^{+0.45}_{-0.43} \pm 0.22 \pm 0.23 \pm 0.60) \times 10^{-7}$;

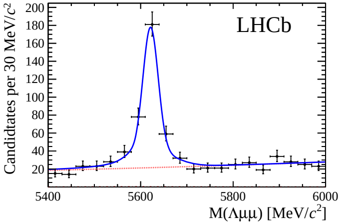
  (errors: stat., syst., extrapolation to full q^2 region, norm.)
- All angular observables in agreement with SM.

SM predictions from arXiv:1411.3161 and arXiv:1503.05534

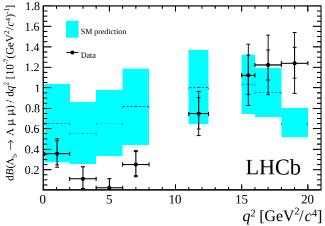
$\Lambda_b^0 \to \Lambda[\to p\pi]\mu^+\mu^-$

[LHCb, JHEP 06 (2015) 115]





- Baryon $\Rightarrow$ access to different information (non-integer spin, different hadronic physics);
- $\mathcal{B}$ compatible with SM in the high-q^2 region and **below predictions in the low-q^2 region** (first observation).



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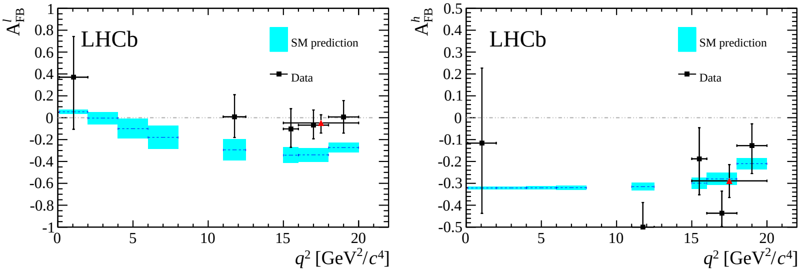
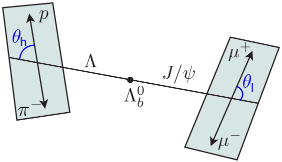


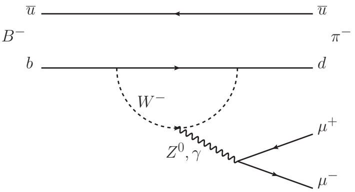
(red triangle: value for $15 < q^2 < 20 GeV^2/c^4$)

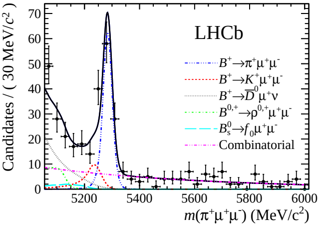
- Asymmetries only computed in the bins where a statistically significant signal yield is found;
- first measurement of the forward-backward asymmetries in the dimuon ($A^\ell_{\rm FB}$) and hadron ($A^h_{\rm FB}$) system;
- $A^\ell_{\rm FB}$ is consistently above SM, but compatible at 2σ level; $A^h_{\rm FB}$ is fully compatible.



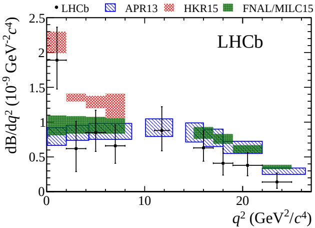
$B^+ \to \pi^+\mu^+\mu^-$

[LHCb, JHEP 10 (2015) 034]





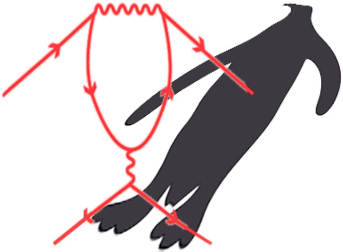
- $b \to d\mu^+\mu^-$ suppressed wrt $b \to s\mu^+\mu^-$ because of $\left|\frac{V_{td}}{V_{ts}}\right|^2 \simeq \frac{1}{25}$;
- $\mathcal{B}(q^2)$ in good agreement with but slightly lower than SM;
- $\mathcal{B} = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$;
- $\mathcal{A}_{CP} = 0.11 \pm 0.12 \pm 0.01$;
- $\left|\frac{V_{td}}{V_{ts}}\right| = 0.24^{+0.05}_{-0.04}$.



predictions from Phys. Rev. D89 (2014) 094021, arXiv:1506.07760, arXiv:1507.01618

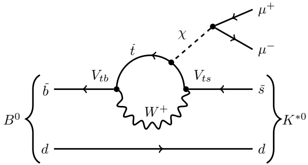
Hidden sector boson searches

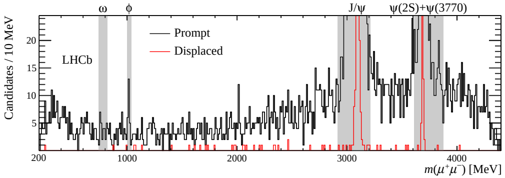
- Dark matter is expected to interact feebly with all known particles, thus it has always escaped detection;
- coupling between the SM and hidden-sector particles may arise via **mixing between the hidden-sector field and any SM field whose particle does not carry electromagnetic charge (Z, H, γ, ν)**;
- many theories predict that TeV-scale dark matter particles interact via GeV-scale bosons.



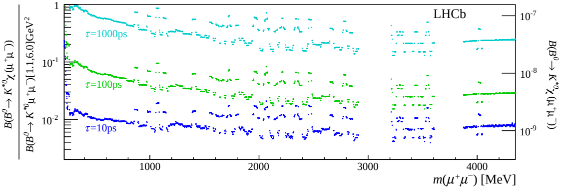
$B^0 \to K^{*0}[\to K^+\pi^-]\,\chi[\to \mu^+\mu^-]$

[LHCb, PHYS. REV. LETT. 115 (2015) 161802]





- Scan $m(\mu^+\mu^-)$ for an excess;
- accessible $m(\chi)$ in $[214, 4350] MeV$;
- prompt & displ. χ vertices considered;
- $\omega, \phi, J/\psi, \psi(2S)$ and $\psi(3770)$ vetoed;
- normalization: prompt events in $1.1 < m^2(\mu^+\mu^-) < 6.0 GeV^2$;
- no significant signal observed $\Rightarrow$ set 95% CL upper limits.

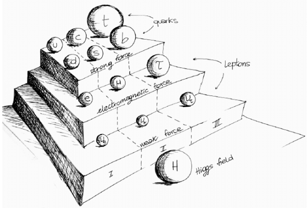


Lepton flavour violation

- LFV predicted in various extensions of the SM (heavy-neutrino), or scenarios beyond SM as the Pati-Salam model or SUSY;
- predictions can vary strongly depending on the model;
- recently renewed interest for LFV after LHCb measurement of [1]

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

which hints for existence of LFV at accessible BR.[2]

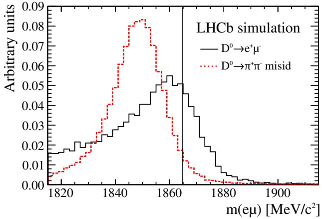


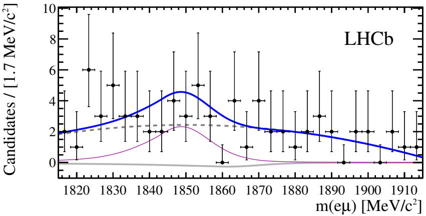
[1][LHCB, PHYS. REV. LETT. 113 (2014) 151601]
[2]S. L. Glashow, D. Guadagnoli and K. Lane, PHYS. REV. LETT. 114 (2015) 091801

$D^0 \to e^{\pm}\mu^{\mp}$

[LHCb, arXiv:1512.00322]

New!

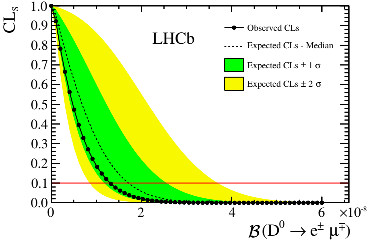




Most signal-like BDT bin. Thick grey: signal, thin purple: misidentified $D^0 \to \pi^-\pi^-$, dashed grey: combinatorial bkg.

- Select D^0 from $D^{*+} \to D^0\pi^+$ decays;
- $D^0 \to K^-\pi^+$ as normalization channel;
- $D^0 \to \pi^+\pi^-$ misID dominant bkg;
- data splitted in 3 bins of BDT output;
- No evidence for any signal, set world's best upper limit (CL_S method):

$$\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-8}$$



Conclusions

- Rare decays constitute an excellent laboratory to search for BSM effects;
- LHCb is an ideal environment for these searches;
- most measurements in good agreement with SM predictions, setting strong constraints on NP;
- some puzzling deviations, though, are appearing: new physics or hadronic effects?
- $3\,fb^{-1}$ data @ $\sqrt{s} = 7$ and $8\,TeV$ (Run I) are still under study, new analyses are about to come;
- Run II has started; expected $\sim 5\,fb^{-1}$ @ $\sqrt{s} = 13\,TeV$...

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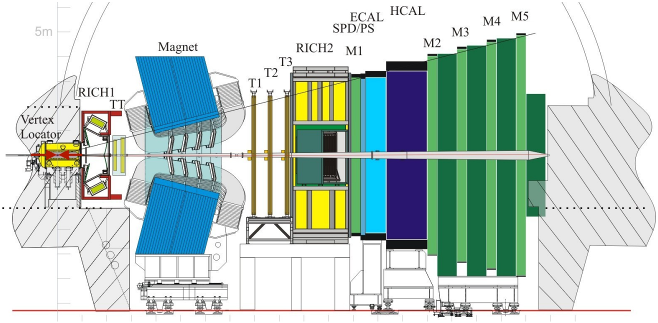
Exciting times ahead!

The End

The LHCb experiment



- designed to study b and c quarks physics;
- single arm spectrometer
- high resolution on vertices and momenta - vertex detector, tracker;
- particle identification - RICH, calorimeters, muon chambers.

$\mathbf{B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-}$, the observables.

- Differential decay rates of $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}\mu^+\mu^-$ decays given by

$$\frac{\mathrm{d}^4\Gamma[\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

$$\frac{\mathrm{d}^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega}) \ ,$$

- q^2-dependent CP averages, S_i, and CP asymmetries, A_i, can be defined as

$$S_i = \frac{\left(I_i + \bar{I}_i\right)}{\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)}, \qquad A_i = \frac{\left(I_i - \bar{I}_i\right)}{\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)}.$$

  Conventionally replace: $S_{1c} = F_{\mathrm{L}}$ and $S_{6s} \to A_{\mathrm{FB}} = \frac{3}{4}S_{6s}$
  (c, s = sin^2 or cos^2 dep.)

- additional observables, for which the leading $B^0 \to K^{*0}$ form-factor uncertainties cancel, e.g.:

$$P_5' = \frac{S_5}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}};$$

- S-wave pollution: $K^+\pi^-$ not in resonant P-wave K^{*0} but in spin 0 configuration $\Rightarrow$ more observables; angular distribution modified:

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{S+P}} = (1-F_\mathrm{S})\,\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} + \frac{3}{16\pi}F_\mathrm{S}\sin^2\theta_l + \text{S-P interference}$$

- F_S scales P-wave observables $\Rightarrow$ needs to be determined $\Rightarrow$ fit on $m_{K\pi}$.

- Additional observables, for which the leading $B^0 \to K^{*0}$ form-factor uncertainties cancel:

$$
\begin{aligned}
P_1 &= \frac{2\,S_3}{(1-F_\mathrm{L})} = A_\mathrm{T}^{(2)}\,, \\
P_2 &= \frac{2}{3}\frac{A_\mathrm{FB}}{(1-F_\mathrm{L})}\,, \\
P_3 &= \frac{-S_9}{(1-F_\mathrm{L})}\,, \\
P'_{4,5,8} &= \frac{S_{4,5,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}\,, \\
P'_6 &= \frac{S_7}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}\,.
\end{aligned}
$$

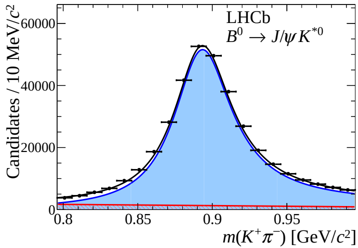
- ...and even other observables introduced by the $K^+\pi^-$ S-wave, present in addition to the resonant P-wave K^{*0}!

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

S-wave pollution:

- $K^+\pi^-$ not in resonant P-wave K^{*0} but in spin 0 configuration $\Rightarrow$ more observables; angular distribution modified:

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{S+P}} = (1-F_{\mathrm{S}})\,\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} + \frac{3}{16\pi}F_{\mathrm{S}}\sin^2\theta_l + \text{S-P interference}$$



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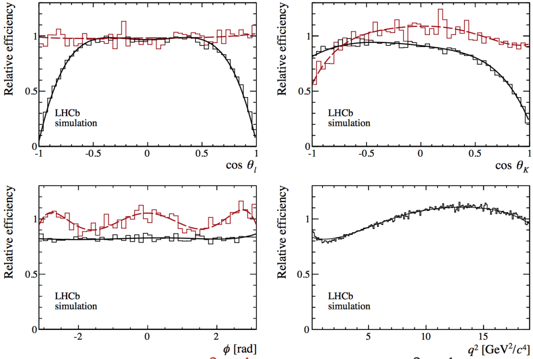
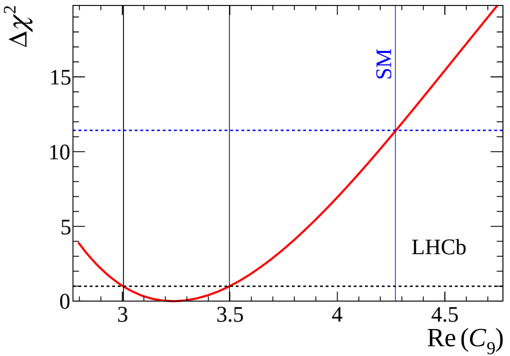
$B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$



$[0.1, 1.0] GeV^2/c^4$, $[18.0, 19.0] GeV^2/c^4$

- acceptance effects: trigger, reconstruction and selection distorts decay angles and q^2 distribution $\Rightarrow$ obtain parametrization of efficiency from MC, cross-checked with data and correct data for this efficiency.

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



- χ^2 fit of measured CP-averaged observables using [EOS] software;
- varying $\mathcal{R}e(\mathcal{C}_9)$ and associated nuisances parameters according;
- $\Delta\mathcal{R}e(\mathcal{C}_9) = 1.04 \pm 0.25$ with global significance of $3.4\,\sigma$.

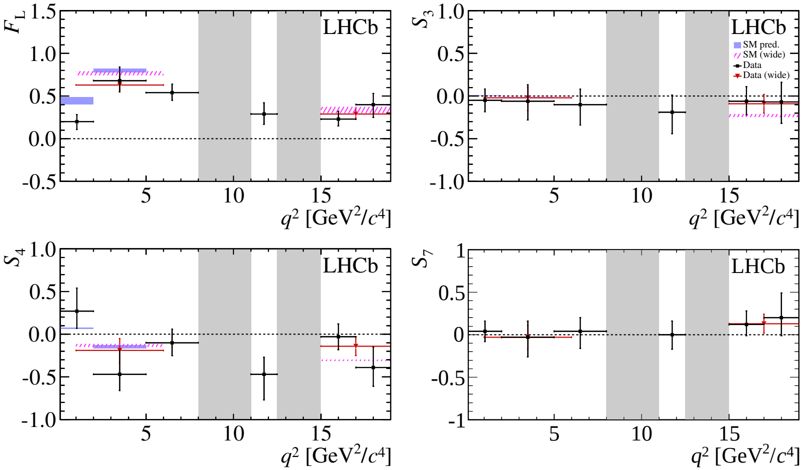
Systematic uncertainties:

Source	F_L	S_3–S_9	A_3–A_9	P_1–P_8'	q_0^2 GeV^2/c^4
Acceptance stat. uncertainty	< 0.01	< 0.01	< 0.01	< 0.01	0.01
Acceptance polynomial order	< 0.01	< 0.02	< 0.02	< 0.04	0.01–0.03
Data-simulation differences	0.01–0.02	< 0.01	< 0.01	< 0.01	< 0.02
Acceptance variation with q^2	< 0.01	< 0.01	< 0.01	< 0.01	–
$m(K^+\pi^-)$ model	< 0.01	< 0.01	< 0.01	< 0.03	< 0.01
Background model	< 0.01	< 0.01	< 0.01	< 0.02	0.01–0.05
Peaking backgrounds	< 0.01	< 0.01	< 0.01	< 0.01	0.01–0.04
$m(K^+\pi^-\mu^+\mu^-)$ model	< 0.01	< 0.01	< 0.01	< 0.02	< 0.01
Det. and prod. asymmetries	–	–	< 0.01	< 0.02	–

$B_s^0 \to \Phi[\to K^+K^-]\mu^+\mu^-$

[JHEP 09 (2015) 179]

All angular observables in agreement with SM.



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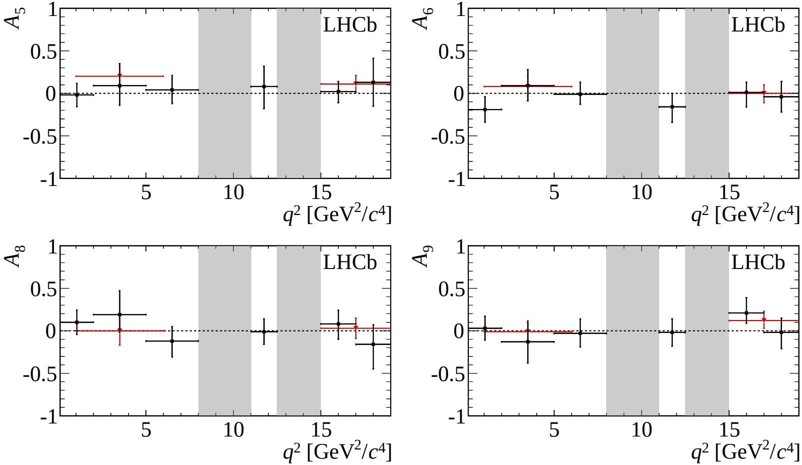
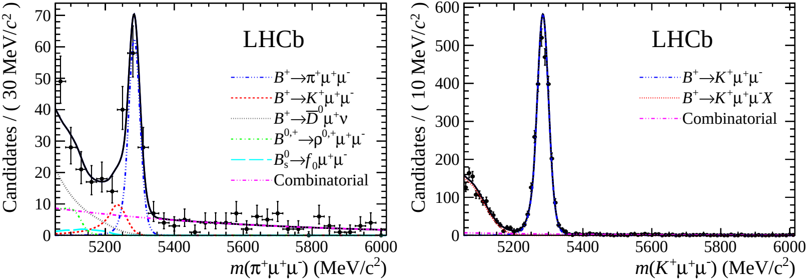
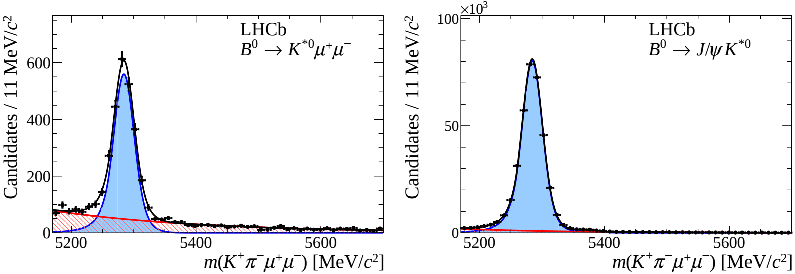
All angular observables in agreement with SM.



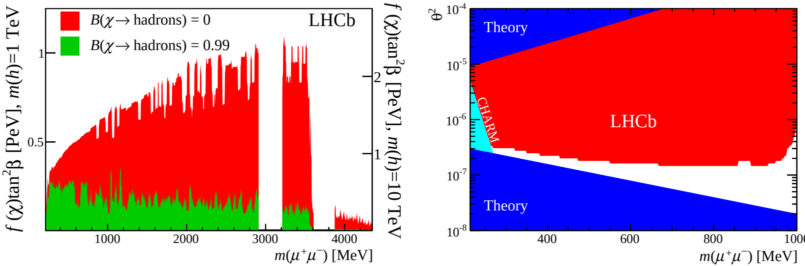

LHCb
Candidates / (30 MeV/c^2)
$m(\pi^+\mu^+\mu^-)$ (MeV/c^2)
$B^+\to\pi^+\mu^+\mu^-$
$B^+\to K^+\mu^+\mu^-$
$B^+\to\overline{D}^0\mu^+\nu$
$B^{0,+}\to\rho^{0,+}\mu^+\mu^-$
$B_s^0\to f_0\mu^+\mu^-$
Combinatorial
LHCb
Candidates / (10 MeV/c^2)
$m(K^+\mu^+\mu^-)$ (MeV/c^2)
$B^+\to K^+\mu^+\mu^-$
$B^+\to K^+\mu^+\mu^- X$
Combinatorial



LHCb
$B^0 \to K^{*0}\mu^+\mu^-$
Candidates / 11 MeV/c^2
0
200
400
600
5200
5400
5600
$m(K^+\pi^-\mu^+\mu^-)$ [MeV/c^2]
LHCb
$B^0 \to J/\psi K^{*0}$
Candidates / 11 MeV/c^2
$\times 10^3$
0
50
100
5200
5400
5600
$m(K^+\pi^-\mu^+\mu^-)$ [MeV/c^2]

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

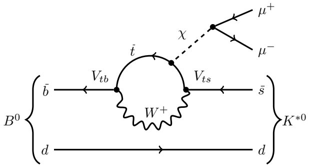
[LHCb, PHYS. REV. LETT. 115 (2015) 161802]

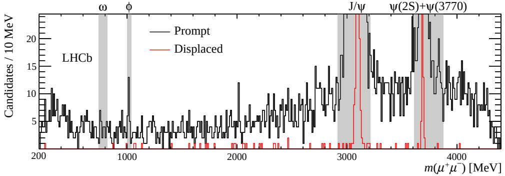


- Axion model (left)[M. Freytsis et al., PRD 81 (2010) 034001]
  Exclusion regions for large $tan\beta$, large $m(h)$;
- Inflaton model (right)[F. Bezrukov et al., PLB 736 (2014) 494]
  Constraints on mixing angle θ between Higgs and inflaton fields.

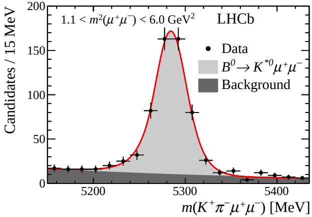
$B^0 \to K^{*0}[\to K^+\pi^-]\,\chi[\to \mu^+\mu^-]$

[LHCb, PHYS. REV. LETT. 115 (2015) 161802]



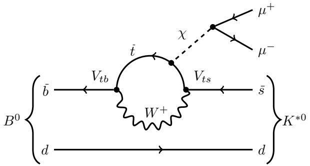


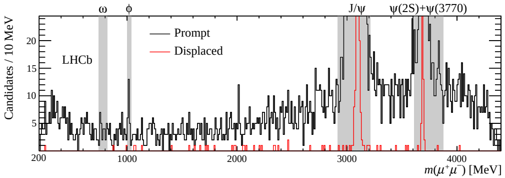
- Scan $m(\mu^+\mu^-)$ distribution for an excess;
- both prompt and displaced χ vertices are considered;
- $\omega, \phi, J/\psi, \psi(2S)$ and $\psi(3770)$ vetoed;
- prompt events in $1.1 < m^2(\mu^+\mu^-) < 6.0 GeV^2$ used for normalization;
- accessible χ mass in $[214, 4350] MeV$.



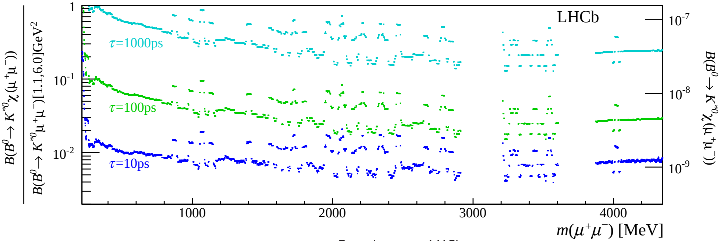
$B^0 \to K^{*0}[\to K^+\pi^-]\, \chi[\to \mu^+\mu^-]$

[LHCb, PHYS. REV. LETT. 115 (2015) 161802]



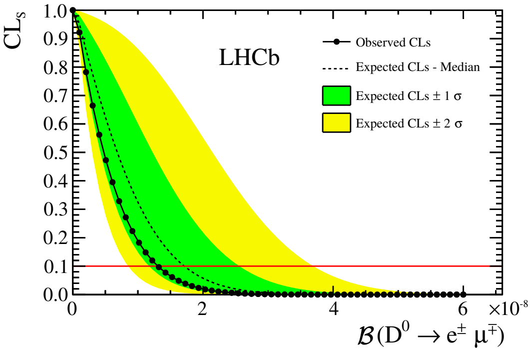


- no significant signal observed ⇒ set 95% CL upper limits (and thus implied limits on theoretical models)



$D^0 \to e^\pm \mu^\mp$

[LHCB-PAPER-2015-048]



- No evidence for any signal;
- World's best upper limit, obtained from CL_S method:

$$\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 1.3 \times 10^{-8}$$