Rare FCNC t, b and c decays

T. Blake on behalf of the LHCb collaboration
including results from ATLAS and CMS

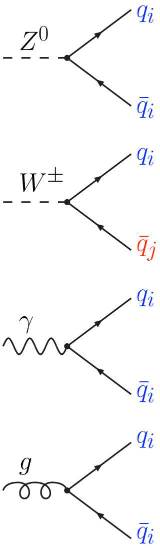
Outline

1. Why are FCNC t, b and c decays interesting?
2. The very rare decays $B^0_{(s,d)} \to \mu^+\mu^-$.
3. Photon polarisation in $b \to s\gamma$ decays.
4. Branching fractions and angular distributions of $b \to s\ell^+\ell^-$ decays.
5. Rare c and t decays.

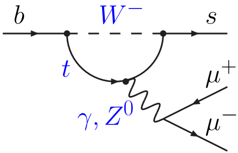
- For more details see the talks in the heavy flavour/top sessions by F. Scuri, F. Ligabue, M. de Cian, J. F. Kamenik and W. Altmannshofer.

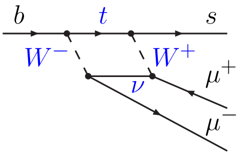
Standard Model couplings

- In the SM only the charged current interaction is flavour changing.
  - All other interactions are flavour conserving.
- Flavour changing $b \to s$ and $b \to d$ transitions only occur at loop order in the SM.
  - SM contribution is suppressed.



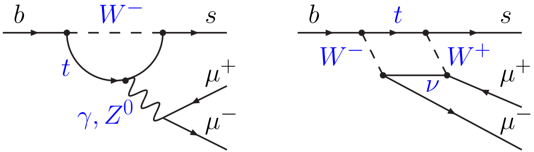
Standard Model



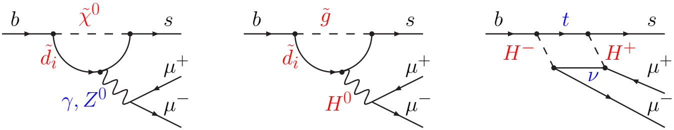


$b \to s\mu^+\mu^-$ example

Standard Model



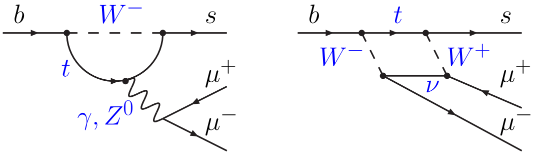
"New physics" (loop order)



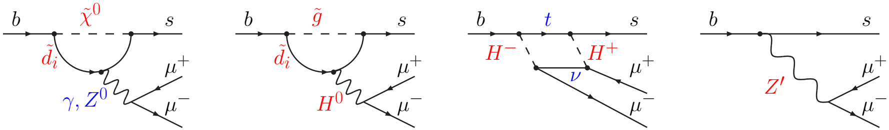
- Sensitivity to the different SM & NP contributions through decay rates, angular observables and CP asymmetries.

$b \to s\mu^+\mu^-$ example

Standard Model



"New physics" (loop order and at tree level)



- Sensitivity to the different SM & NP contributions through decay rates, angular observables and CP asymmetries.

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

$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

- B^0 and $B_s^0 \to \mu^+\mu^-$ are both GIM (loop) and helicity suppressed in the SM.
- Sensitive to contributions from (pseudo)scalar sector → interesting probe of NP models with extended Higgs sectors (e.g. MSSM, 2HDM, ...)

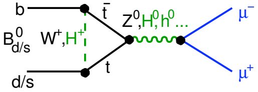
e.g. in MSSM, branching fraction scales approximately as $\tan^6\beta / M_A^4$

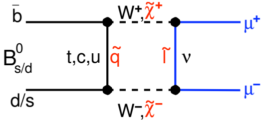
- Predicted precisely in the SM:

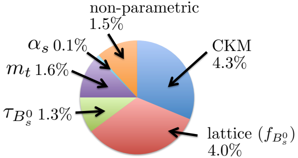
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

[Bobeth et al. PRL 112 101801 (2014)]

NB $\mathcal{B}(B^0 \to \mu^+\mu^-)$ suppressed by $|V_{td}/V_{ts}|^2$.

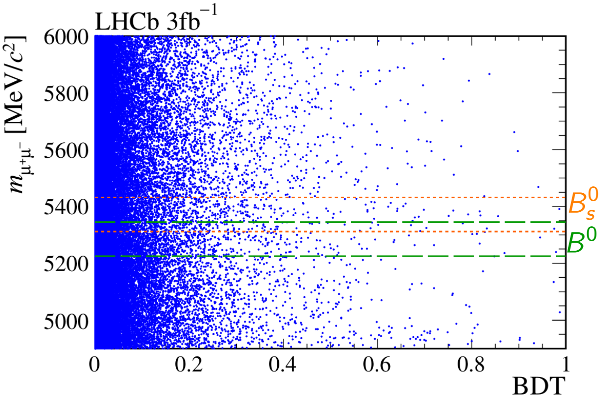






Bobeth et al. PRL 112 101801 (2014)

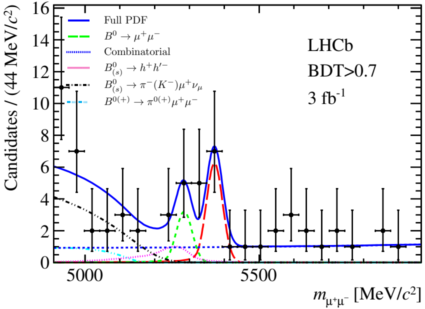
- Background rejection key for rare decay searches $\to$ use multivariate classifiers (BDTs) and tight particle identification requirements.

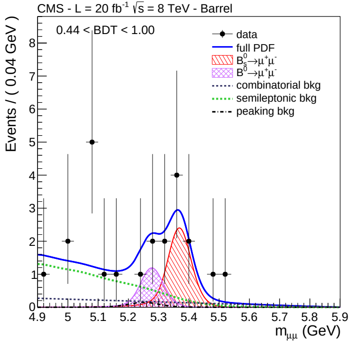


Calibrate the BDT response on MC (CMS) or $B \to hh$ data (LHCb).

Branching fraction normalised w.r.t. $B^+ \to J/\psi K^+$ (and $B^0 \to K^+\pi^-$ at LHCb).

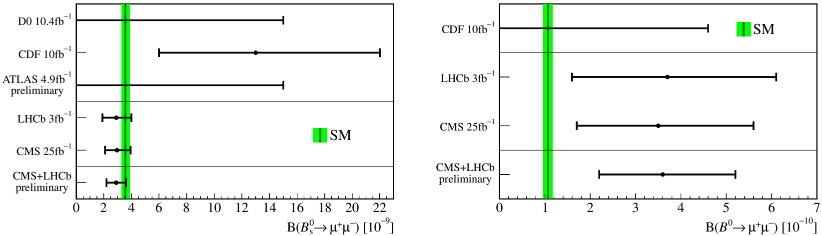
$B_s^0 \to \mu^+\mu^-$ at LHCb and CMS





- In $3\,\text{fb}^{-1}$ LHCb sees evidence for $B_s^0 \to \mu^+\mu^-$ at 4.0σ with $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}{}^{+0.3}_{-0.1}) \times 10^{-9}$. [PRL 111 (2013) 101805]
- In $20\,\text{fb}^{-1}$ CMS sees evidence for $B_s^0 \to \mu^+\mu^-$ at 4.3σ with $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$. [PRL 111 (2013) 101805]

Naïve $B_s^0 \to \mu^+\mu^-$ combination [CMS-PAS-BPH-13-007,LHCb-CONF-2013-012]



- Naïve combination of CMS and LHCb results gives:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.6\,{}^{+1.6}_{-1.4}) \times 10^{-10}$$

$\to B_s^0 \to \mu^+\mu^-$ is observed at more than 5σ

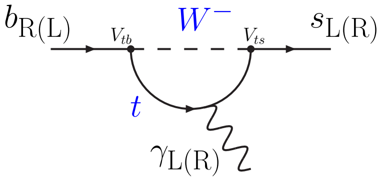
- Work is ongoing to do a proper combination of the two results.
- Unfortunately, measured BFs are consistent with SM expectations.

Photon polarisation in $b \to s\gamma$

Photon polarisation in $b \to s\gamma$ decays

- $B^0 \to K^{*0}\gamma$ was the first penguin decay ever observed, by CLEO in 1992 .[PRL 71 (1993) 674]
- We already know from the B-factories that inclusive & exclusive $b \to s\gamma$ branching fractions are compatible with SM expectations.
- What else do we know?

⇝ In the SM, photons from $b \to s\gamma$ decays are predominantly left-handed ($C_7/C_7' \sim m_b/m_s$) due to the charged-current interaction.



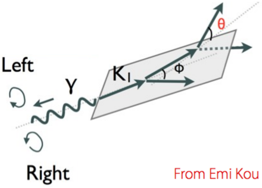
- Can test C_7/C_7' using:

⇝ Mixing-induced CP violation [Atwood et al PRL 79 (1997) 185-188],

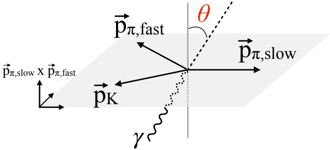
⇝ Λ_b^0 baryons [Hiller & Kagan PRD 65 (2002) 074038],

OR $B \to K^{**}\gamma$ decays such as $B^+ \to K_1(1270)\gamma$.
[Gronau & Pirjol PRD 66 (2002) 054008]

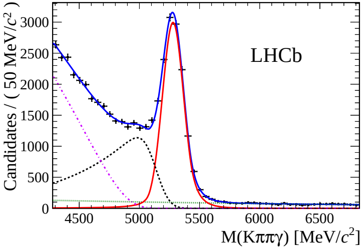
- Can infer the photon polarisation from the up-down asymmetry of the photon direction in the $K^+\pi^-\pi^+$ rest-frame. Unpolarised photons would have no asymmetry.
- This is conceptionally similar to the Wu experiment, which first observed parity violation.

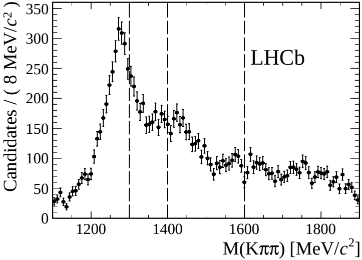


From Emi Kou

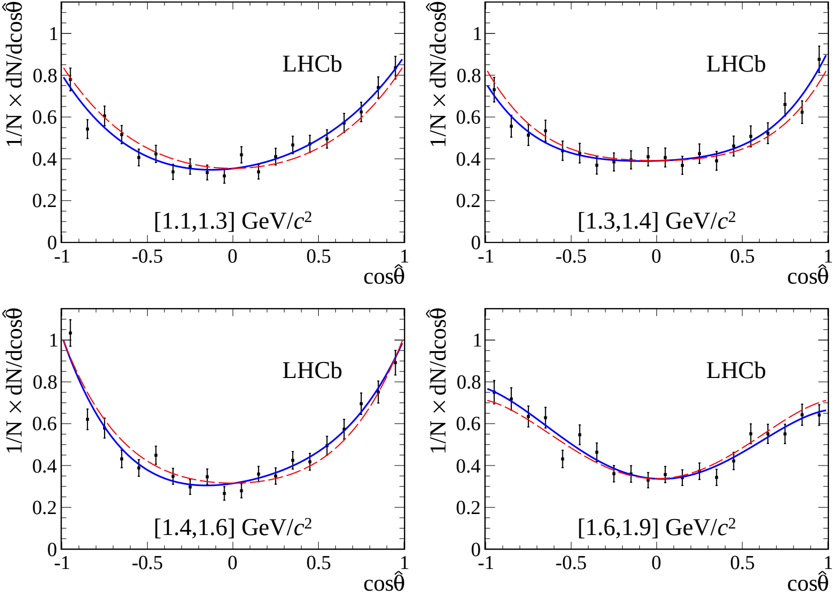


- At LHCb we look at $B^+ \to K^+\pi^-\pi^+\gamma$ decays using calorimeter photons.
- Observe $\sim 13,000$ signal candidates in $3\,\text{fb}^{-1}$.
- There are a large number of overlapping resonances in the $m(K^+\pi^-\pi^+)$ mass spectra. No attempt is made to separate these in the analysis, we simply bin in 4 bins of $m(K^+\pi^-\pi^+)$.

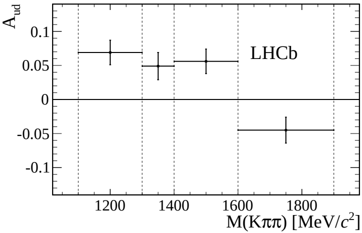




Best fit, Fit with $(C_7' - C_7)/(C_7' + C_7) = 0$



- Combining the 4 bins, the photon is observed to be polarised at 5.2σ.
- Unfortunately you need to understand the hadronic system to know if the polarisation is left-handed, as expected in the SM.

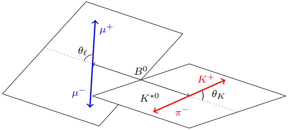


$\rightarrow$ First observation of photon polarisation in $b \rightarrow s\gamma$ decays

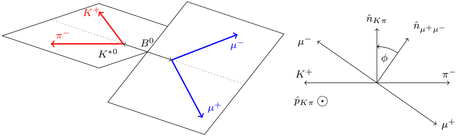
$b \to s\ell^+\ell^-$ decays

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

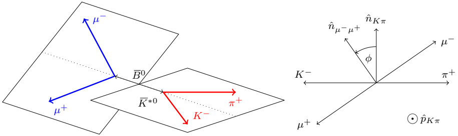
- Can also probe photon polaristion using virtual photons in $b \to s\ell^+\ell^-$ decays, e.g. through the angular distribution of the $B^0 \to K^{*0}\mu^+\mu^-$ decay.
- Also sensitive to new left- and right-handed vector currents.
- Decay described by three angles $(\theta_\ell, \theta_K, \phi)$ and the dimuon invariant mass squared, q^2.
- Analyses are performed in bins of q^2.



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay



(c) ϕ definition for the $\overline{B}^0$ decay

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

- Angular distribution depends on 11 angular terms:

$$\frac{\mathrm{d}^4\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[J_1^s \sin^2\theta_K + J_1^c \cos^2\theta_K + J_2^s \sin^2\theta_K \cos 2\theta_\ell + J_2^c \cos^2\theta_K \cos 2\theta_\ell + J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + J_6 \cos^2\theta_K \cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big]$$

where the J_i's are bilinear combinations of seven decay amplitudes $A_\parallel^{L,R}$, $A_\perp^{L,R}$, $A_0^{L,R}$ & A_t (L/R for the chirality of the $\mu^+\mu^-$ system).

- Large number of terms, simplified by angular folding, e.g. $\phi \to \phi + \pi$ if $\phi < 0$ to cancel terms in $\cos\phi$ and $\sin\phi$ (LHCb).

- Angular distribution depends on 11 angular terms:

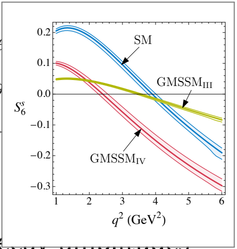
Altmannshofer et al. [JHEP 01 (2009) 019]

$$\frac{d^4\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2} = \frac{9}{32\pi}\Big[J_1^s \sin^2\theta_K + J_1^c \cos^2\theta_K + J_2^s \sin^2\theta_K \cos 2\theta \ldots$$

$$J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta \ldots$$

$$J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + J_6 \cos^2\theta_K \cos\theta_\ell \ldots$$

$$J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \ldots$$

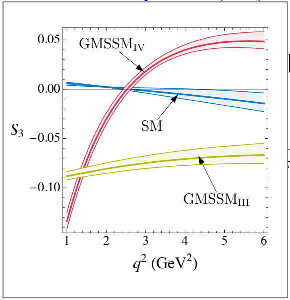


where the J_i's are bilinear combinations of seven decay amplitudes $A_\parallel^{L,R}$, $A_\perp^{L,R}$, $A_0^{L,R}$ & A_t (L/R for the chirality of the $\mu^+\mu^-$ system).

- Large number of terms, simplified by angular folding, e.g. $\phi \to \phi + \pi$ if $\phi < 0$ to cancel terms in $\cos\phi$ and $\sin\phi$ (LHCb).

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

Altmannshofer et al. [JHEP 01 (2009) 019]



- …pends on 11 angular terms:

$$\Big[J_1^s \sin^2\theta_K + J_1^c \cos^2\theta_K + J_2^s \sin^2\theta_K \cos 2\theta_\ell + J_2^c \cos^2\theta_K \cos 2\theta_\ell +$$
$$J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi +$$
$$J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + J_6 \cos^2\theta_K \cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi +$$
$$J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big]$$

where the J_i's are bilinear combinations of seven decay amplitudes $A_\parallel^{L,R}$, $A_\perp^{L,R}$, $A_0^{L,R}$ & A_t (L/R for the chirality of the $\mu^+\mu^-$ system).

- Large number of terms, simplified by angular folding, e.g. $\phi \to \phi + \pi$ if $\phi < 0$ to cancel terms in $\cos\phi$ and $\sin\phi$ (LHCb).

- Angular distribution depends on 11 angular terms:

$$\frac{\mathrm{d}^4\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[J_1^s \sin^2\theta_K + J_1^c \cos^2\theta_K + J_2^s \sin^2\theta_K \cos 2\theta_\ell + J_2^c \cos^2\theta_K \cos 2\theta_\ell + J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + \cancel{J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi} + \cancel{J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi} + J_6 \cos^2\theta_K \cos\theta_\ell + \cancel{J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi} + \cancel{J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi} + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big]$$

  where the J_i's are bilinear combinations of seven decay amplitudes $A_\parallel^{L,R}$, $A_\perp^{L,R}$, $A_0^{L,R}$ & A_t (L/R for the chirality of the $\mu^+\mu^-$ system).

- Large number of terms, simplified by angular folding, e.g. $\phi \to \phi + \pi$ if $\phi < 0$ to cancel terms in $\cos\phi$ and $\sin\phi$ (LHCb).

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

OR by integrating over two of the three angles (ATLAS and CMS):

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\phi} = \frac{1}{2\pi}\left(1 + S_3\cos 2\phi + A_9 \sin 2\phi\right) \ ,$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{\mathrm{d}\cos\theta_K} = \frac{3}{2}F_{\rm L}\cos^2\theta_K + \frac{3}{4}(1 - F_{\rm L})(1 - \cos^2\theta_K) \ ,$$

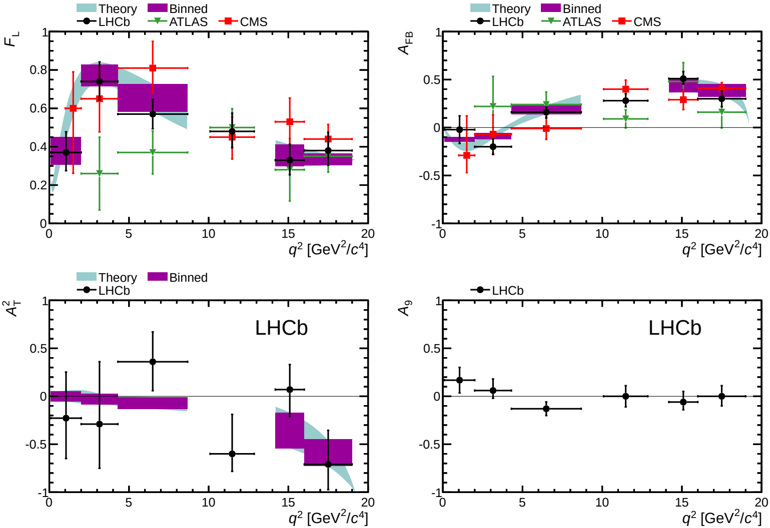
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4}F_{\rm L}(1 - \cos^2\theta_\ell) + \frac{3}{8}(1 - F_{\rm L})(1 + \cos^2\theta_\ell) + A_{\rm FB}\cos\theta_\ell \ .$$

- Leaves 4 observables:

$A_{\rm FB}$	Dimuon forward-backward asymmetry.
$F_{\rm L}$	Fraction of longitudinal K^{*0} polarisation.
$A_{\rm T}^2/S_3$	Asymmetry sensitive to the (virtual) photon polarisation.
A_9	A CP asymmetry.

$B^0 \to K^{*0}\mu^+\mu^-$ angular distribution (part 1)

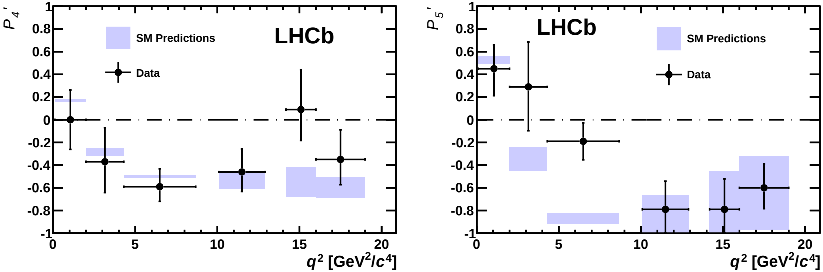
ATLAS (prelim.) [ATLAS-CONF-2013-038] , CMS 5.2 fb^{-1} [PLB 727 (2013) 77] , LHCb 1 fb^{-1} [JHEP 08 (2013) 131]



Theory prediction from Bobeth et al. [JHEP 07 (2011)] and references therein.

$B^0 \to K^{*0}\mu^+\mu^-$ angular distribution (part 2)

- Can also apply different angular foldings to access different angular terms [PRL 111 191801 (2013)].

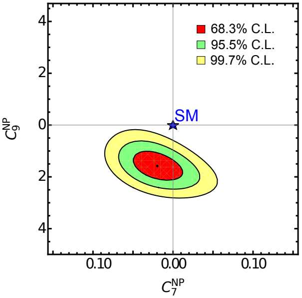


SM predictions from [Decotes-Genon et al. JHEP 05 (2013) 137]

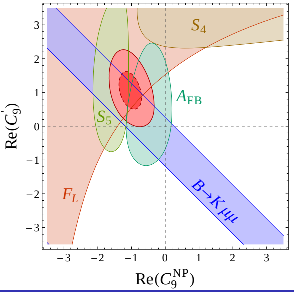
- Focus on observables where leading form-factor uncertainties cancel, e.g. $P'_{4,5} = S_{4,5}/\sqrt{F_{\rm L}(1-F_{\rm L})}$.
- In $1\,{\rm fb}^{-1}$, LHCb observes a local discrepancy of 3.7σ in P'_5 (probability that at least one bin varies by this much is 0.5%).

Understanding the P_5' anomaly?

- Decotes-Genon, Matias & Virto perform a global fit to the available $b \to s\gamma$ and $b \to s\ell^+\ell^-$ data $\to$ 4.5σ discrepancy from SM. Fit favours $C_9^{\rm NP} \approx -1.5$ (non-SM vector current). [PRD 88 074002 (2013)]



- Altmannshofer & Straub perform a global analysis and find discrepancies at the level of 3σ. Data best described by modified C_9 (and C_9'). Data can be explained by introducing a flavour-changing Z' boson at $\mathcal{O}(1\,\mathrm{TeV})$. [EPJC 73 2646 (2013)]



Understanding the P_5' anomaly?

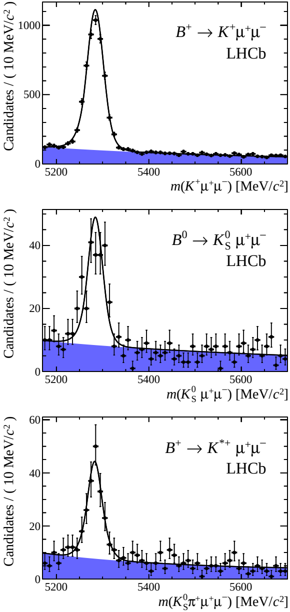
- Gaul, Goertz & Haisch also favour Z', but with mass $\mathcal{O}(7\,\mathrm{TeV})$. [JHEP 01 (2014) 069]
- Beaujean, Bobeth & van Dyk float form-factor uncertainties as nuisance parameters and find the discrepancy can be reduced to 2σ. [arXiv:1310.2478].
- Jaeger & Camalich also explore form-factor uncertainties and try to address their size in the large recoil region. [JHEP 05 (2013) 043]

In general:

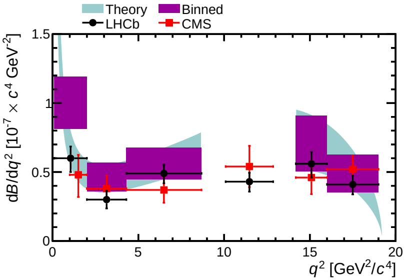
- ⇝ Difficult to explain data in SUSY scenarios or using partial compositeness (why only $C_9^{(\prime)}$?).
- ⇝ Data can be described using Z' with flavour violating couplings, but mass must be $\mathcal{O}(7\,\mathrm{TeV})$ to avoid direct limits and limits from mixing (Δm_s).
- ⇝ Could we just be underestimating the theory uncertainties?

Differential branching fraction of $B \to K^{(*)}\mu^+\mu^-$

- If $C_9^{\rm NP} = -1.5$, then expect to see a suppression of the rate of $B \to K^{(*)}\mu^+\mu^-$ decays.
- Can reconstruct the $K^{(*)}$ as either K^+, $K^0_{\rm S}$, K^{*+} ($\to K^0_{\rm S}\ \pi^+$) or K^{*0}. $K^0_{\rm S}$ and K^{*+} modes are experimentally challenging due to the long $K^0_{\rm S}$ lifetime.
- We see large signals for all four $K^{(*)}$ modes in the 3 fb^{-1} LHCb dataset [arXiv:1403.8044].
- Look at $d\mathcal{B}/dq^2$, using $B \to J/\psi\, K^{(*)}$ decays to normalise the branching fraction.

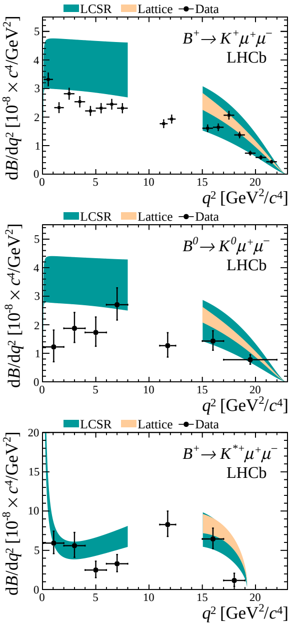


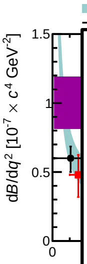
Differential branching fraction of $B \to K^{(*)}\mu^+\mu^-$



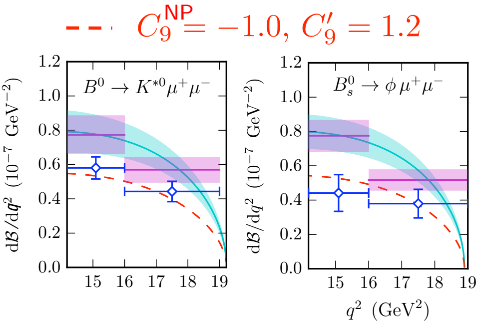
LHCb $1\,\text{fb}^{-1}$ ($B^0 \to K^{*0}\mu^+\mu^-$) [JHEP 08 (2013)]
LHCb $3\,\text{fb}^{-1}$ [arXiv:1403.8044]
CMS $5.2\,\text{fb}^{-1}$ [PLB 727 (2013) 77]

- SM predictions based on [JHEP 07 (2011) 067], [JHEP 01 (2012) 107].
- Lattice input from [PRL 111 (2013) 162002], [arXiv:1310.3887].

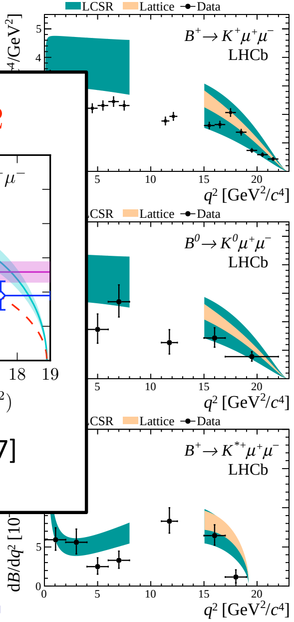




LHCb 1 fb^{-}
LH
CMS



Horgan et al [arXiv:1310.3887]



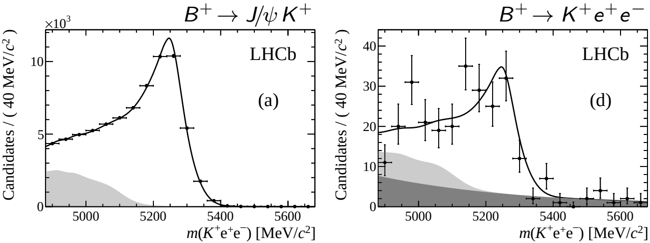
- SM predi
  [JHEP 07 (2011) 067], [JHEP 01 (2012) 107].
- Lattice input from
  [PRL 111 (2013) 162002], [arXiv:1310.3887].

- If a Z' is responsible for the anomoly in P_5', does it couple equally to all flavours of leptons?
- Dominant SM processes couple with equal strength to leptons:

$$R_{\mathrm{K}} = \frac{\int_{q^2=1\ \mathrm{GeV}^2/c^4}^{q^2=6\ \mathrm{GeV}^2/c^4} (\mathrm{d}\mathcal{B}[B^+ \to K^+\mu^+\mu^-]/\mathrm{d}q^2)\mathrm{d}q^2}{\int_{q^2=1\ \mathrm{GeV}^2/c^4}^{q^2=6\ \mathrm{GeV}^2/c^4} (\mathrm{d}\mathcal{B}[B^+ \to K^+e^+e^-]/\mathrm{d}q^2)\mathrm{d}q^2} = 1 \pm \mathcal{O}(10^{-3}) \ .$$

- Selection of the $B^+ \to K^+e^+e^-$ decay is experimentally challenging, due to bremstrahlung emission from the $e^\pm$.

$B^+ \to J/\psi(\to e^+e^-)K^+$ and $B^+ \to K^+e^+e^-$ candidates triggered by the $e^\pm$.

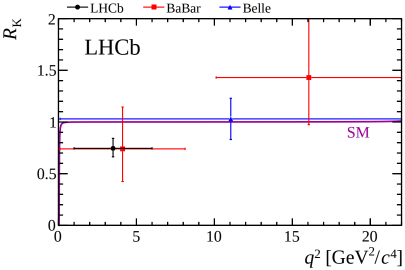


Lepton universality?

- Correct for bremstrahlung using calorimeter photons (with $E_{\mathrm{T}} > 75\,\mathrm{MeV}$).
- Migration of events into/out-of the $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$ window is corrected using MC.
- Take double ratio with $B^+ \to J/\psi\, K^+$ decays to cancel possible systematic biases.
- In $3\,\mathrm{fb}^{-1}$ LHCb determines

  $R_{\mathrm{K}} = 0.745^{+0.090}_{-0.074}(\mathrm{stat})^{+0.036}_{-0.036}(\mathrm{syst})$

  which is consistent with SM at 2.6σ.



LHCb-PAPER-2014-024 [Preliminary],

Belle [PRL 103 (2009) 171801] ,

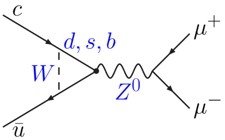
BaBar [PRD 86 (2012) 032012]

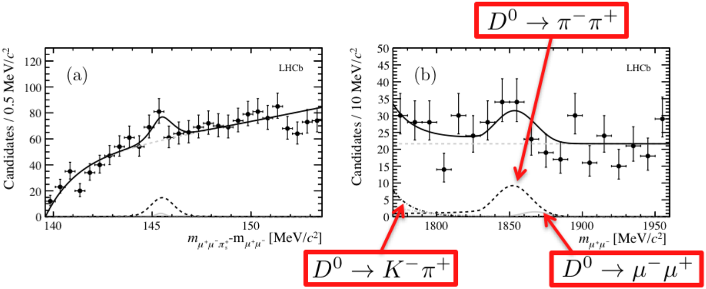
FCNC charm decays

✓ Effective GIM cancellation due to presence of $b-, s-, d$-quark in loop.

e.g. $\mathcal{B}(D^0 \to \mu^+\mu^-) \approx 10^{-18}$ in SM.

✗ Long distance contributions.



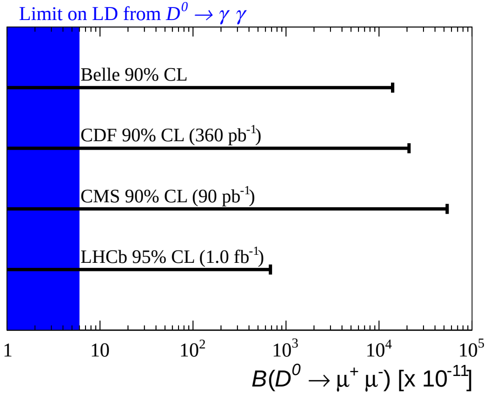


- Exploit small Δm in $D^{*\pm}$ decays to suppress backgrounds.
- Experimental precision limited by hadronic $\pi \to \mu$ mis-id.

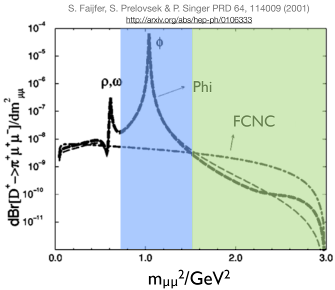
$D^0 \to \mu^+\mu^-$ at LHCb and CMS

- Using $1\,\text{fb}^{-1}$ LHCb sets a limit of:

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.8 \times 10^{-9} \text{ at } 95\% \text{ CL}$$

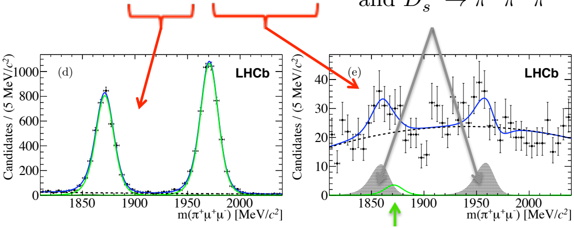


Belle
[PRD 81 (2010) 091102]
CDF
[PRD 82 (2010) 091105]
CMS
[CMS-PAS-BPH-11-017]
LHCb
[PLB 725 (2013) 15-24]



- Can also look at other $c \to u$ decays, e.g. $D^+_{(s)} \to \pi^+\mu^+\mu^-$.
- ✗ Background from light resonances.

Background from $D^+ \to \pi^+\pi^-\pi^+$ and $D^+_s \to \pi^+\pi^-\pi^+$



best fit $D^+ \to \pi^+\mu^+\mu^-$

Set limits in $1\,\mathrm{fb}^{-1}$ of

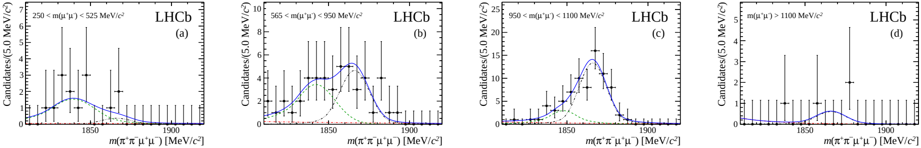
$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 8.3 \times 10^{-8}$

$\mathcal{B}(D^+_s \to \pi^+\mu^+\mu^-) < 4.1 \times 10^{-7}$

at 95% CL

Improving existing limits by 50x.

low $m(\mu^+\mu^-)$ ρ/ω ϕ high $m(\mu^+\mu^-)$



Signal, $D^0 \to \pi^+\pi^-\pi^+\pi^-$ background

- Using $1\,\text{fb}^{-1}$ of integrated luminosity, LHCb sets a limit of:

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) < 5.5 \times 10^{-7} \text{ at } 90\%$$

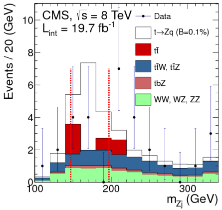
c.f. SM predictions of $\mathcal{O}(10^{-9})$, improving on previous limits by 50x.

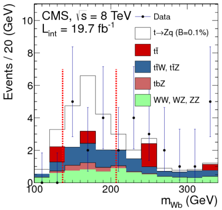
FCNC top decays

- Effective GIM cancellation leads to $\mathcal{B}(t \to Z^0 q) < 10^{-14}$ in the SM, see e.g. [ActaPhys. Polon. B35 (2004) 2671-2694]

- CMS perform a search for $t \to Z^0 j$ with $Z^0 \to \ell^+\ell^-$, where j is a jet, reconstructing the other top through $t \to Wb$.
  [PRL 112 171802 (2014)]
  CMS sets a limit of
  $\mathcal{B}(t \to Z^0 q) < 5 \times 10^{-4}$ at 95% CL

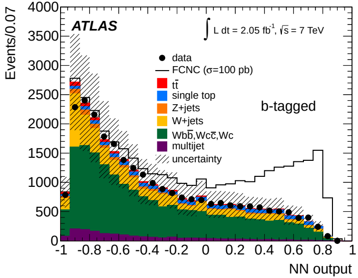
- Earlier ATLAS results using 2011 dataset in [JHEP 09 (2012) 139]



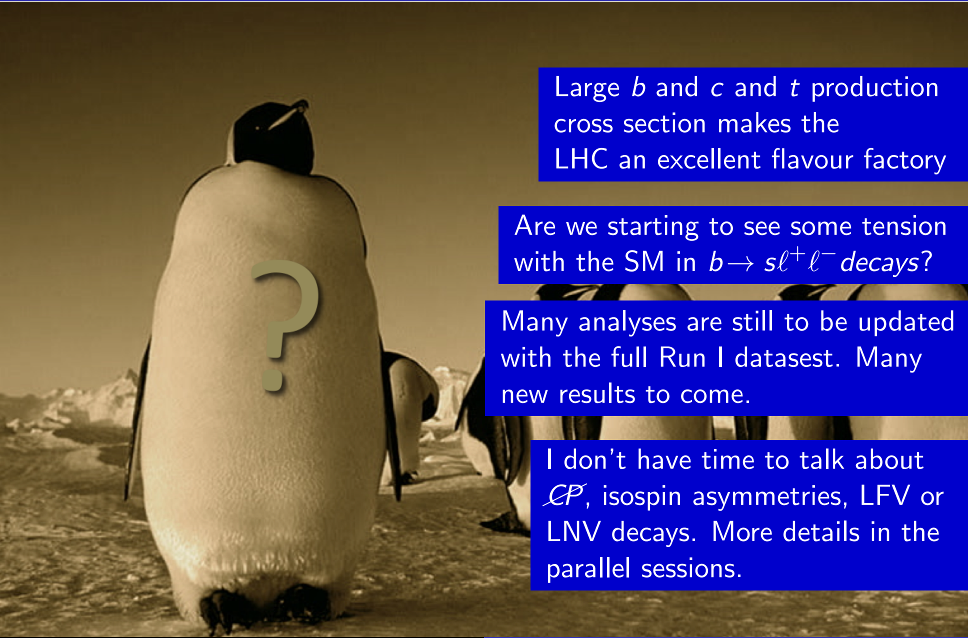


- Can also set limits on FCNC top coupling by looking at top production, e.g. anomalous single top production through $qg \to t$.
- Search carried out by the ATLAS collaboration, with $t \to Wb$, sets limits of:

$$\mathcal{B}(t \to ug) < 5.7 \times 10^{-5} \text{ at 95\% CL}$$
$$\mathcal{B}(t \to cg) < 2.7 \times 10^{-4} \text{ at 95\% CL}$$



Summary



Large b and c and t production cross section makes the LHC an excellent flavour factory

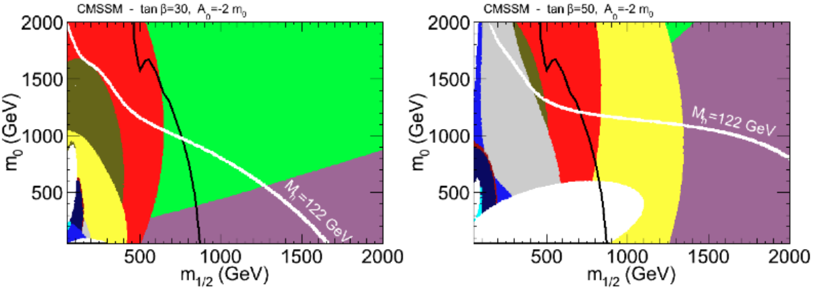
Are we starting to see some tension with the SM in $b \to s\ell^+\ell^-$ *decays*?

Many analyses are still to be updated with the full Run I datasest. Many new results to come.

I don't have time to talk about $\not{C}\!\!\not{P}$, isospin asymmetries, LFV or LNV decays. More details in the parallel sessions.

Constraints

- Flavour constraints depend heavily on model assumptions. Will just pick one example of a concrete model, the CMSSM, from [Mahmoudi arXiv:1310.2556].

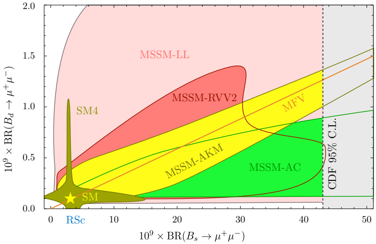


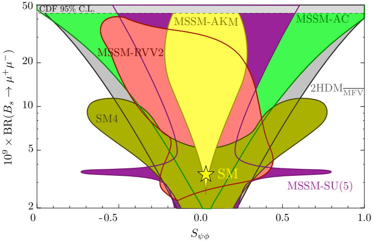
allowed, $\mathcal{B}(b \to s\gamma)$, $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$, $A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$, – direct searches

- Flavour constraints exclude the the whole $m_0 : m_{\frac{1}{2}}$ plane at large $\tan\beta$ and are comparable to direct searches at $\tan\beta \approx 30$.

Summer 2010:

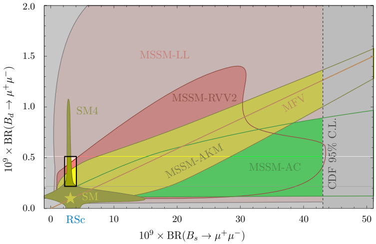
Straub arXiv:1107.0266

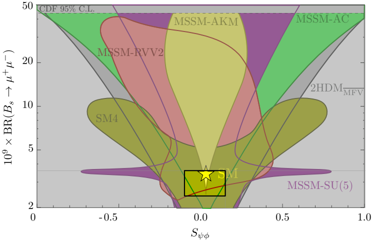




Today:

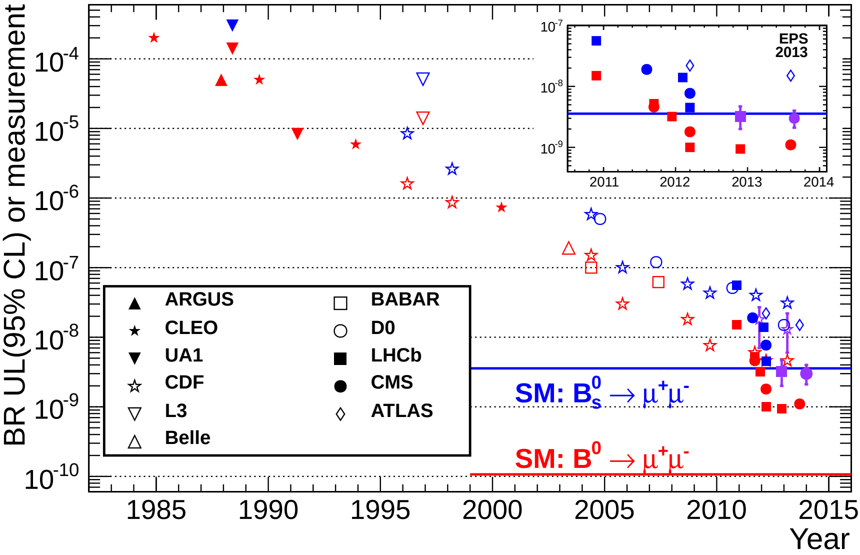
Straub arXiv:1107.0266



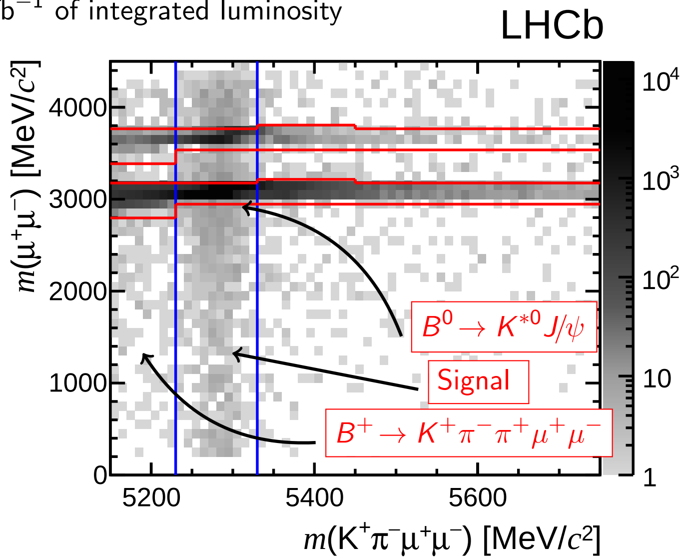


Can exploit correlations with other flavour observables, e.g. B_s^0 mixing phase ϕ_s.

$B_s^0 \to \mu^+\mu^-$ progress with time

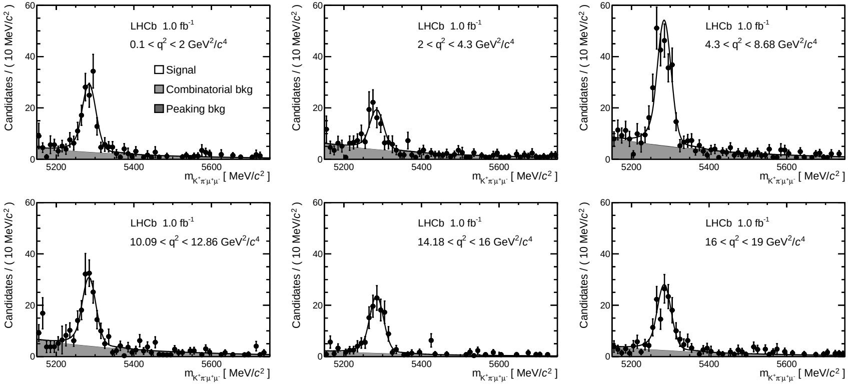


Using 1 fb^{-1} of integrated luminosity



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

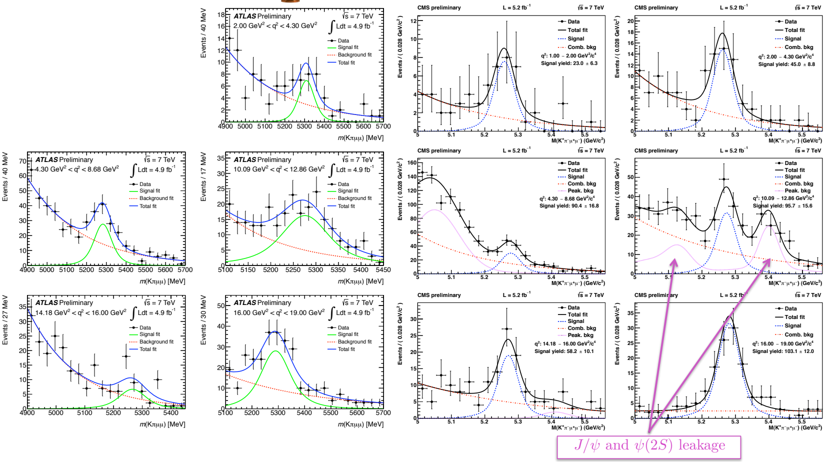
[JHEP 08 (2013) 131]



- Perform measurements in six bins of $q^2 = m^2_{\mu^+\mu^-}$.
- The binning scheme was originally optimised for the Belle experiment (not particularly optimal for the LHC experiments).

$B^0 \to K^{*0}\mu^+\mu^-$ at ATLAS and CMS

ATLAS CMS

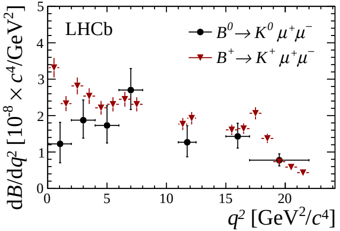


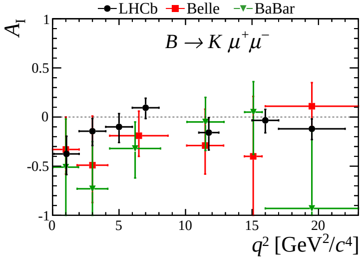
- Large data sets are also available at ATLAS [ATLAS-CONF-2013-038] and CMS [PLB 727 (2013) 77].

- In the SM expect the partial widths of $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^0\mu^+\mu^-$ to be almost identical

$$A_{\rm I} = \frac{\Gamma[B^+ \to K^+\mu^+\mu^-] - \Gamma[B^0 \to K^0\mu^+\mu^-]}{\Gamma[B^+ \to K^+\mu^+\mu^-] + \Gamma[B^0 \to K^0\mu^+\mu^-]} \approx 0$$

- In our $1\,{\rm fb}^{-1}$ dataset, LHCb found $A_{\rm I} < 0$ at 4.4σ.
- Updating the measurement to the full $3\,{\rm fb}^{-1}$ dataset. Still favour negative $A_{\rm I}$, but $A_{\rm I}$ is compatible with $A_{\rm I} = 0$ at 1.5σ.





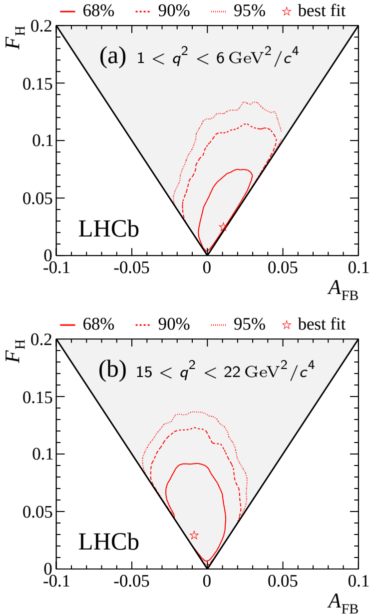
Belle [PRL 103 (2009) 171801]

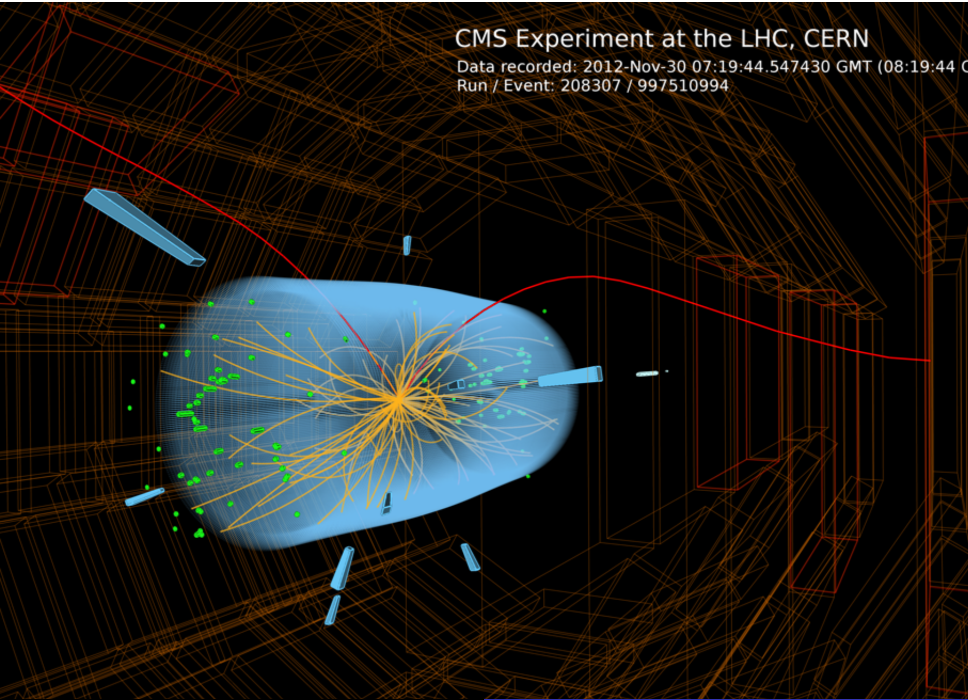
BaBar [PRD 86 (2012) 032012]

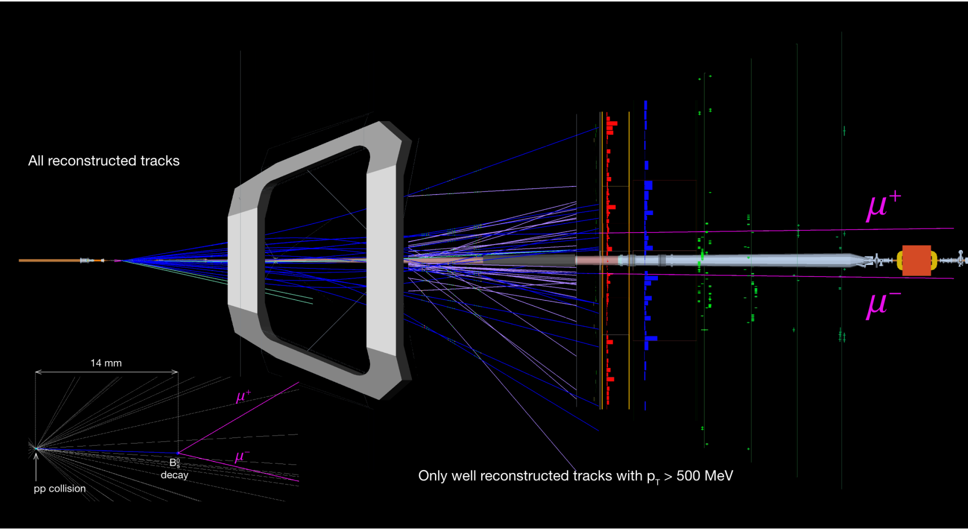
- Single angle and two paremeters describe the decay:

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_l} = \frac{3}{4}(1 - F_{\rm H}) + \frac{1}{2}F_{\rm H} + A_{\rm FB}\cos\theta_l$$

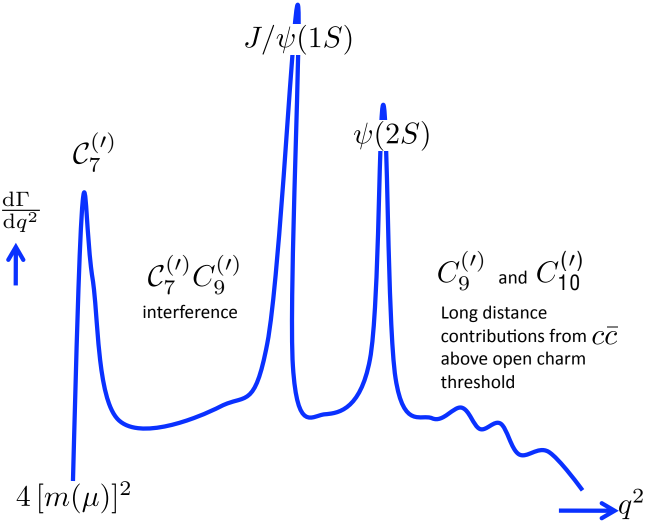
- $F_{\rm H}$ corresponds to the fractional contribution of (pesudo)scalar and tensor operators to Γ.
- Angular distribution is only +ve for $A_{\rm FB} \leq F_{\rm H}/2$ and $F_{\rm H} \geq 0$.
- Unfortunately the angular distribution is insensitive to $C_9^{\rm NP}$.
- It is also consistent with the SM expectation of $A_{\rm FB} \approx 0$ and $F_{\rm H} \approx 0$.




CMS Experiment at the LHC, CERN
Data recorded: 2012-Nov-30 07:19:44.547430 GMT (08:19:44
Run / Event: 208307 / 997510994


All reconstructed tracks
μ^+
μ^-
14 mm
μ^+
μ^-
B_s^0
decay
pp collision
Only well reconstructed tracks with p_T > 500 MeV

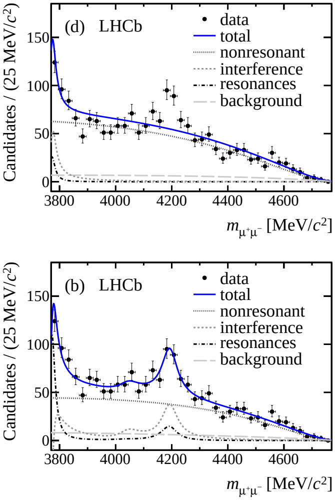
Anatomy of the $B^0 \to K^{*0}\mu^+\mu^-$ decay



No photon (C_7) enhancement of $B \to K\mu^+\mu^-$ decays at low q^2.

- $B^+ \to K^+\mu^+\mu^-$ data shows clear resonant structure.

$\to$ First observation of $B^+ \to \psi(4160)K^+$ and $\psi(4160) \to \mu^+\mu^-$. [PRL 111 (2013) 112003]



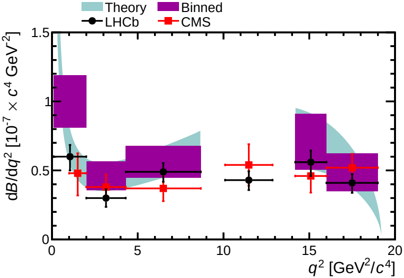
- Beylich, Buchalla & Feldman Theory calculations take $c\bar{c}$ contributions into account (through an OPE) but not their resonant structure. [EPJC 71 (2011) 1635]

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

- Normalise the observed event yields w.r.t. $B^0 \to K^{*0} J/\psi$ to determine $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$.

$\to$ Sensitivity of $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$ to NP contributions limited by hadronic uncertainties.

- With larger datasets also need to consider S-wave interference under the K^{*0} from $B^0 \to K^+\pi^-\mu^+\mu^-$ (and $B^0 \to K^+\pi^- J/\psi$).



LHCb 1 fb^{-1} [JHEP 08 (2013)]
CMS 5.2 fb^{-1} [PLB 727 (2013) 77]

Angular observables $J_i(q^2)$ for $B^0 \to K^{*0}\mu^+\mu^-$

For completeness

$$J_1^s = \frac{3}{4}\left\{\frac{(2+\beta_\mu^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)\right] + \frac{4m_\mu^2}{q^2}\Re(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*})\right\}$$

$$J_1^c = \frac{3}{4}\left\{|A_0^L|^2 + |A_0^R|^2 + \frac{4m_\mu^2}{q^2}\left[|A_t|^2 + 2\Re(A_0^L A_0^{R*})\right]\right\}$$

$$J_2^s = \frac{3\beta_\mu^2}{16}\left\{|A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)\right\}$$

$$J_2^c = -\frac{3\beta_\mu^2}{4}\left\{|A_0^L|^2 + (L \to R)\right\}$$

$$J_3 = \frac{3\beta_\mu^2}{8}\left\{|A_\perp^L|^2 - |A_\parallel^L|^2 + (L \to R)\right\}$$

$$J_4 = \frac{3\beta_\mu^2}{4\sqrt{2}}\left\{\Re(A_0^L A_\parallel^{L*}) + (L \to R)\right\}$$

$$J_5 = \frac{3\sqrt{2}\beta_\mu}{4}\left\{\Re(A_0^L A_\perp^{L*}) - (L \to R)\right\}$$

$$J_6 = \frac{3\beta_\mu}{2}\left\{\Re(A_\parallel^L A_\perp^{L*}) - (L \to R)\right\}$$

$$J_7 = \frac{3\sqrt{2}\beta_\mu}{4}\left\{\Im(A_0^L A_\parallel^{L*}) - (L \to R)\right\}$$

$$J_8 = \frac{3\beta_\mu^2}{4\sqrt{2}}\left\{\Im(A_0^L A_\perp^{L*}) + (L \to R)\right\}$$

$$J_9 = \frac{3\beta_\mu^2}{4}\left\{\Im(A_\parallel^{L*} A_\perp^L) + (L \to R)\right\}$$

J_i depend on 7 complex amplitudes: $A_\parallel^{L,R}$, $A_\perp^{L,R}$ and $A_0^{L,R}$, A_t

At "leading order"

$$A_\perp^{L(R)} = N\sqrt{2\lambda}\left\{\left[(\mathbf{C_9^{eff}} + \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} + \mathbf{C_{10}^{\prime eff}})\right]\frac{\mathbf{V(q^2)}}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} + \mathbf{C_7^{\prime eff}})\mathbf{T_1(q^2)}\right\}$$

$$A_\parallel^{L(R)} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}})\right]\frac{\mathbf{A_1(q^2)}}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} - \mathbf{C_7^{\prime eff}})\mathbf{T_2(q^2)}\right\}$$

$$A_0^{L(R)} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}})\right]\left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})\mathbf{A_1(q^2)} - \lambda\frac{\mathbf{A_2(q^2)}}{m_B + m_{K^*}}\right]\right.$$

$$\left. + 2m_b(\mathbf{C_7^{eff}} - \mathbf{C_7^{\prime eff}})\left[(m_B^2 + 3m_{K^*} - q^2)\mathbf{T_2(q^2)} - \frac{\lambda}{m_B^2 - m_{K^*}^2}\mathbf{T_3(q^2)}\right]\right\}$$

$$A_t = \frac{N}{\sqrt{q^2}}\sqrt{\lambda}\left\{2(\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}}) + \frac{q^2}{m_\mu}(\mathbf{C_P^{eff}} - \mathbf{C_P^{\prime eff}})\right\}\mathbf{A_0(q^2)}$$

$$A_S = -2N\sqrt{\lambda}(\mathbf{C_S} - \mathbf{C_S})\mathbf{A_0(q^2)}$$

- C_i are Wilson coefficients that we want to measure (they depend on the heavy degrees of freedom).
- A_0, A_1, A_2, T_1, T_2 and V are form-factors (these are effectively nuisance parameters).

Comments on angular distribution

- The L & R indices refer to the chirality of the leptonic system.
  - Different due to the axial vector contribution to the amplitudes.
- If $C_{10} = 0$, $A^{L}_{0,\|,\perp} = A^{R}_{0,\|,\perp}$ and the angular distribution reduces to the one for $B^0 \to K^{*0} J/\psi$.
- Zero-crossing point of A_{FB} comes from interplay between the different vector-like contributions.
- In the SM there are 7 different amplitudes that contribute, corresponding to different polarisations states:

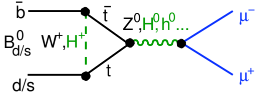
$$K^* \text{ on-shell} \to 3 \text{ polarisation states } \epsilon_{K^*}(m = +, -, 0)$$
$$V^* \text{ off-shell} \to 4 \text{ polarisation states } \epsilon_{K^*}(m = +, -, 0, t)$$

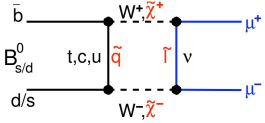
- A_t corresponds to a longitudinally polarised K^* and time-like $\mu^+\mu^-$. It's suppressed, so can be neglected.

- B^0 and $B_s^0 \to \mu^+\mu^-$ are both GIM (loop) and helicity suppressed in the SM.
- Sensitive to contributions from (pseudo)scalar sector → interesting probe of NP models with extended Higgs sectors (e.g. MSSM, 2HDM, . . .)

e.g. in MSSM, branching fraction scales approximately as $\tan^6\beta/M_A^4$

- More generally:





$$\mathcal{B}(B_q^0 \to \mu^+\mu^-) \approx \frac{G_F \alpha^2 M_{B_q^0}^3 f_{B_q^0}^2 \tau_{B_q^0}}{64\pi^3 \sin^4\theta_W} |V_{tb}V_{tq}^*|^2 \left(1 - \frac{4m_\mu^2}{M_{B_q^0}^2}\right)^{1/2} M_{B_q^0} \times$$
$$\left[\left(1 - \frac{4m_\mu^2}{M_B^2}\right) |\mathcal{C}_S - \mathcal{C}_S'|^2 + |(\mathcal{C}_P - \mathcal{C}_P') + \frac{2m_\mu}{M_B}(\mathcal{C}_{10} - \mathcal{C}_{10}')|^2\right]$$

LHCb-PAPER-2014-024 [Preliminary]