Rare decays at LHCb: from beauty to strange

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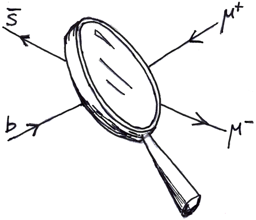
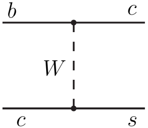
Why rare decays?

- Tiny effects in the SM ⇒ NP can be at the same level
- Virtual particles ⇒ High mass reach
- Precise predictions in SM
- Model independent searches
- Historically the laboratory of many particle physics discoveries

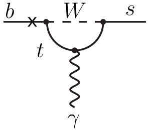


EFT, Wilson coefficients and other “boring” stuff

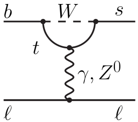
Complex interactions substituted with Fermi-like operators: couplings hide the high energy information



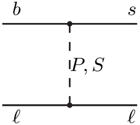
Charged current $G_F V_{cb} V_{cs}^* C_2 \bar{c}_L \gamma^\mu b_L \bar{s}_L \gamma_\mu c_L$



photon penguin $\frac{e}{4\pi^2} G_F V_{tb} V_{ts}^* m_b C_7 \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$



EW penguin $G_F V_{tb} V_{ts}^* C_{9(10)} \bar{s}_L \gamma^\mu b_L \bar{\ell} \gamma_\mu (\gamma_5) \ell$



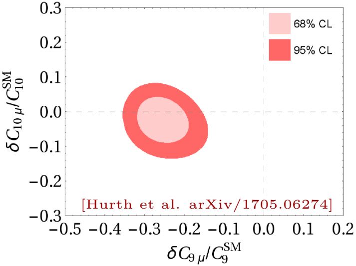
NP (pseudo)-scalar $\propto C_{S(P)} \bar{s}_L b_L \bar{\ell} (\gamma_5) \ell$

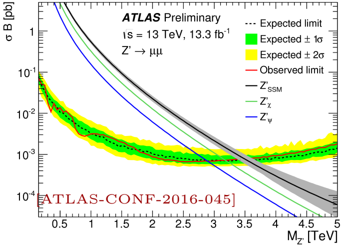
Plus chirally flipped operators...

How are rare decays sensitive?

EFT, Wilson coefficients and other “boring” stuff (2)

- New physics interactions can enter through new operators $(S, P, \ldots)$ or modifying the coefficients of SM operators
- If Wilson coefficients are thought of as effective couplings with a NP scale (e.g. for C_9):
  $\sim G_F V_{tb} V_{ts}^{*} \frac{\alpha}{4\pi} C_9 = \frac{g^2}{\Lambda}$
- Probing scales (masses!) up to hundreds of TeV (depending how large the coupling you allow to be)
- Not necessarily having the CKM flavour structure (MFV)

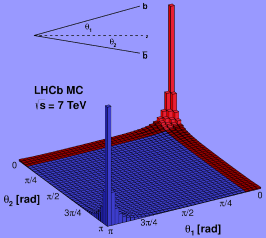


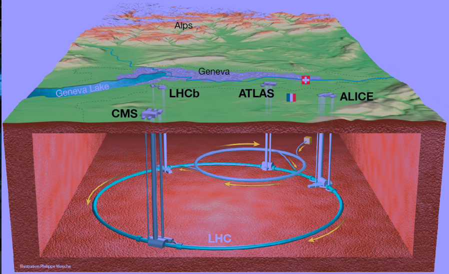


LHCb experiment

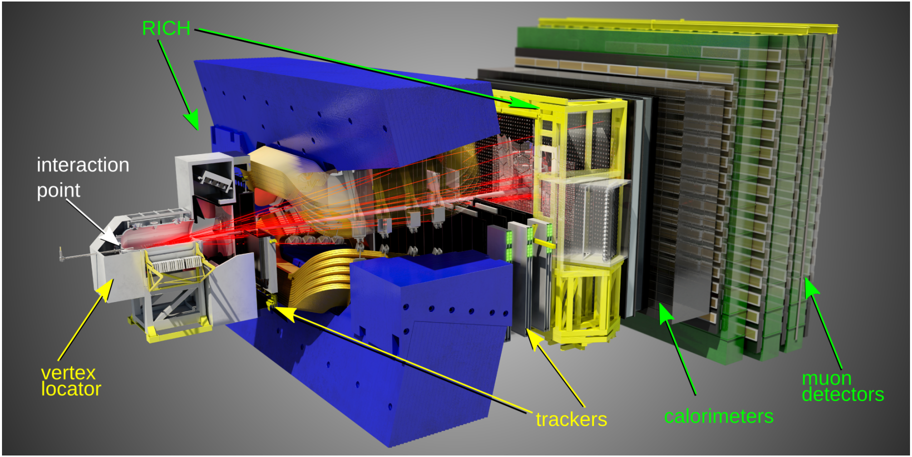
LHCb experiment

- 1150 members, from 69 institutes in 16 countries
- Dedicated experiment for precision measurements of CP violation and rare decays
- *Beautiful*, *charming*, *strange* physics program





- pp collisions at $\sqrt{s} = 7, 8, 13$ TeV
- 3 (2) fb^{-1} in Run I (Run II)
- $b\bar{b}$ quark pairs produced correlated in the forward region
- Luminosity leveled at $4 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$



[Int. J. Mod. Phys. A 30 (2015) 1530022]

Excellent vertex and IP resolution

- $\sigma(IP) \simeq 24\mu\text{m}$ at $p_T = 2$ GeV/c
- $\sigma_{BV} \simeq 16\mu\text{m}$ in x, y

Very good track momentum resolution

- $\sigma(p)/p = 0.4\% - 0.6\%$ for $p \in (0, 100)$ GeV/c
- $\sigma(m) \sim 24(4)$ MeV for two body $B(K_S)$ decays

Muon identification

- $\varepsilon_\mu = 98\%$, $\varepsilon_{\pi\to\mu} = 0.6\%$, $\varepsilon_{K\to\mu} = 0.3\%$, $\varepsilon_{p\to\mu} = 0.3\%$

Trigger

- $\varepsilon_\mu = 90\%$ for B decays

Beauty decays

1. Branching fraction

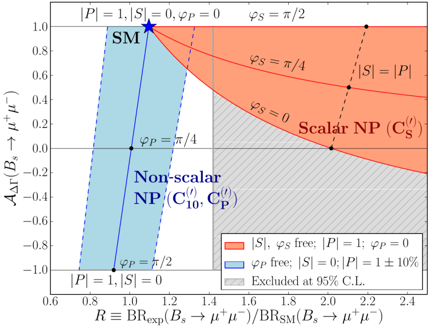
$$\mathcal{B}^{t=0}(B_s^0 \to \mu^+\mu^-) = \frac{G_F^4 M_W^4}{\pi^2}\tau_{B_s^0} f_{B_s}^2 m_{B_s}^3 \sqrt{1-\frac{4m_\mu^2}{m_{B_s}^2}}|V_{tb}V_{ts}^*|^2 \left(|2\frac{m_\mu}{m_{B_s}}(C_{10}-C'_{10}) + C_P - C'_P|^2 + |C_S - C'_S|^2\right)$$

2. Ratio of branching fractions

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = \frac{\tau_{B_d}}{\tau_{B_s}}\left(\frac{f_{B_d}}{f_{B_s}}\right)^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{m_{B_d}\sqrt{1-\frac{4m_\mu^2}{m_{B_d}^2}}}{m_{B_s}\sqrt{1-\frac{4m_\mu^2}{m_{B_s}^2}}}$$

3. Effective lifetime

$$\tau_{\mu\mu} = \frac{\tau_{B_s}}{(1-y_s^2)}\frac{1+2y_s\mathcal{A}_{\Delta\Gamma}+y_s^2}{1+y_s\mathcal{A}_{\Delta\Gamma}}$$



$B_s^0 \to \ell^+\ell^-$ Standard Model predictions

Most recent predictions (time integrated)

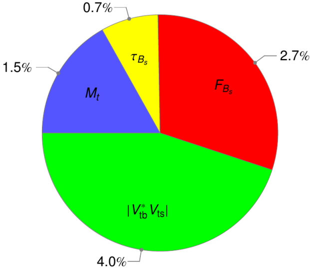
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)^{\langle t\rangle} = (3.65 \pm 0.23)\cdot 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-)^{\langle t\rangle} = (1.06 \pm 0.09)\cdot 10^{-10}$$

$$\mathcal{R} = 0.0287 \pm 0.0026$$

$$A_{\Delta\Gamma} = 1$$

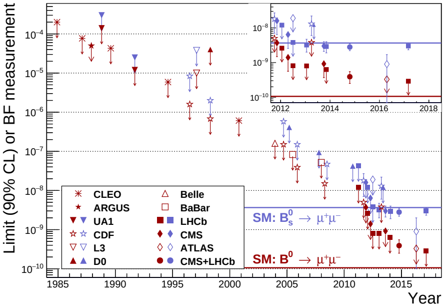
$$\mathcal{B}(B_s^0 \to \tau^+\tau^-)^{\langle t\rangle} = (7.73 \pm 0.49)\times 10^{-7}$$



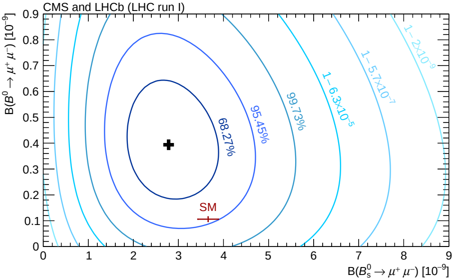
- Impressively precise predictions
- Any significant deviations from these values is sign of new interactions beyond the SM
- Main uncertainties are parametric, dominated by CKM matrix elements.

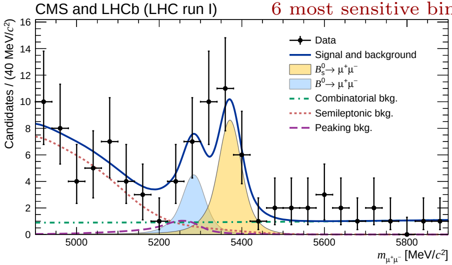
[Bobeth et al. PRL 112 (2014) 101801.] [Bobeth et al. PRD 89, 034023 (2014)] [Hermann et al. JHEP 1312 (2013) 097]

- 30 years search for $B_{d,s}^0 \to \mu^+\mu^-$ decays
- First evidence in LHCb with 1 fb^{-1}
- Observation from CMS+LHCb combined analysis
- Good agreement with SM



[CMS+LHCb - Nature 522, 6872 (2015)]





Observation of $B_s^0 \to \mu^+\mu^-$ at LHCb

And first measurement of the effective lifetime

- 3fb^{-1} Run 1 + 2 fb^{-1} Run 2 data
- Re-optimized particle identification and multivariate operator

Results:

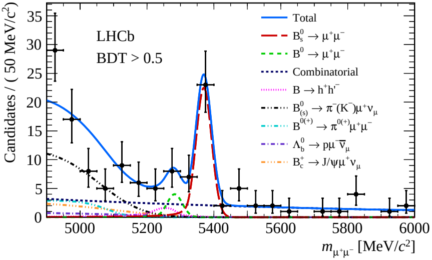
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

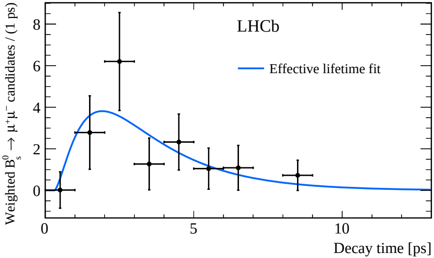
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} (95\% \text{ CL})$$

- First single-experiment observation of $B_s^0 \to \mu^+\mu^-$ with 7.8σ
- First measurement of effective lifetime

$$\tau(B_s^0 \to \mu^+\mu^-) = (2.04 \pm 0.44 \pm 0.05)\text{ps}$$

Compatible with $A_{\Delta\Gamma} = 1(-1)$ at the 1.0 (1.4) σ level





[LHCb- Phys. Rev. Lett. 118 (2017) 191801]

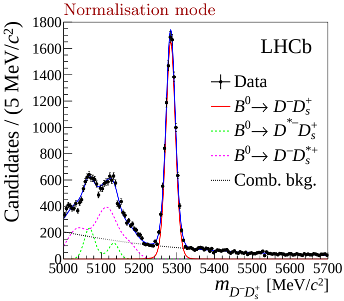
Search for $B^0_{(s)} \to \tau^+\tau^-$ decays at LHCb

- Extremely difficult analyses
- Full Run 1 (3 fb^{-1})
- $\tau \to \pi\pi\pi\nu$ mode (10%)
- Search in NN output

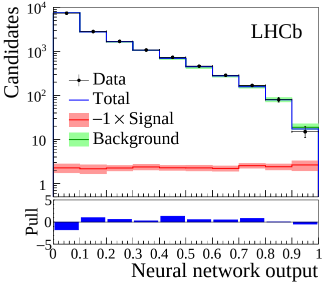
Limits at 95% CL

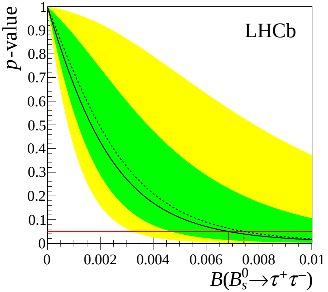
$$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3}$$
$$\mathcal{B}(B^0_d \to \tau^+\tau^-) < 2.1 \times 10^{-3}$$

First (B^0_s) and world best (B^0) limits
Still very far from SM



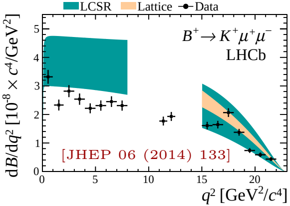
[LHCb - arXiv:1703.02508]

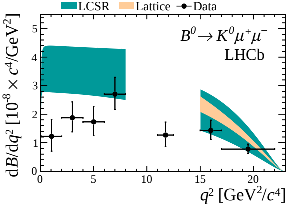


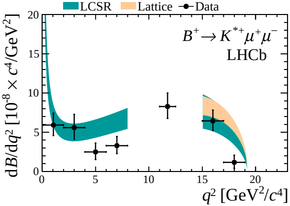


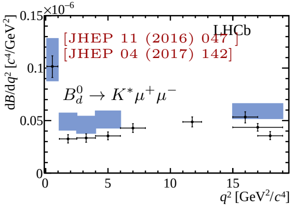
Branching fractions

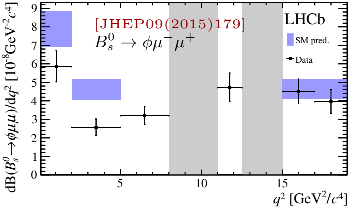
- Measurements of various $b \to s$ transitions systematically below the SM:
- Might be all due to modification of C_9





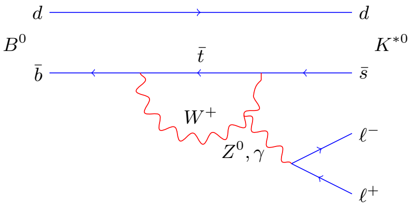


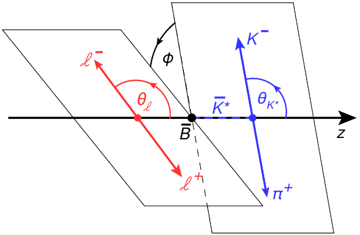




Angular analysis of $B_d^0 \to K^* \ell^+ \ell^-$ decays

- $b \to s$ transition with vector in the final state
- Final state described by $q^2 = m_{\mu\mu}^2$ and three angles $\Omega = (\theta_\ell, \theta_K, \phi)$
- F_L, A_{FB}, S_i sensitive to $C_7^{(\prime)}$ $C_9^{(\prime)}$ $C_{10}^{(\prime)}$

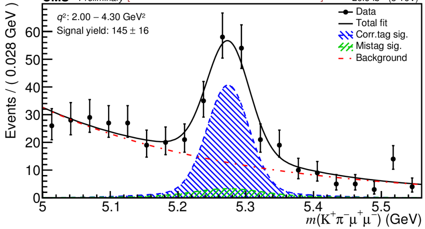




$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\rm L})\sin^2\theta_K + F_{\rm L}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\rm L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\rm L}\cos^2\theta_K\cos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

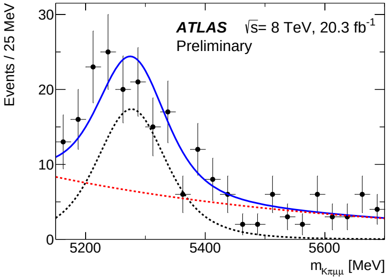
Angular analysis of $B_d^0 \to K^* \mu^+ \mu^-$ decays

Many recent measurements

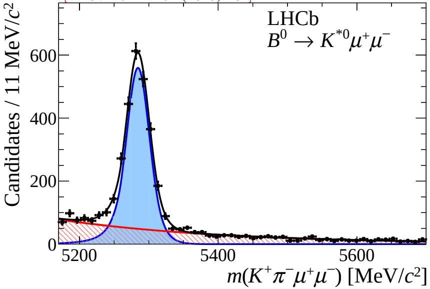


[CMS - CMS-PAS-BPH-15-008]

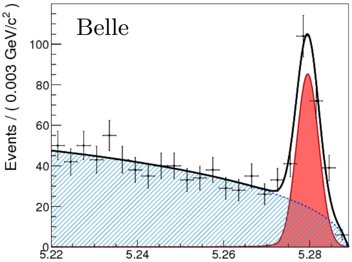
[ATLAS - ATLAS-CONF-2017-023]



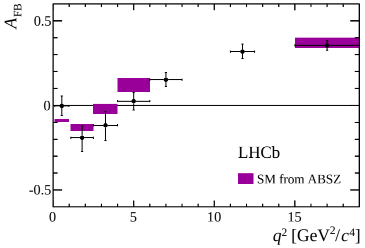
[LHCb - JHEP 02 (2016) 104]

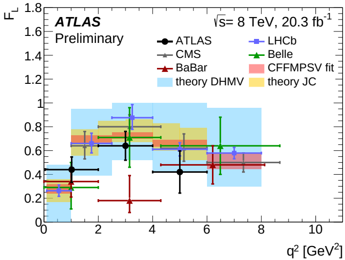


[Belle - Phys.Rev.Lett. 118 (2017) no.11, 111801]

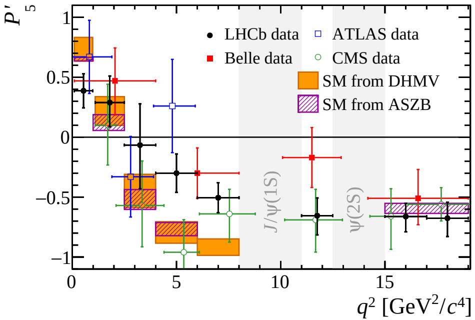


$B_d^0 \to K^*\mu^+\mu^-$ results





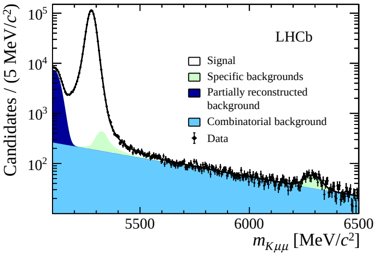
- Several observables appear different than SM
- In particular P_5' has significant discrepancy
- Global fits show large disagreement

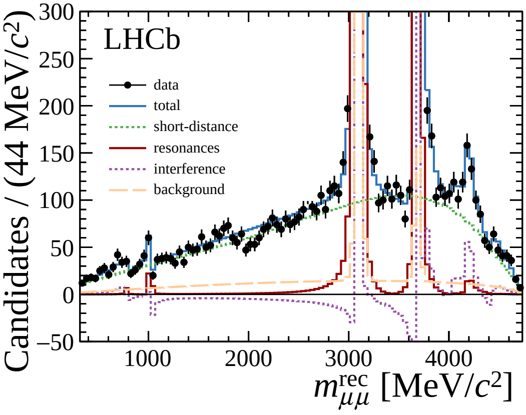


Phase space difference in $B^+ \to K^+\mu^+\mu^-$ decays

- Fit to full dimuon mass distribution
  - ⋆ Resonances: ρ, ω, ϕ, J/ψ, $\psi(2S)$
  - ⋆ Broad charmonium states: $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$,
- Four-fold ambiguity in J/ψ and $\psi(2S)$ phase signs:
  Compatible with $\pi/2$, hence low interference with non-resonant

[LHCb - Eur. Phys. J. C (2017) 77: 161]





Phase space difference in $B^+ \to K^+\mu^+\mu^-$ decays

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{128\pi^5}|\mathbf{k}|\beta\left\{\frac{2}{3}|\mathbf{k}|^2\beta^2\left|\mathcal{C}_{10}f_+(q^2)\right|^2 + \frac{4m_\mu^2(m_B^2-m_K^2)^2}{q^2m_B^2}\left|\mathcal{C}_{10}f_0(q^2)\right|^2 + |\mathbf{k}|^2\left[1-\frac{1}{3}\beta^2\right]\left|\mathcal{C}_9f_+(q^2)+2\mathcal{C}_7\frac{m_b+m_s}{m_B+m_K}f_T(q^2)\right|^2\right\},$$

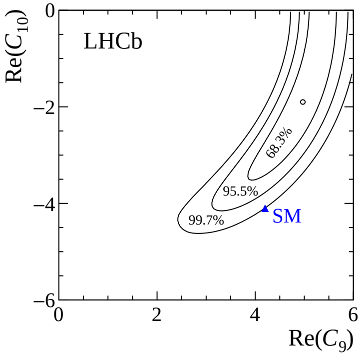
[Bailey et al. Phys. Rev. D 93, 025026 (2016)]

[LHCb - Eur. Phys. J. C (2017) 77: 161]

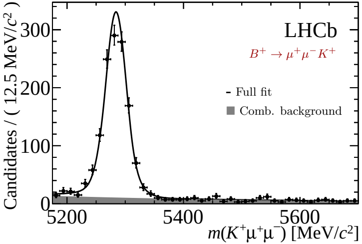
- Fit to Wilson coefficients
- Non resonant sensitive to C_9 and C_{10}
- Deviation of 3.0σ from SM
- Low $B^+ \to K^+\mu^+\mu^-$ BR not explained by resonance interferences

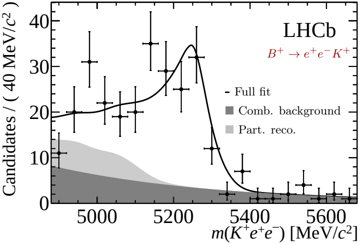
$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37\pm0.15\pm0.23)\times10^{-7}$$

in agreement with previous measurement



Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays





$q^2 \in [1,6]\mathrm{GeV}^2/c^4$

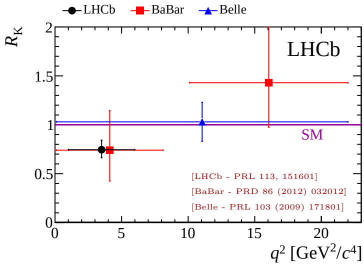
Electron Trigger

[LHCb - Phys. Rev. Lett. 113, 151601]

The combination of the various trigger channels gives:

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

Most precise measurement to date, compatible with SM at 2.6σ level



The branching fraction of $B^+ \to e^+e^-K^+$ is measured as

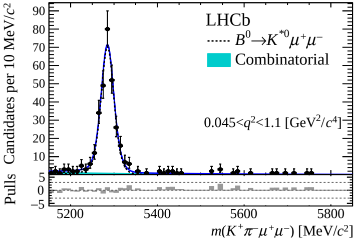
$$\mathcal{B}(B^+ \to e^+e^-K^+) = 1.56^{+0.19}_{-0.15}(\text{stat})^{+0.06}_{-0.05}(\text{syst}) \times 10^{-7}$$

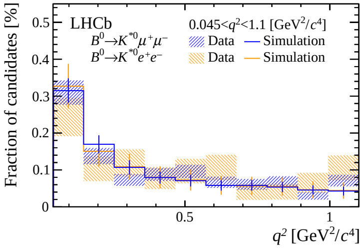
well compatible with SM predictions

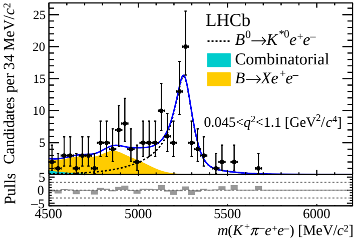
$$R_{K^*} = \frac{\mathcal{B}(B_d^0 \to K^* \mu^+ \mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^{*+})} \Big/ \frac{\mathcal{B}(B_d^0 \to K^* e^+ e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^{*+})}$$

[LHCb - arXiv/1705.05802]

- Very clean theoretical predictions
- Double ratio to cancel systematics
- Two q^2 bins and three independent triggers
- Excluded low q^2 region (dominated by photons)



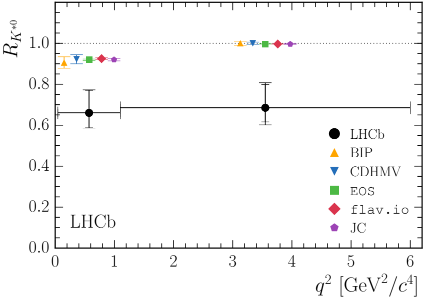


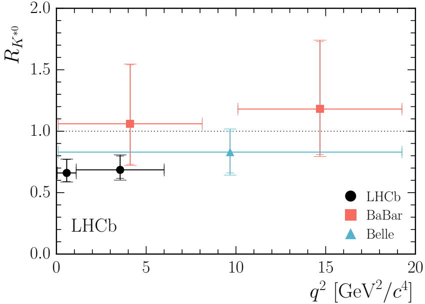


Lepton Universality Test in $B_d^0 \to K^* \ell^+ \ell^-$

[LHCb - arXiv/1705.05802]

$$R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\,\text{GeV}^2/c^4 \\ 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 < q^2 < 6.0\,\text{GeV}^2/c^4 \end{cases}$$

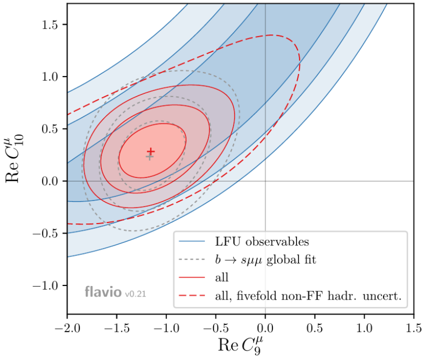




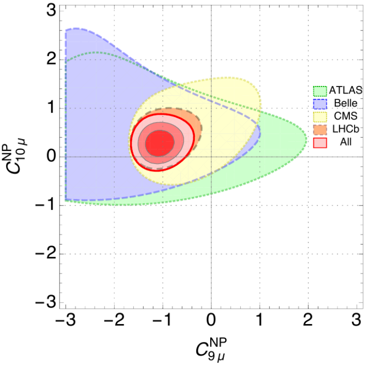
- Statistically dominated
- SM compatibility: $[2.1 - 2.3]\sigma$ and $[2.4 - 2.5]\sigma$ for the two bins respectively

Global fits

- Two examples of global fits (but many more in literature)
- Consistent results: new physics preferred in C_9 (possibly μ-only)



[Altmannshofer et al.]



[Capdevila et al.]

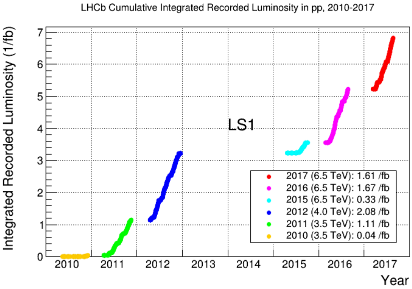
Summary of B anomalies

Are we there yet?

1. Low $b \to s\mu\mu$ branching fractions
2. Discrepancies in angular observables of $B_d^0 \to K^*\mu^+\mu^-$
3. Signs of lepton non-universality in: $B^+ \to K^+\mu^+\mu^-$ and $B_d^0 \to K^*\mu^+\mu^-$

- All seems to be related to a change in the C_9 coefficient (or maybe C_9 and C_{10}, but V-A)
- Global fits start to exhibit several standard deviations of discrepancy
- $c\bar{c}$ interference explanation seems not justified
- Additional discrepancies in tree-level $B \to D^{(*)}\ell\nu$ decays
- Many NP explanations: Z', leptoquarks, low mass resonances etc!

- Most of the analysis at LHCb based on Run 1 data
- 3.6 fb^{-1} on tape in Run 2 ($\times 2$ of cross-section) + 2018 data-taking
- Many observables not probed yet
- Soon the possibility to have 5σ deviations on single channels
- The best is yet to come



Charm decays

Same but different:

- Stronger GIM suppression due to absence of high mass down quark
- Larger theoretical uncertainties due to long distance effects
- Unique probe of up-sector FCNC

At LHCb

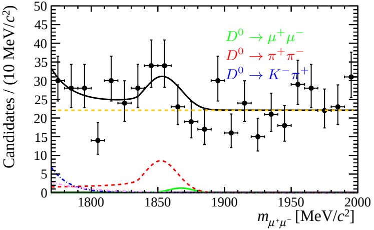
- Massive production of D mesons

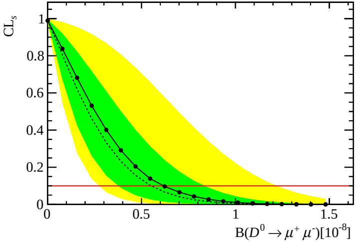
Search for $D^0 \to \mu^+\mu^-$ at LHCb

- $D^0 \to \mu^+\mu^-$ arises at tree levels in some leptoquarks model used for B decays: important complementary bounds! [Bauer et al. PRL116 (2016) no.14, 141802]
- $D^{*+} \to D^0(\to \mu^+\mu^-)\pi^+$ search
- $0.9\ \text{fb}^{-1}$ at 7 TeV

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 7.6 \times 10^{-9}$$

- Similar complementary constraints from other rare charm decays



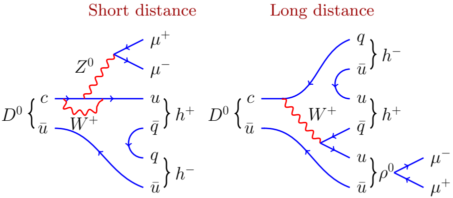


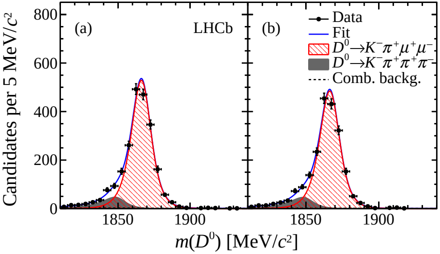
[LHCb - Phys.Lett. B725 (2013) 15-24]

Observation of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

[LHCb - Phys. Rev. Lett. 119, 181805]

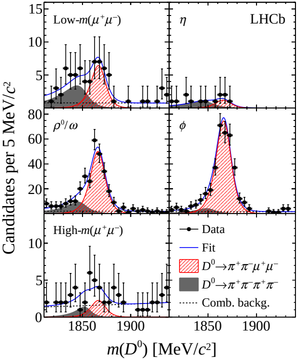
- Short distance rate at 10^{-9}, dominated by long distance
- Search based on 2 fb^{-1} at 8 TeV
- Use $D^{*+} \to D^0\pi^+$ tagged candidates
- Normalised to $D^0 \to K^-\pi^+\rho/\omega(\to \mu^+\mu^-)$
- No attempt to disentangle long and short distance contribution: dedicated angular analysis in progress



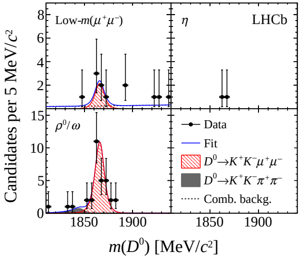


Observation of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

- First observation of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ decays
- Rarest charm decays ever observed



$D^0 \to \pi^+\pi^-\mu^+\mu^-$		
$m(\mu^+\mu^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-8}]
Low mass	< 525	$7.8 \pm 1.9 \pm 0.5 \pm 0.8$
η	525–565	$< 2.4\,(2.8)$
ρ^0/ω	565–950	$40.6 \pm 3.3 \pm 2.1 \pm 4.1$
ϕ	950–1100	$45.4 \pm 2.9 \pm 2.5 \pm 4.5$
High mass	> 1100	$< 2.8\,(3.3)$
$D^0 \to K^+K^-\mu^+\mu^-$		
$m(\mu^+\mu^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-8}]
Low mass	< 525	$2.6 \pm 1.2 \pm 0.2 \pm 0.3$
η	525–565	$< 0.7\,(0.8)$
ρ^0/ω	> 565	$12.0 \pm 2.3 \pm 0.7 \pm 1.2$

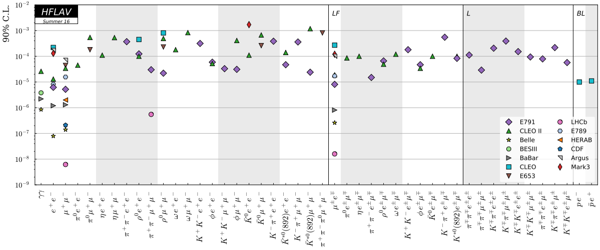


[LHCb - Phys. Rev. Lett. 119, 181805]

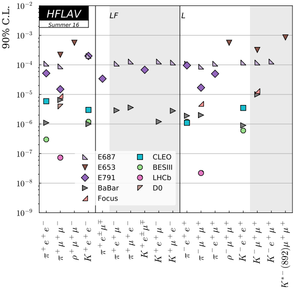
Charm rare decays at LHCb: outlook

- LHCb has only exploited Run 1 and contributed to few of the dozen important decay modes
- Possibility to put world best limits in each of them
- Upgrade will see an increase of charm yields thanks to L0 removal
- Will reach the SM in many modes

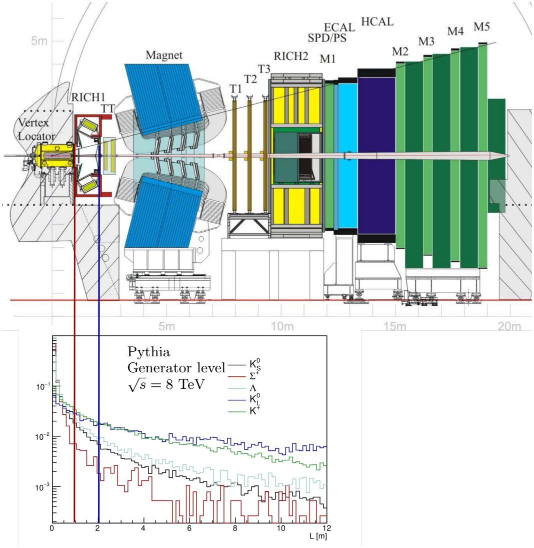
D^0 rare decays



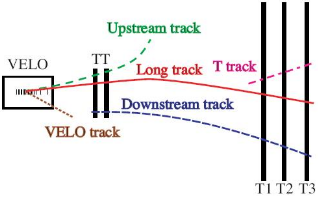
D^+ rare decays



Strange decays



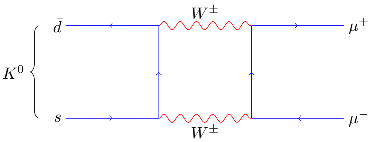
- Huge strange hadrons production cross-section at LHCb:
  O(1) strange hadron per minbias event
- Large lifetimes for LHCb... but the peak of an exponential is at zero!

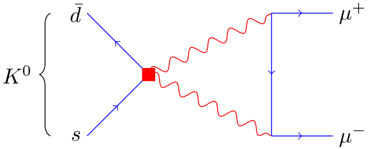


Search for $K_S^0 \to \mu^+\mu^-$ decays

LHCb-PAPER-2017-009 - hep-ex/1706.00758

- $K_L^0 \to \mu^+\mu^-$ is the "father" of flavour physics
  motivating the need for charm quark and GIM mechanism
- $K_S^0 \to \mu^+\mu^-$ in addition suppressed by CPV
- SM prediction $\mathcal{B}(K_S^0 \to \mu^+\mu^-) = (5.1 \pm 1.5) \cdot 10^{-12}$
  [Ecker, Pich - Nucl Phys B366 (1991)] [Isidori, Unterdorfer - JHEP 01 (2004) 009]
- Dominated by long distance contributions
- Sensitive to NP, e.g. light scalars with CP-violating Yukawa couplings
- Best limit before LHCb was $\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 3.1 \cdot 10^{-7}$ at 90% CL at CERN PS in 1973 [S. Gjesdal et al. PLB44(1973)217]
- Recent theoretical interest following LHCb results:
  possibility to study the interference of K_L^0 and K_S^0 to two muons [D'Ambrosio et al. hep-ph/1707.06999]





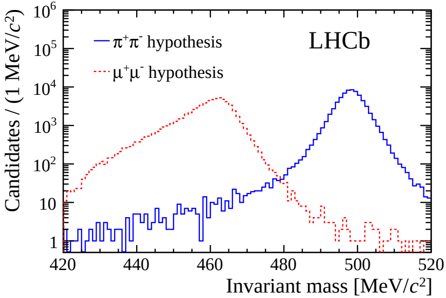
LHCb-PAPER-2017-009 - hep-ex/1706.00758

Selection strategy

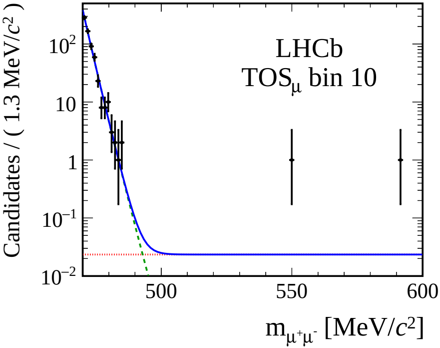
- Common selection of $K_S^0 \to \mu^+\mu^-$ and $K_S^0 \to \pi^+\pi^-$, control and normalisation channel as well as main background
- Veto for $\Lambda \to p\pi^-$ and particle identification against $K^* \to K\pi$ and other backgrounds
- Two multivariate operators to fight different backgrounds:
  - ⋆ Dedicated multivariate particle identification algorithm developed
  - ⋆ BDT to fight combinatorial background

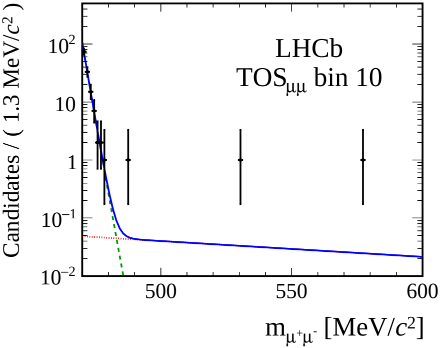
Trigger strategy

- Two categories based different trigger paths



- $K_S^0 \to \mu^+\mu^-$ distribution fitted in the [470,600] MeV range
- Simultaneous maximum likelihood fit performed over the 30 bins
- Combinatorial and misID $K_S^0 \to \pi^+\pi^-$ background components included
- **No excess of events is observed with respect to background expectations**



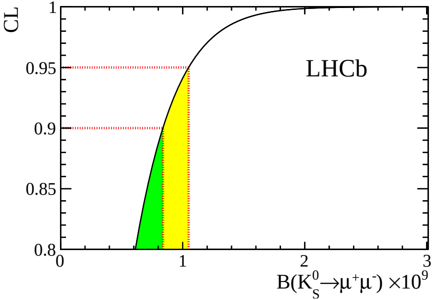


LHCb-PAPER-2017-009 - hep-ex/1706.00758

- The upper limit of the previous search is reinterpreted as posterior on the branching fraction and included as prior in this search
- The new upper limit on the branching fraction is

$$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 0.8(1.0) \times 10^{-9} \text{ at } 90\ (95\%)\text{ CL}$$

- Factor 400 improvement with respect to the best limit before LHCb

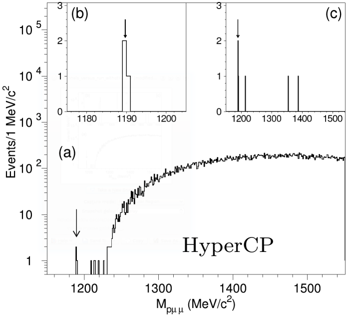


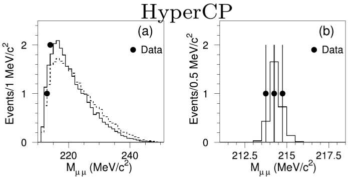
LHCb-PAPER-2017-009 - hep-ex/1706.00758

Search for $\Sigma^+ \to p\mu^+\mu^-$ at LHCb

The HyperCP anomaly

- $\Sigma^+ \to p\mu^+\mu^-$ is a very rare FCNC
- Short distance SM branching fraction is $O(10^{-12})$
- Dominated by long distance contributions: $1.6 \cdot 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 9.0 \cdot 10^{-8}$ [He et al. - Phys.Rev. D72 (2005) 074003]
- An evidence for this decay was found by the HyperCP experiment with 3 events in absence of background
- Measured branching fraction is: $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$ [Phys.Rev.Lett. 94 (2005) 021801]
- This evidence attracted large attention since all the **3** observed signal events have the same dimuon invariant mass: pointing towards a $\Sigma^+ \to pX^0(\to \mu\mu)$ decay with $m^0_X = 214.3 \pm 0.5$ MeV $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu\mu)) = (3.1^{+2.4}_{-1.9} \pm 5.5) \cdot 10^{-8}$
- Large theoretical and experimental attention but no other direct search for $\Sigma^+ \to p\mu^+\mu^-$



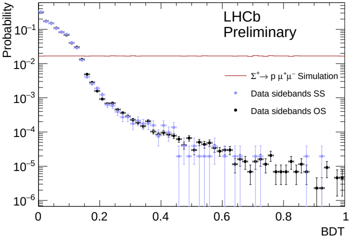


Sample and selection:

- Full 2011+2012 statistics, luminosity 3 fb^{-1}
- Decays reconstructed with long tracks (i.e. decays in VELO)
- Prompt decays (no displacement of the dimuon pair)

Datasets strategy

- Very soft signal to be triggered
- Two trigger strategies:
  1. Full - all events are retained, for search purposes, no normalisation
  2. TIS - for normalization purposes (sub sample)
- Soft pre-selection to reduce dataset
- Cut on BDT and PID to remove most of the background
- Explicit veto of $\Lambda \to p\pi$ background, no other peaking background contributes



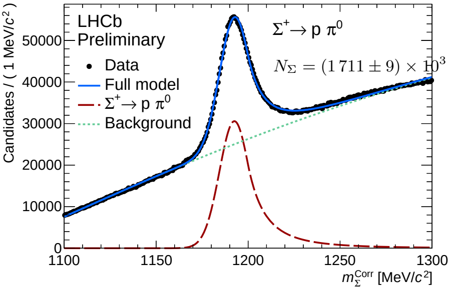
Normalisation

- No fully charged final state available in the Σ^+ to normalize
- Use high branching fraction $\Sigma^+ \to p\pi^0$ ($\mathcal{B} = (51.57 \pm 0.30)\%$)

$$\begin{aligned}\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) &= \frac{\varepsilon_{\Sigma^+\to p\pi^0}}{\varepsilon_{\Sigma^+\to p\mu^+\mu^-}} \frac{\mathcal{B}(\Sigma^+ \to p\pi^0)}{N_{\Sigma^+\to p\pi^0}} N_{\Sigma^+\to p\mu^+\mu^-} \\ &= \alpha N_{\Sigma^+\to p\mu^+\mu^-}\end{aligned}$$

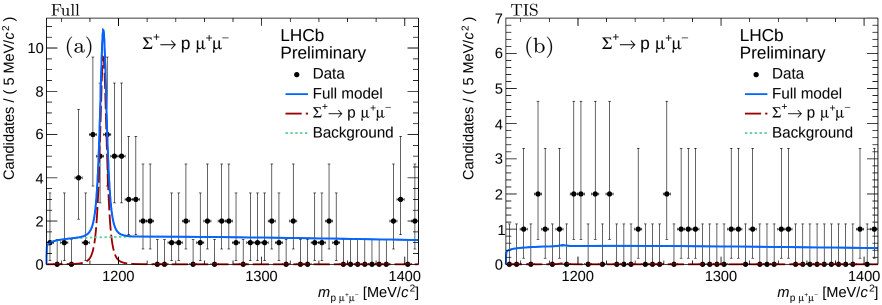
- Selection for $\Sigma^+ \to p\pi^0$ with $\pi^0 \to \gamma\gamma$ (resolved clusters) from calorimeter

For full Run I dataset, only TIS: single event sensitivity $\alpha_{TIS} = (1.1 \pm 0.6) \times 10^{-8}$
(Correspondent to 4.6 ± 4.2 expected events in the TIS sample with a SM BR)



Results

LHCb-CONF-2016-013

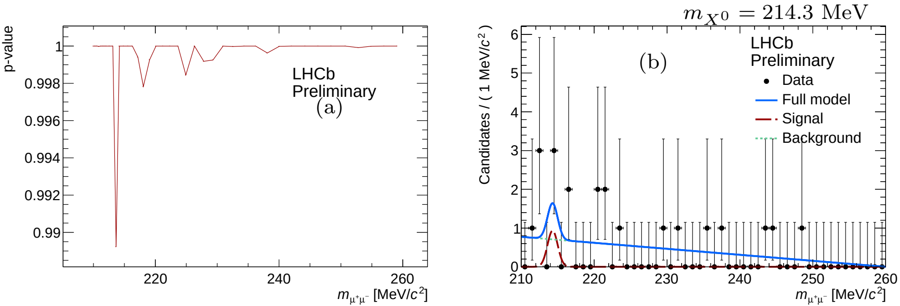


- Excess of events w.r.t. background with a significance of $4.0\,\sigma$
- Fitted signal yield: $12.9^{+5.1}_{-4.2}$
- No excess of events in the TIS sub-sample for which normalisation is performed
- Upper limit with CLs method: $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 6.3 \times 10^{-8}$ at 95% CL

Results: analysis of the dimuon mass

LHCb-CONF-2016-013

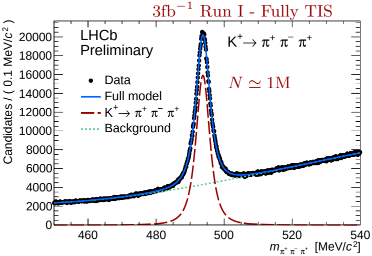
- Consider candidates within $2\,\sigma$ from the Σ mass in the full selection
- Scan dimuon invariant mass for possible peaks
- Fit with gaussian of known mass and resolution
- No significant peak found
- Most pronounced at 213.7 MeV (but not significant)
- Fit at $m_{X^0} = 214.3$ MeV yields 1.6 ± 1.9 events corresponding to a fraction 0.078 ± 0.092 of the total seen signal



- Found signal only in the full sample:
  most of the seen events have only one of the three trigger layers not being TIS
- Full detailed study of $\Sigma^+ \to p\mu^+\mu^-$ trigger efficiency is under way
- The main conclusions are anyway independent of absolute normalisation:
  1. Evidence of $\Sigma^+ \to p\mu^+\mu^-$ decay
  2. SM-like distribution of the dimuon invariant mass
  3. **Contribution from putative X^0 particle consistent with zero**
- Long-awaited paper with full normalisation is in preparation

Strange physics at LHCb: outlook

- Several analysis in progress
  - ⋆ $K^0_S \to \pi^0 \mu^+ \mu^-$
- Run 2 includes dedicated triggers
- Upgrade will bring rates up by an order of magnitude due to removel of hardware trigger
- LHCb major player for K^0_S and hyperon decays
- Complementary to K_L and K^+ dedicated experiments
- Possible physics reach also in charged kaons decays



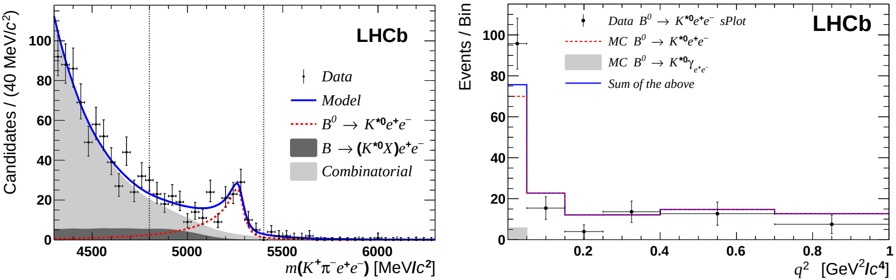
Summary

- Rare decays are a great laboratory to test the SM:
  precise predictions and clean experimental observables
- Model independent sensitivity to NP:
  - ⋆ Possible new (pseudo)-scalar interactions tightly constrained by $B_s^0 \to \mu^+\mu^-$ decays
  - ⋆ Possible new vector (or V-A) interactions seem to explain several B anomalies
- Variety of complementary observables
- For some decays: healthy competition between 4 experiments!
- Vibrant field: many new results will come soon to confirm or disprove this tantalising results!
- LHCb is probing the full spectrum:
  - ⋆ Rare charm decays complementarily probe the up-sector constraining models used to explain B-anomalies
  - ⋆ Expanding physics program in strange-hadron physics: world best sensitivity on in K_S and hyperons
- The near future will reveal if these anomalies will form a coherent picture

Backup

Angular analysis of $B_d^0 \to K^* e^+ e^-$ decays

- Angular analysis of $B_d^0 \to K^* e^+ e^-$ at very low q^2 ($\in [0.002, 1.120]\mathrm{GeV}^2/\mathrm{c}^4$)
- Folded angular observables ($\phi = \phi + \pi$ if $\phi < 0$)
- Measurement of F_L, $A_T^{(2)}$, $A_T^{(\mathrm{Im})}$, $A_T^{(\mathrm{Re})}$, * sensitive to C_7' as $q^2 \to 0$



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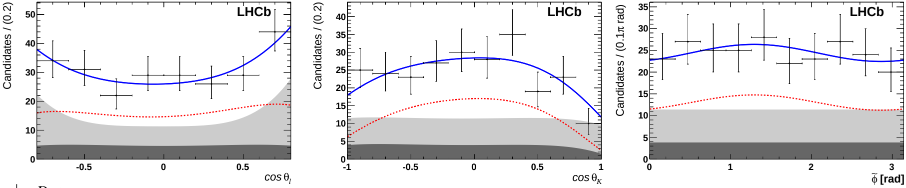
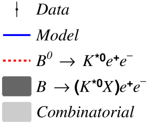
* $A_T^{(\mathrm{Re})} = \frac{4}{3} A_{FB}/(1 - F_L)$, $A_T^{(2)} = \frac{1}{2} S_3/(1 - F_L)$ and $A_T = \frac{1}{2} S_9/(1 - F_L)$

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

[LHCb - JHEP04(2015)064]





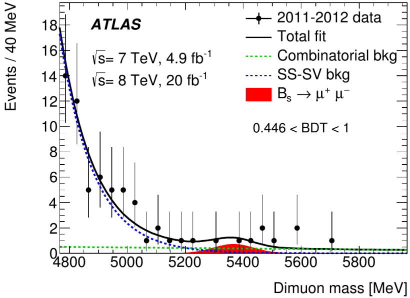
Observable	Measurement	SM prediction[†]
F_{L}	$+0.16 \pm 0.06 \pm 0.03$	$+0.10^{+0.11}_{-0.05}$
$A_{\mathrm{T}}^{(2)}$	$-0.23 \pm 0.23 \pm 0.05$	$0.03^{+0.05}_{-0.04}$
$A_{\mathrm{T}}^{\mathrm{Re}}$	$+0.10 \pm 0.18 \pm 0.05$	$-0.15^{+0.04}_{-0.03}$
$A_{\mathrm{T}}^{\mathrm{Im}}$	$+0.14 \pm 0.22 \pm 0.05$	$(-0.2^{+1.2}_{-1.2}) \times 10^{-4}$

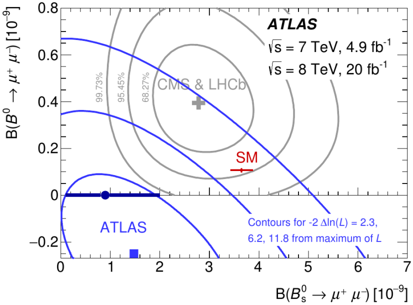
- Measurements well in agreement with SM predictions
- Constraints on $C_7^{(\prime)}$ competitive with radiative decays

[†] S. Jäger, J. M. Camalich [arXiv/1412.3283]

$B_s^0 \to \mu^+\mu^-$ in ATLAS

- 25 fb^{-1} of 7-8 TeV pp collisions
- Normalised to $B^+ \to J/\psi K^+$ events
- Search in three bins of a BDT operator

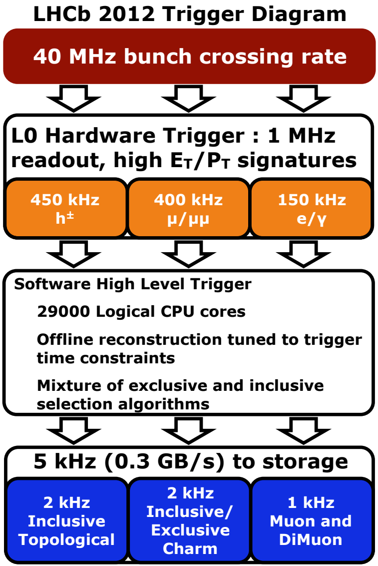




$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9} \quad \mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

B_s^0 signal significance is 1.4σ
The 2D likelihood is compatible with SM at 2σ

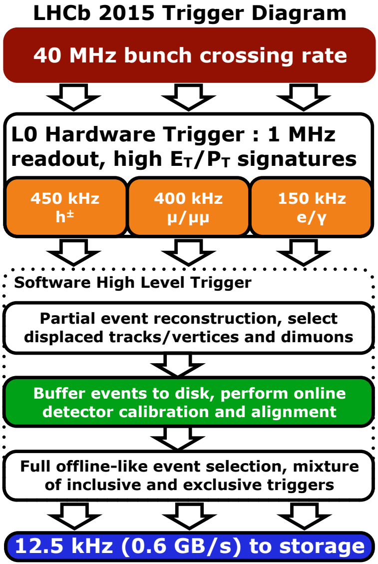
[ATLAS - Eur. Phys. J. C 76 (2016) 513]



- LHCb trigger designed for heavy flavours
- Muon (hadron) L0 trigger require $p_{\mathrm{T}} > [1-5] GeV$
- **Too hard for primary strange hadrons**

- Hlt1 and Hlt2 are software and customizable
- No dedicated triggers in 2011, added a $K_S^0 \to \mu^+\mu^-$ dedicated trigger in 2012
- Several generic (topological) triggers allowed good efficiencies

- Typical events contain more than one strange hadron
- ⇒ Strange physics Run I analyses mostly based on data triggered by the rest of the event

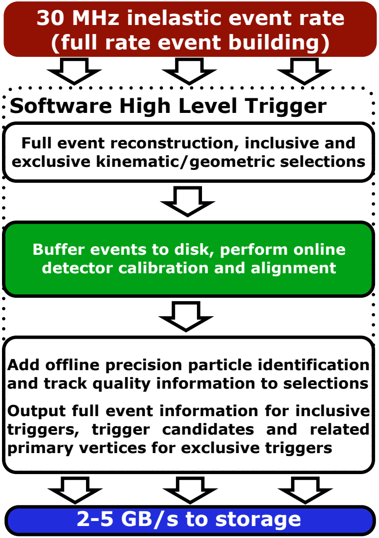


- Higher bandwidth from improved farm and algorithms allows higher yields
- Real time calibration between Hlt1 and Hlt2
- **L0 trigger still limiting factor for strange hadrons**
- *Turbo* stream allows high rate channels to be stored: [Aaij et al. JCPC208(2016)35] important for non rare strange physics

Software improvements for strange

- Complement forward tracking for very soft muons implemented
- New Hlt1 inclusive lines developed with focus on strange physics
- Various novel Hlt2 inclusive and exclusive lines written, dedicated to strange

LHCb Upgrade Trigger Diagram



- Upgraded detector for 40 MHz full readout
- $\mathcal{L} = 10^{33} cm^{-2} s^{-1} \Rightarrow$ about 5 fb^{-1} per year

- L0 hardware trigger is removed in Upgrade
- Hlt1 run directly on collision data

Fundamental step forward for strange physics!