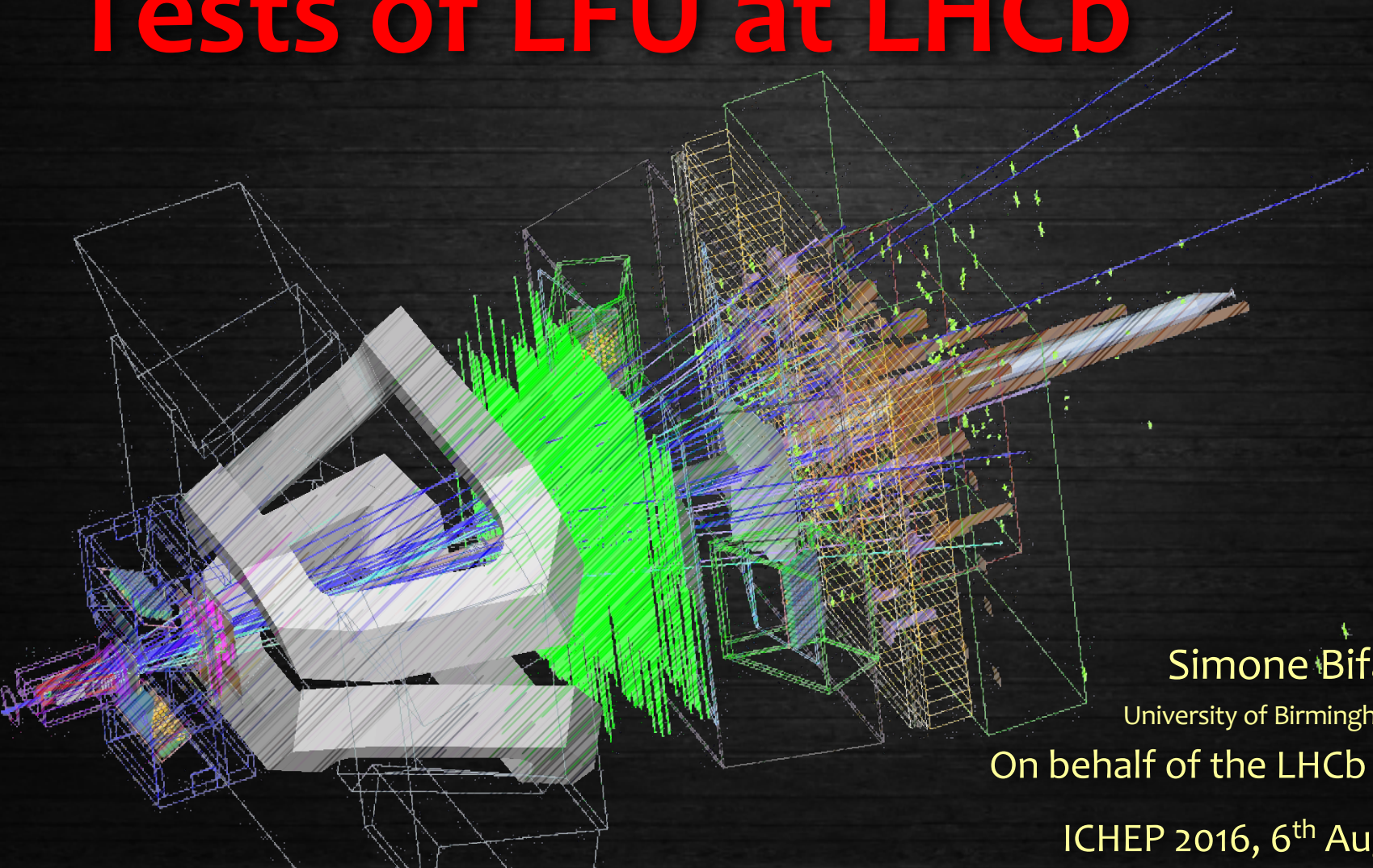
Rare b Decays and Tests of LFU at LHCb



Simone Bifani

University of Birmingham (UK)

On behalf of the LHCb Collaboration

ICHEP 2016, 6th August 2016

A Forward Spectrometer

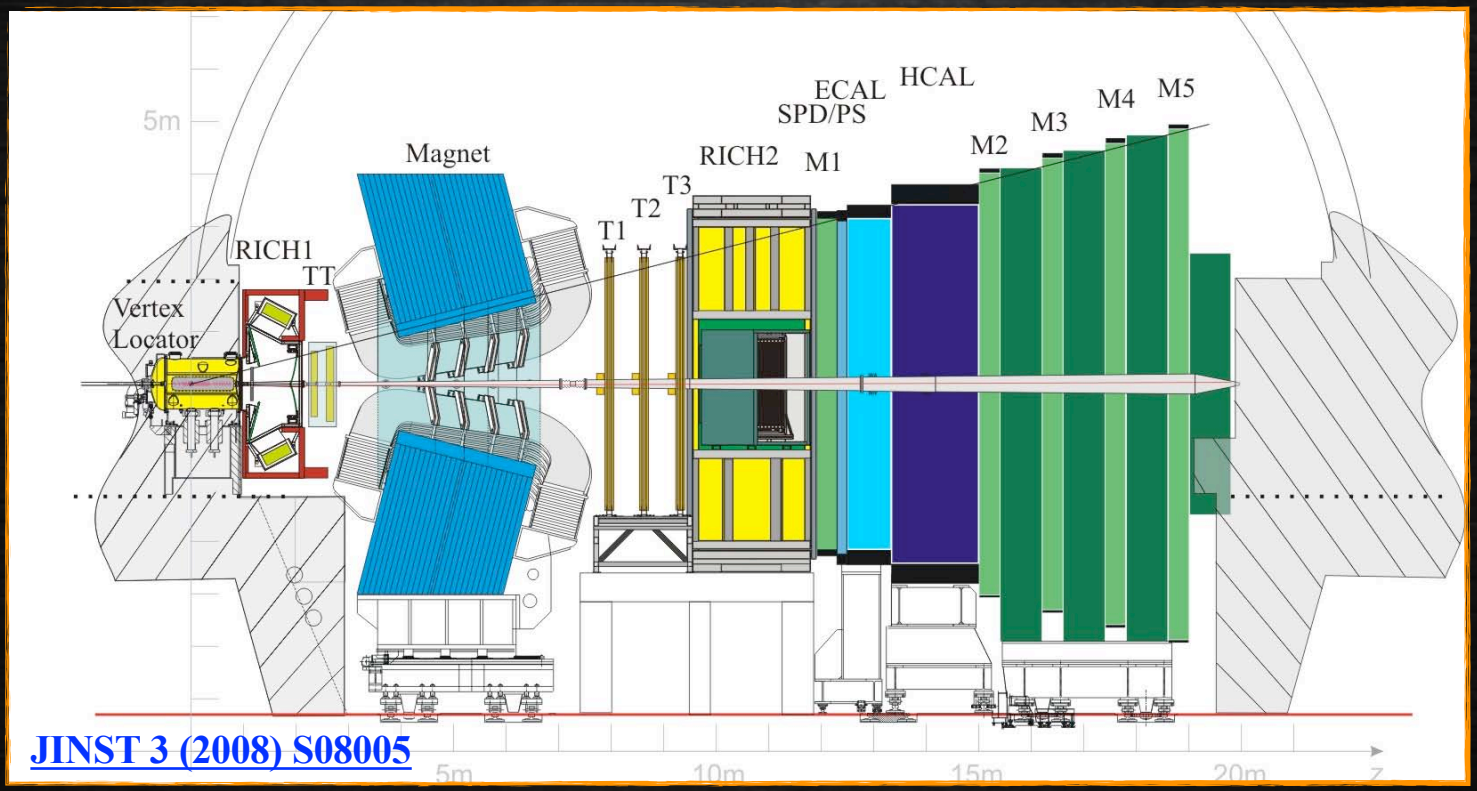
› Optimized for beauty and charm physics at large pseudorapidity ($2<\eta<5$)

» **Trigger**: ~90% efficient for di-muon channels, ~30% for all-hadronic

» Tracking: σ_p/p 0.4%–0.6% (p from 5 to 100 GeV), $\sigma_{IP} < 20\ \mu m$

» Vertexing: σ_τ ~45 fs

» **PID**: 97% μ ID for 1–3% $\pi \rightarrow \mu$ misID



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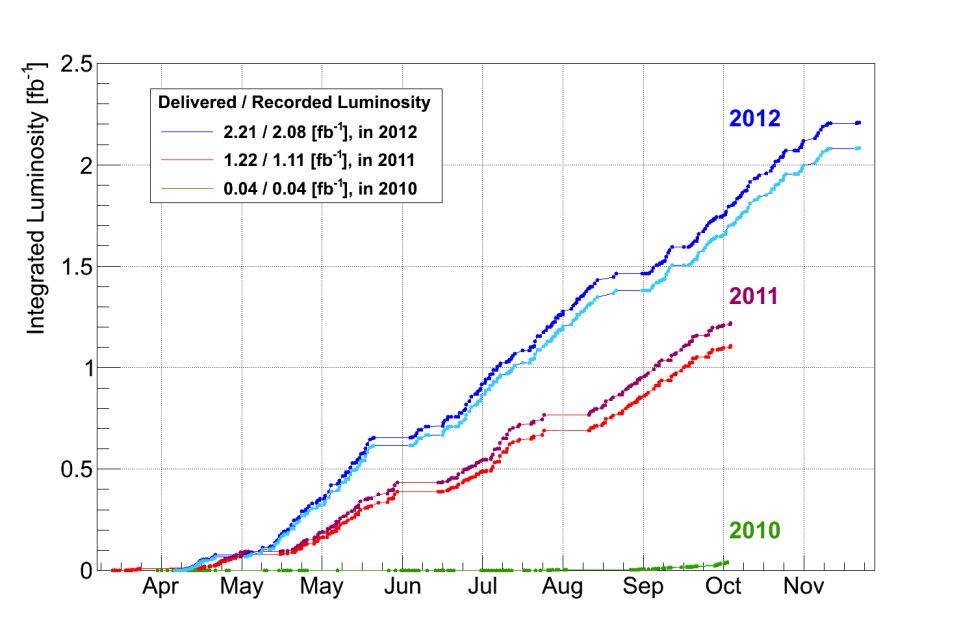
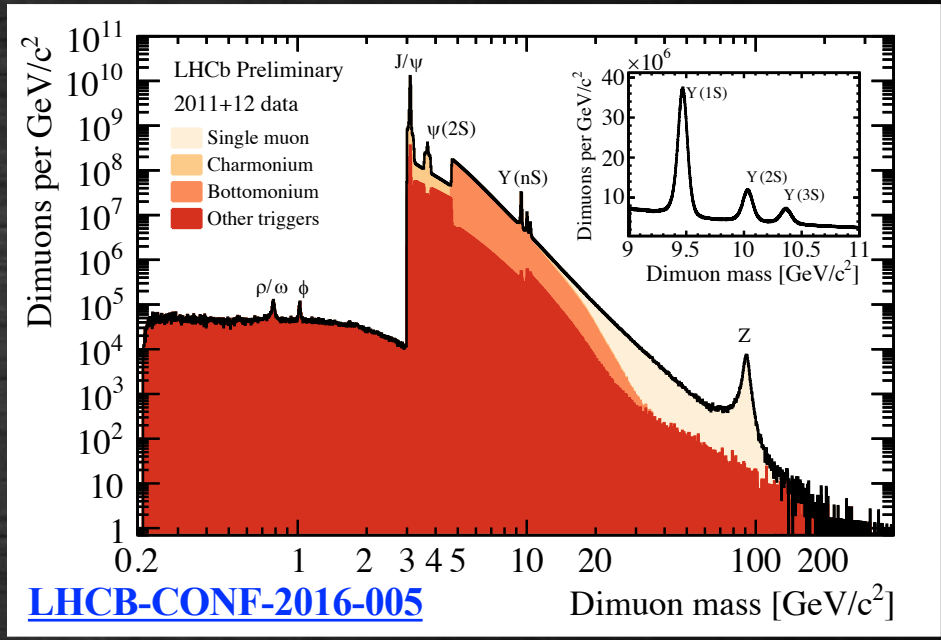
Datasets

› Analyses presented today based on the **Run 1** dataset

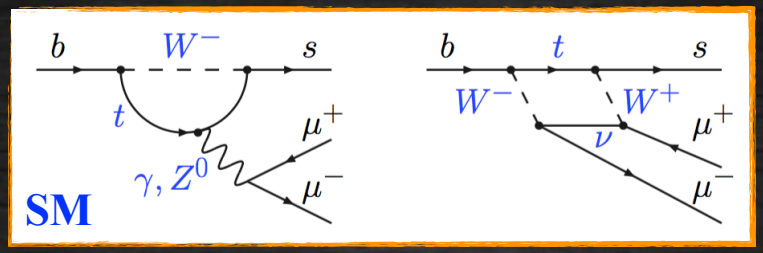




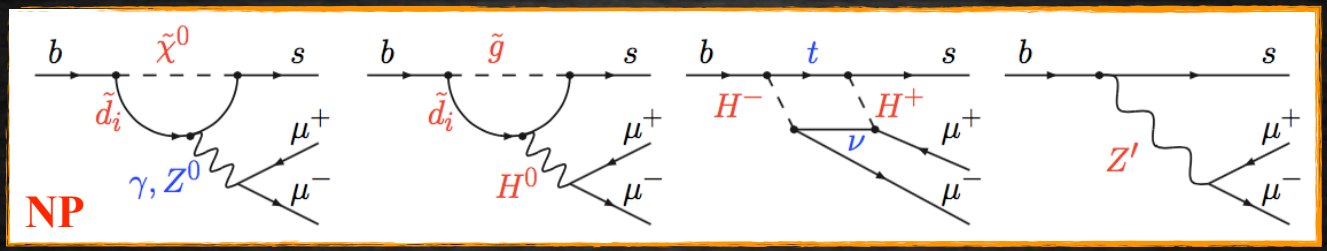
› Due to luminosity levelling, same running conditions throughout fills

Why Rare b Decays?

› b⟶sll decays proceed via **FCNC transitions** that only occur at loop order (and beyond) in SM



› New particles can contribute to loop or tree level enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of the final-state particles



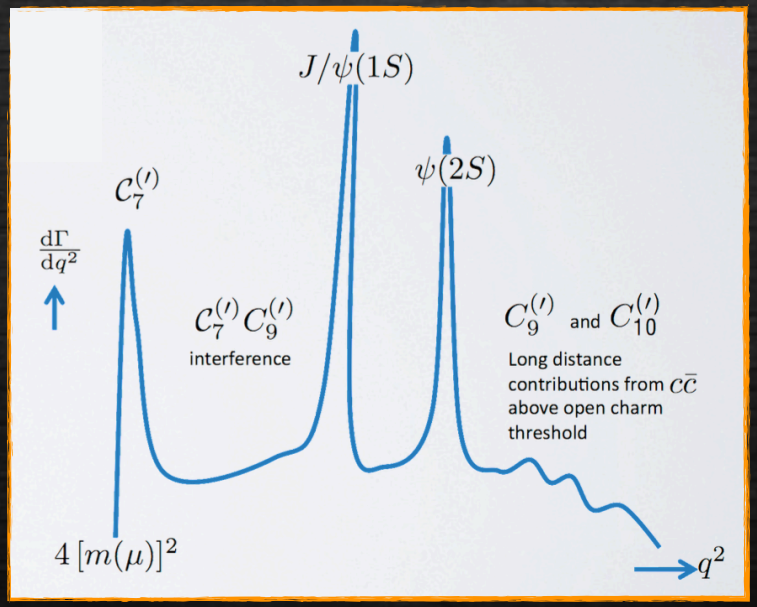
› Goal

» **Make precise measurements of rare FCNC decays as precision tests of the SM**

» **Make null tests of the SM, e.g. look for LFV or LNV decays that are essentially forbidden in the SM**

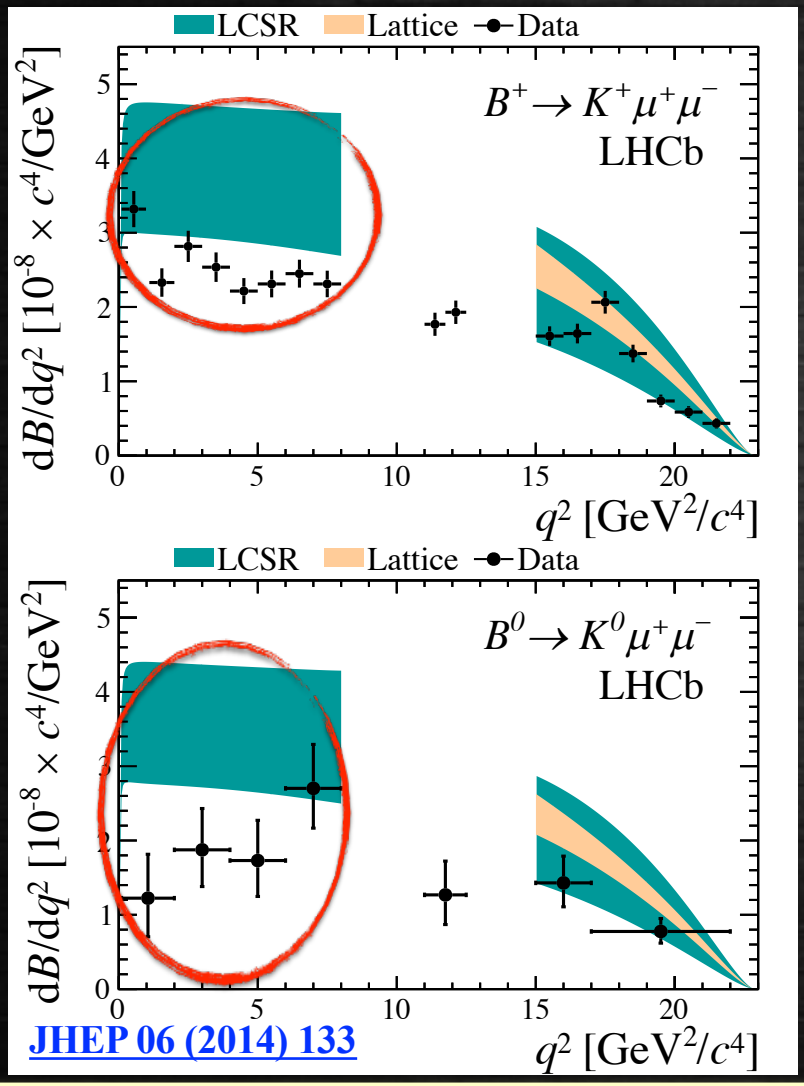
Shopping List

- **Differential branching fractions** of $B^0 \to K^{(*)0}\mu\mu$, $B^+ \to K^{(*)+}\mu\mu$, $B_s \to \phi\mu\mu$, $B^+ \to \pi^+\mu\mu$ and $\Lambda_b \to \Lambda\mu\mu$ decays
  - Large hadronic uncertainties in theory predictions
- **Angular analyses** of $B \to K^{(*)}\mu\mu$, $B_s \to \phi\mu\mu$, $B^0 \to K^{*0}ee$ and $\Lambda_b \to \Lambda\mu\mu$
  - Define observables with small theory uncertainties
- **Test of Lepton Flavour Universality** in $B^+ \to K^+ll$
  - Cancellation of hadronic uncertainties in theory predictions



Differential Branching Fractions

› Results **consistently lower than SM predictions** despite large theory uncertainties from form-factors



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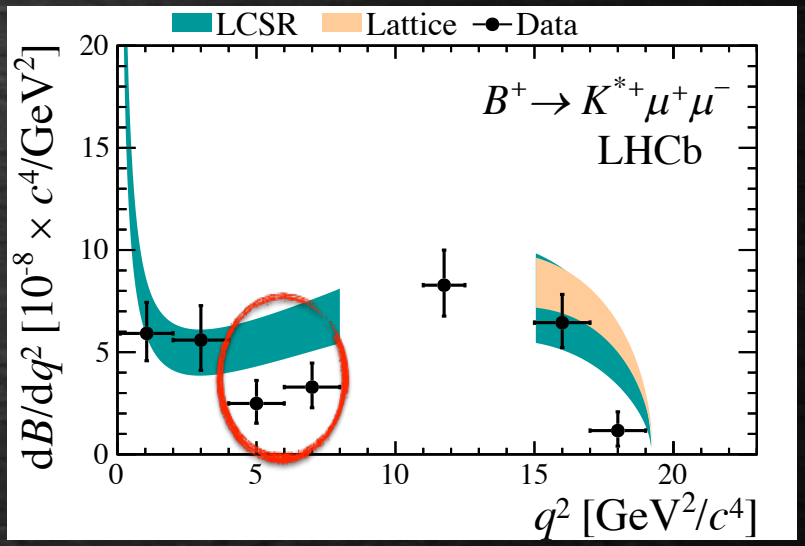

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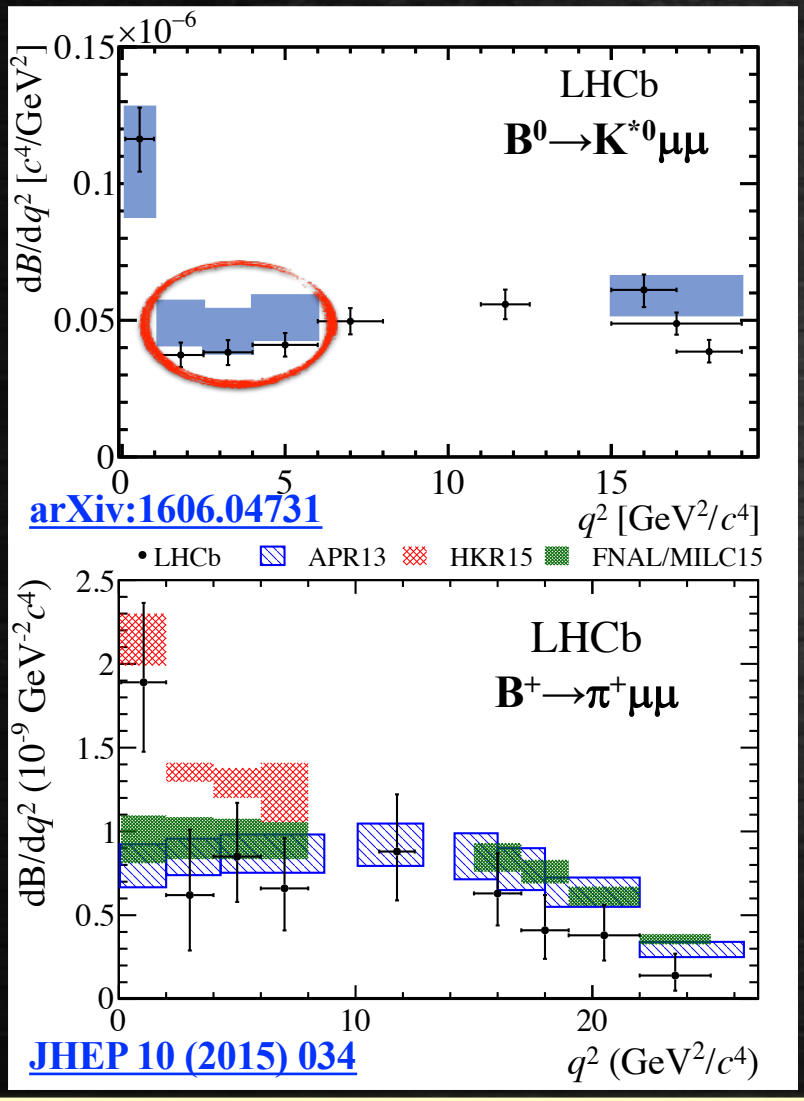
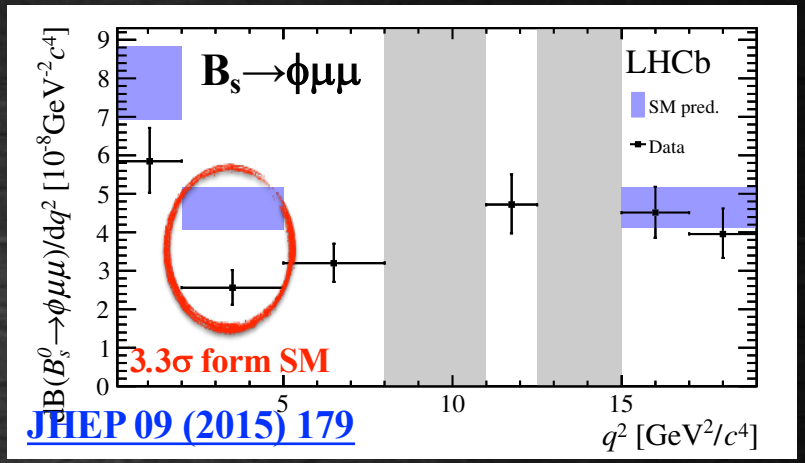
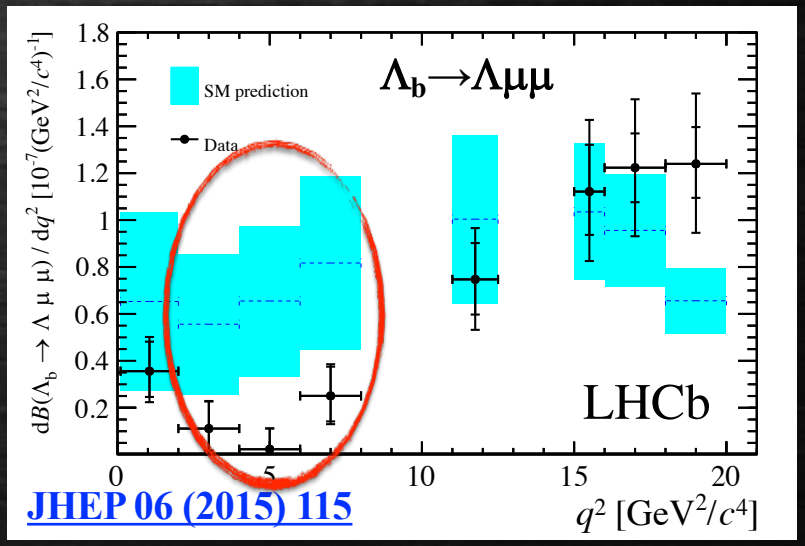
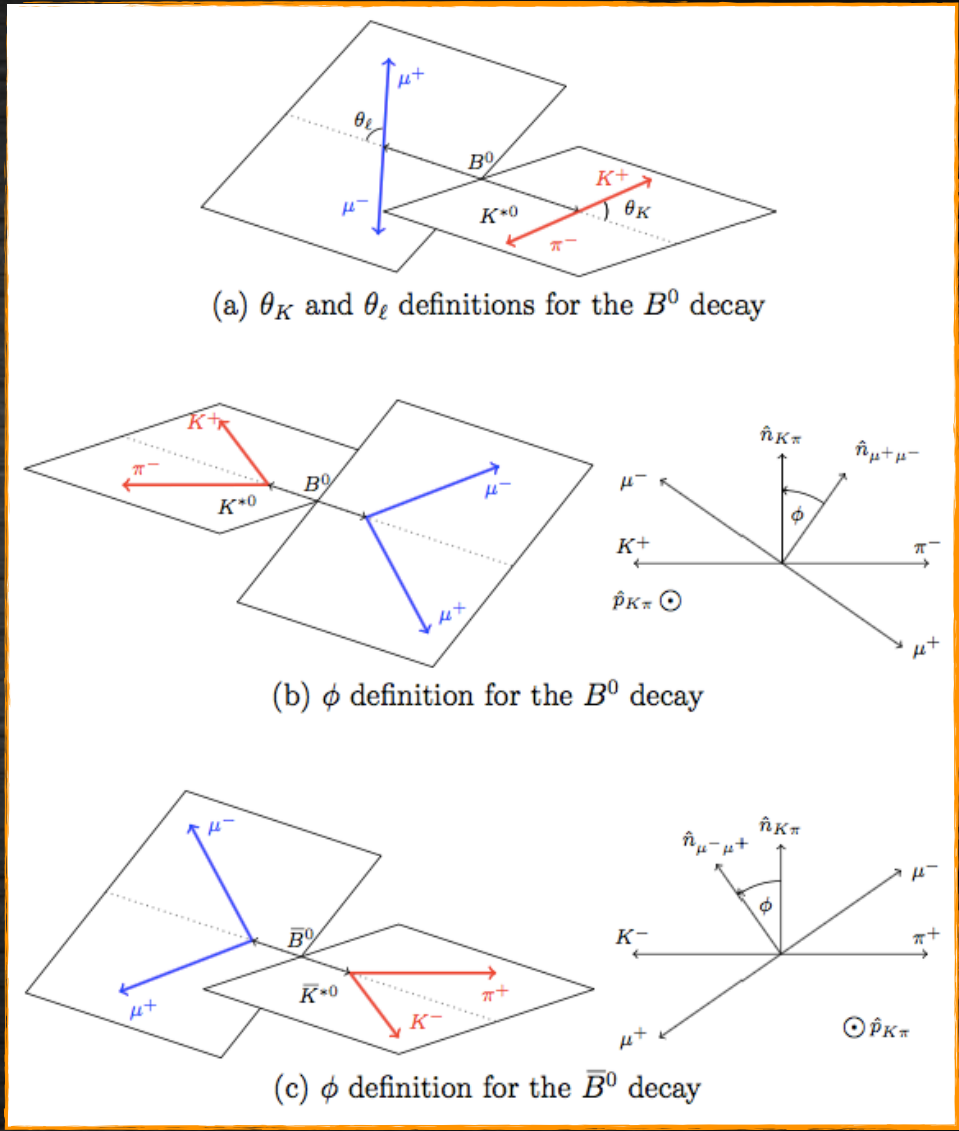






Angular Analyses

- **Four-body** final states
- System described by **three angles** (helicity basis) and the **di-lepton invariant mass squared**, q^2
- Complex angular distribution that provides **many observables sensitive to different types of NP**
- Each observable depends on different Wilson coefficients (underlying short-distance physics) and form-factors (hadronic matrix elements)



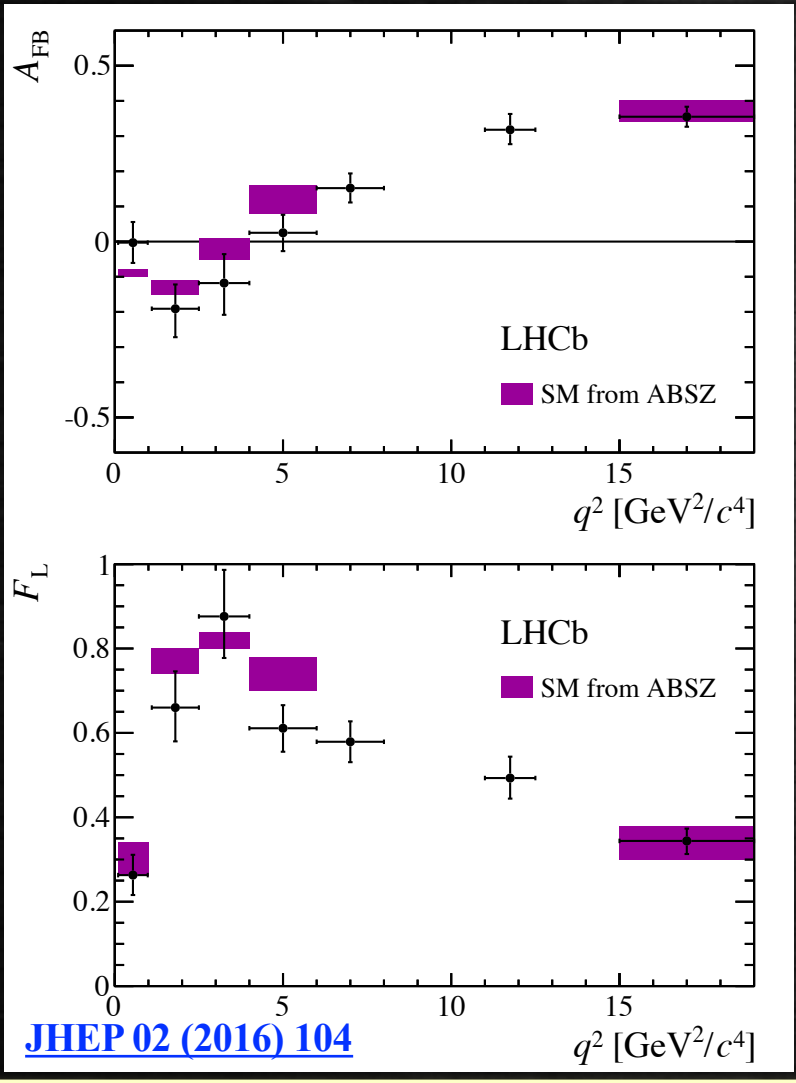
(a) θ_K and θ_ℓ definitions for the B^0 decay

(b) ϕ definition for the B^0 decay

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

Angular Analyses

› First **full angular analysis** of $B^0 \to K^{*0}\mu\mu$: full set of CP-averaged angular terms and correlations as well as full set of CP-asymmetries



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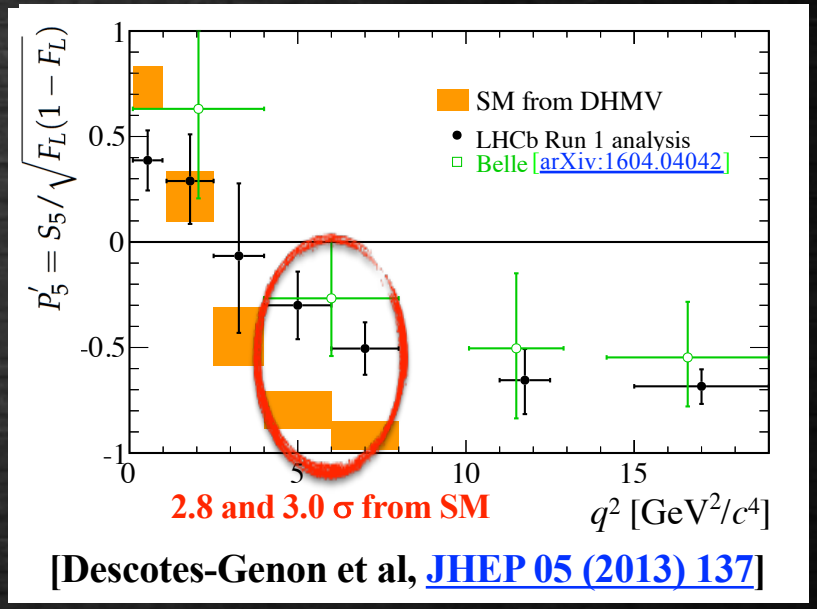
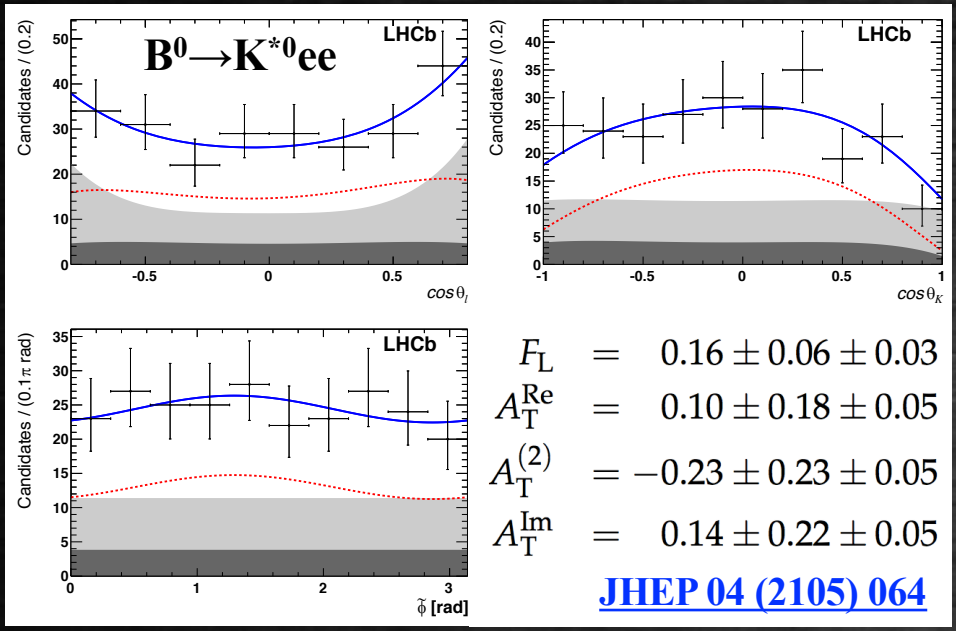


New Belle result consistent with LHCb

Angular Analyses

› Results **consistent with SM predictions**



$$F_L = 0.16 \pm 0.06 \pm 0.03$$
$$A_T^{Re} = 0.10 \pm 0.18 \pm 0.05$$
$$A_T^{(2)} = -0.23 \pm 0.23 \pm 0.05$$
$$A_T^{Im} = 0.14 \pm 0.22 \pm 0.05$$

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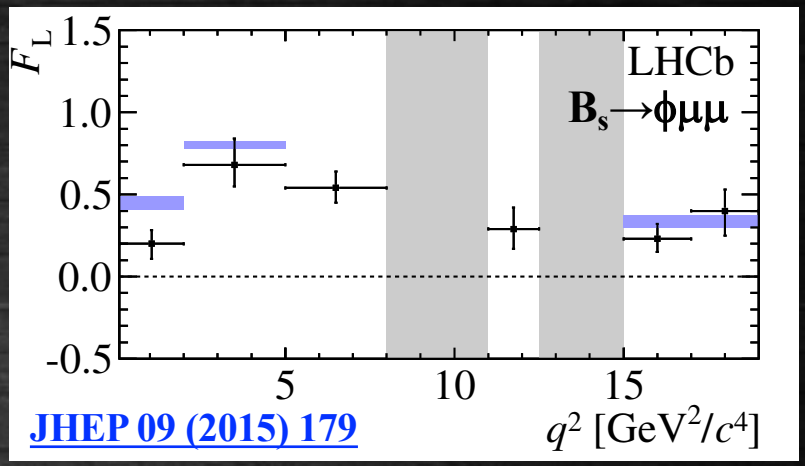
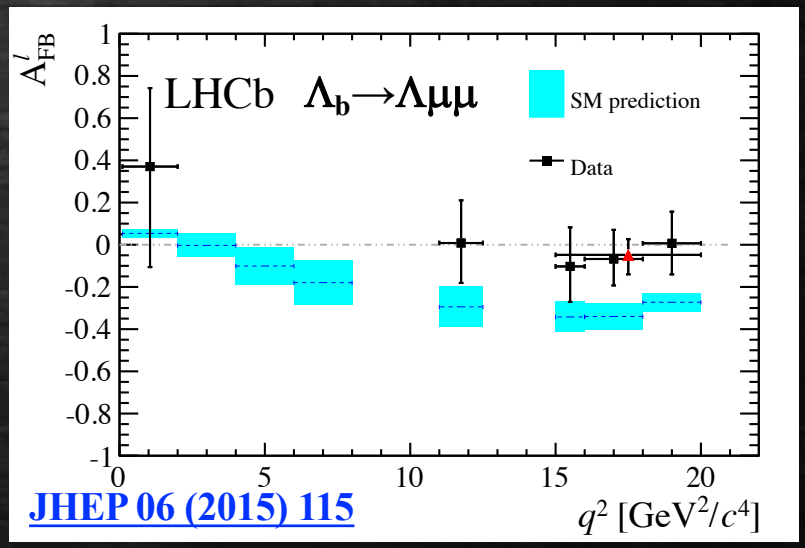


› **Low-q^2**: 0.0004–1 GeV^2
› Challenging due to Bremsstrahlung
› Sensitive to photon polarisation



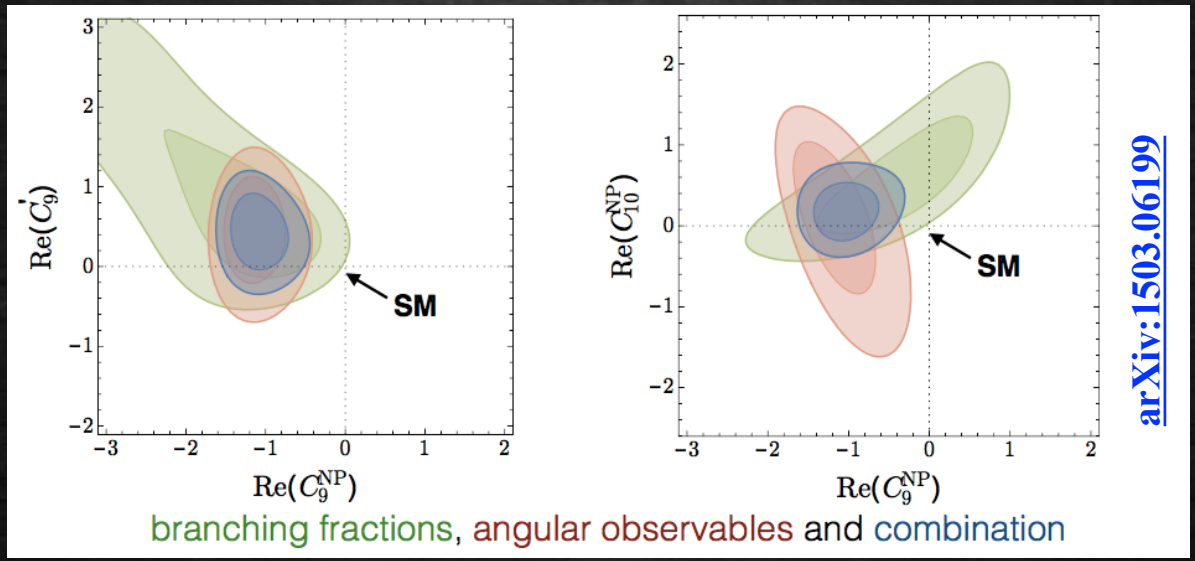
› **Λ_b**: gives access to different combinations of Wilson coefficients

Global Fits

› Several attempts to interpret results by performing **global fits to b→s data** (e.g. arXiv:1503.06199, arXiv:1510.04239 and arXiv:1512.07157)

› Take into account ~80 observables from 6 experiments including b→μμ, b→sll and b→sγ transitions

› All global fits require an **additional contribution with respect to the SM to accommodate the data, with a preference for NP in C_9 at ~4σ**



› **Or is this a problem with our understanding of QCD?**
(e.g. are we correctly estimating the contribution for charm loops?)

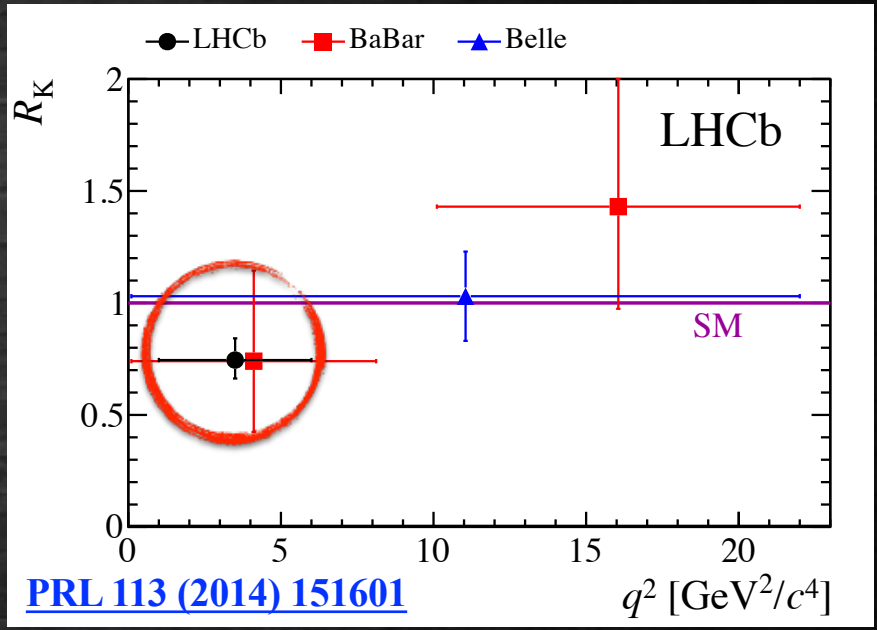
Tests of LFU

› Ratio of branching fractions of $B^+ \to K^+ \mu\mu$ to $B^+ \to K^+ ee$ expected to be unity in the SM (theoretical uncertainty of $O(10^{-3})$)

› **Observation of LFU violations would be a clear sign of NP**

› Extremely challenging due to Bremsstrahlung and different trigger / tracking performances between muons and electrons

› Measured relative to $B^+ \to K^+ J/\psi(ll)$ in order to reduce systematics



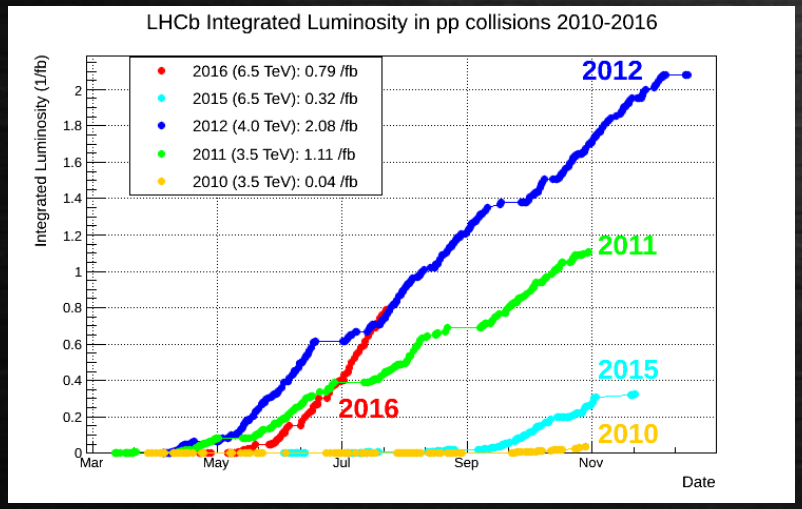
› **Observed a 2.6σ deviation from SM**

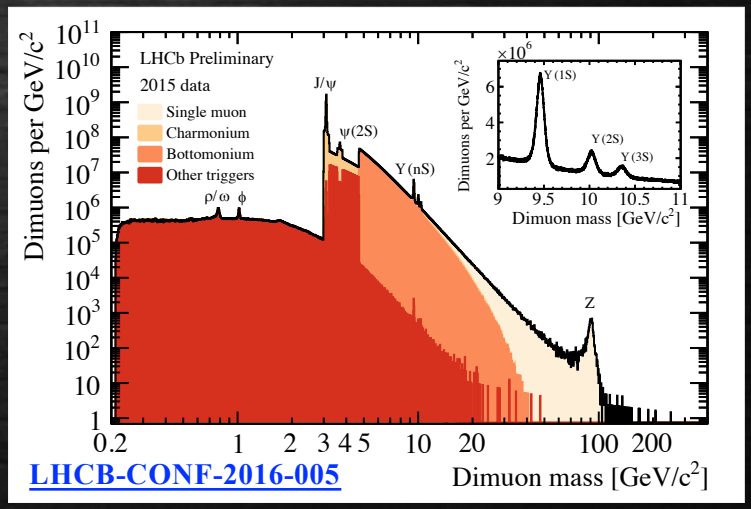
› Consistent with decay rate if NP does not couple to electrons

› **Pursuing other R–like measurements** (e.g see talk by S.Klaver on $R(D^*)$)

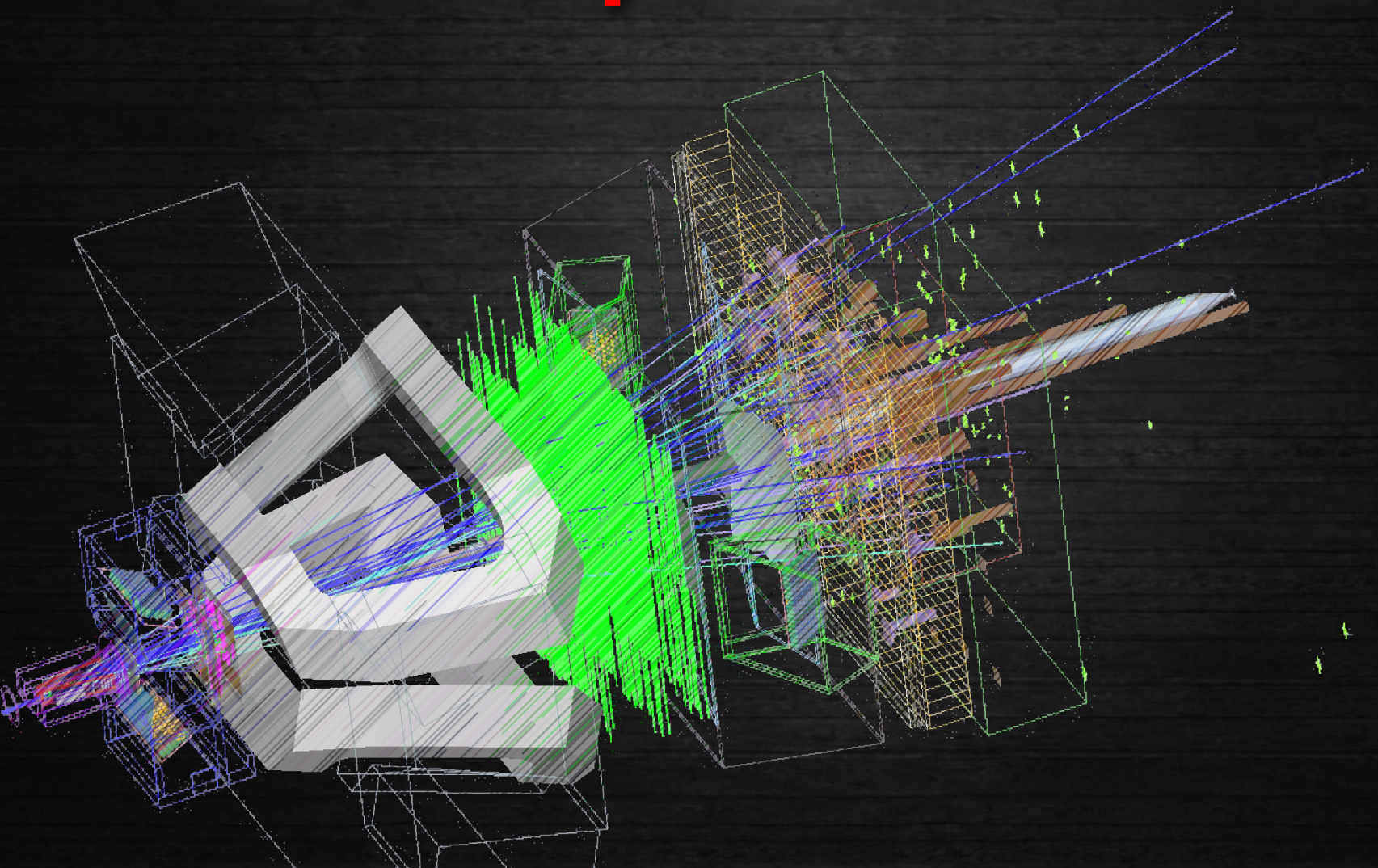
Summary and Outlook

- Rare b decays place strong constraints on many NP models allowing to probe energy scales higher than direct searches
- A large number of analyses have been performed using Run 1 data
- While there is no significant evidence for NP from a single measurement, a clear tension with the SM have been seen in global fits to rare decay observables
- Rare decays will largely benefit from the increase of energy (cross-section) and collected data (~5 fb^{-1} expected in LHCb) in Run 2

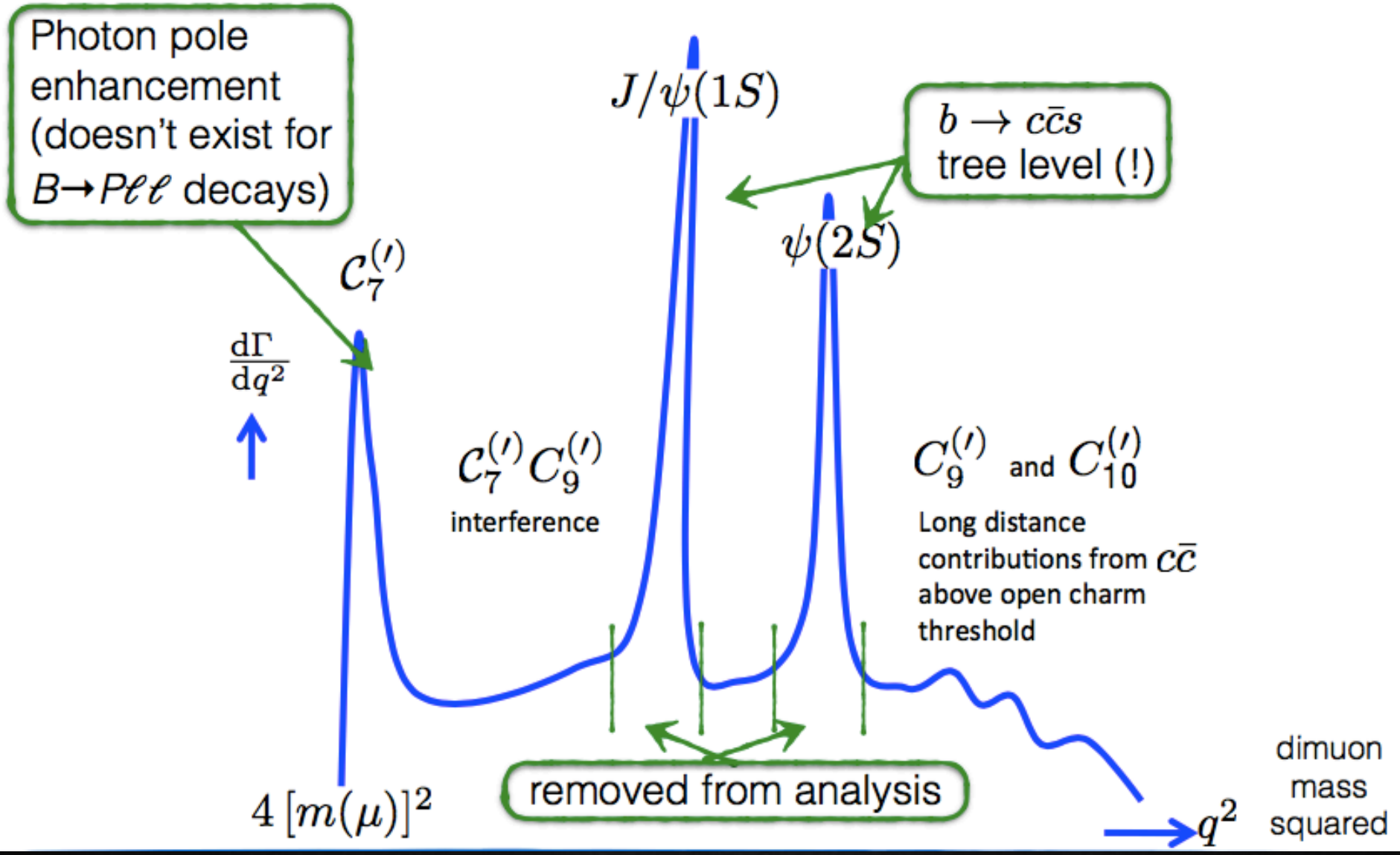




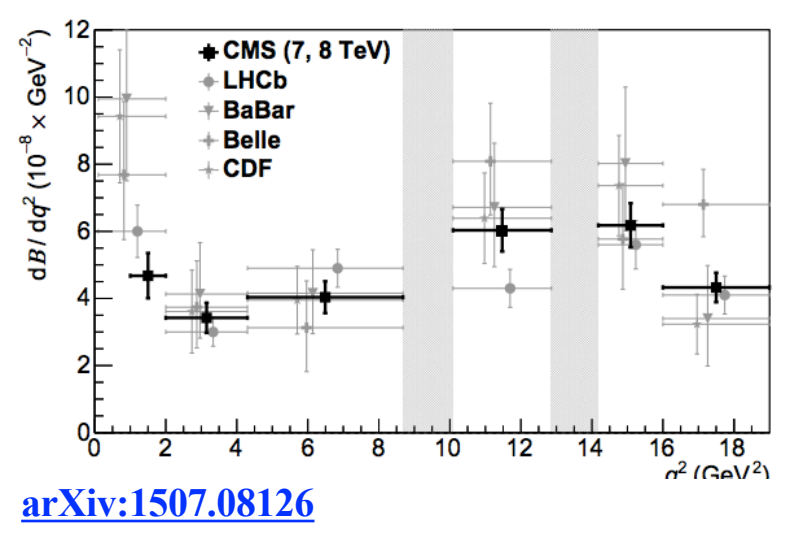
Backup



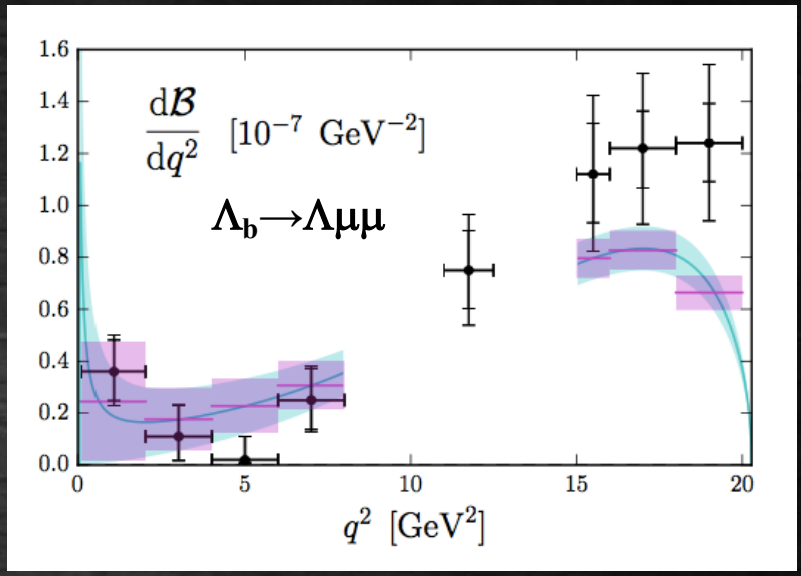
Di-Lepton Mass

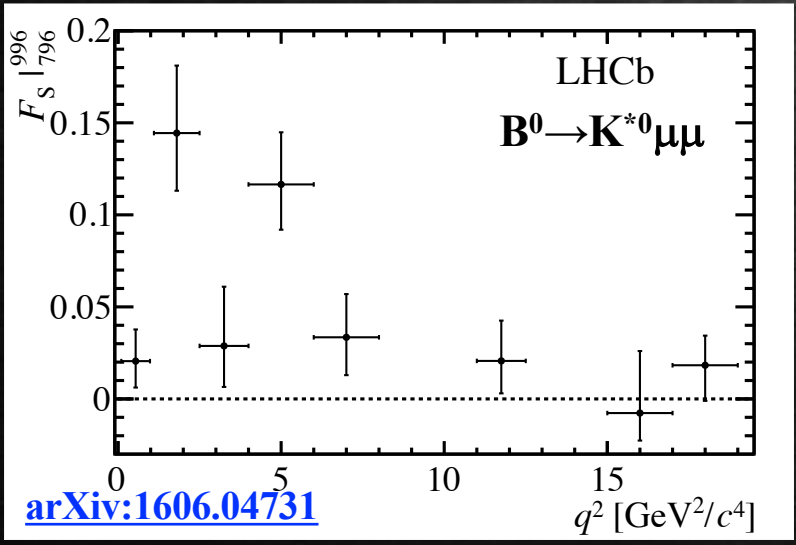


Differential Branching Fractions

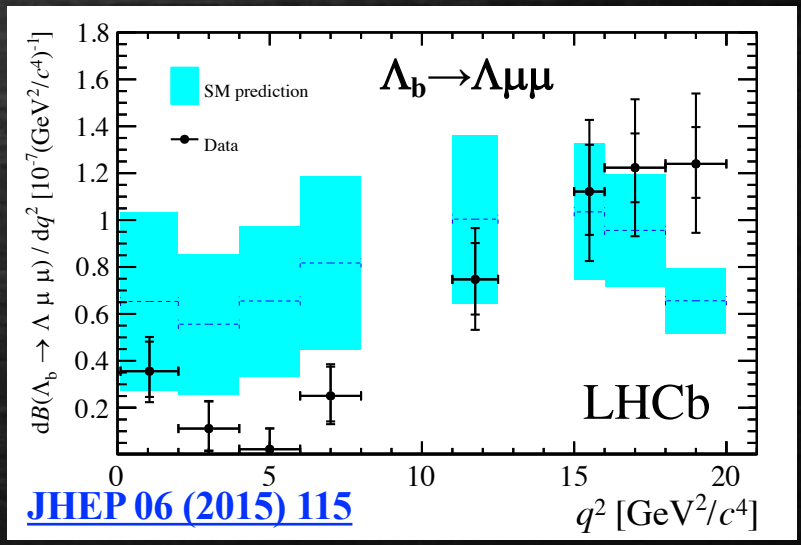


arXiv:1507.08126





arXiv:1606.04731



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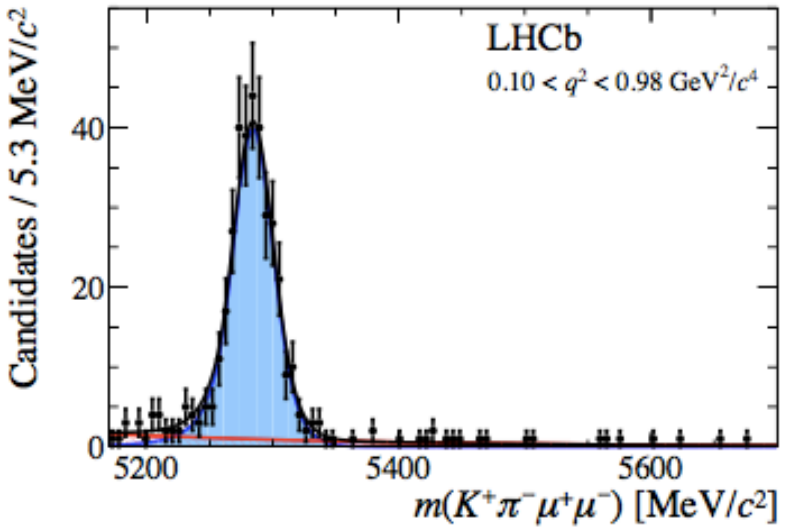
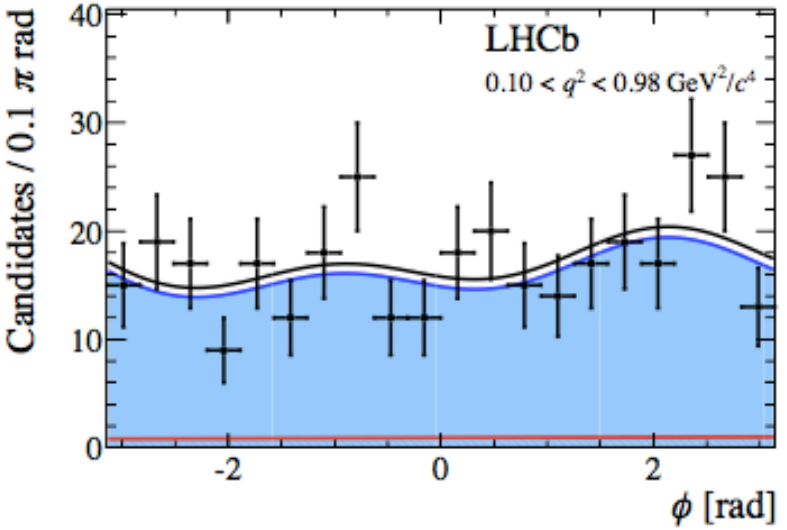
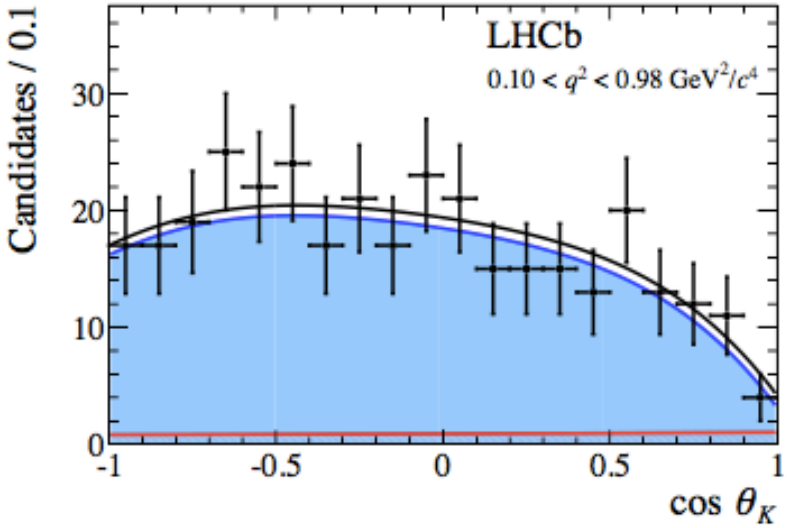
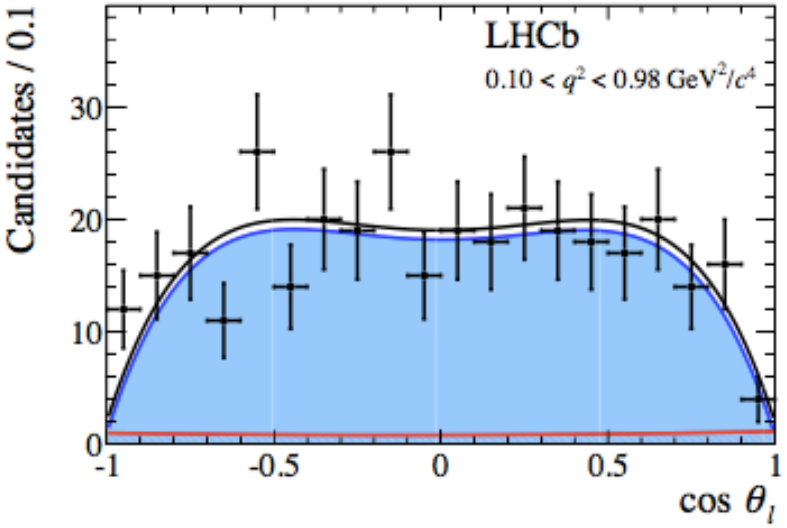
Angular Analyses









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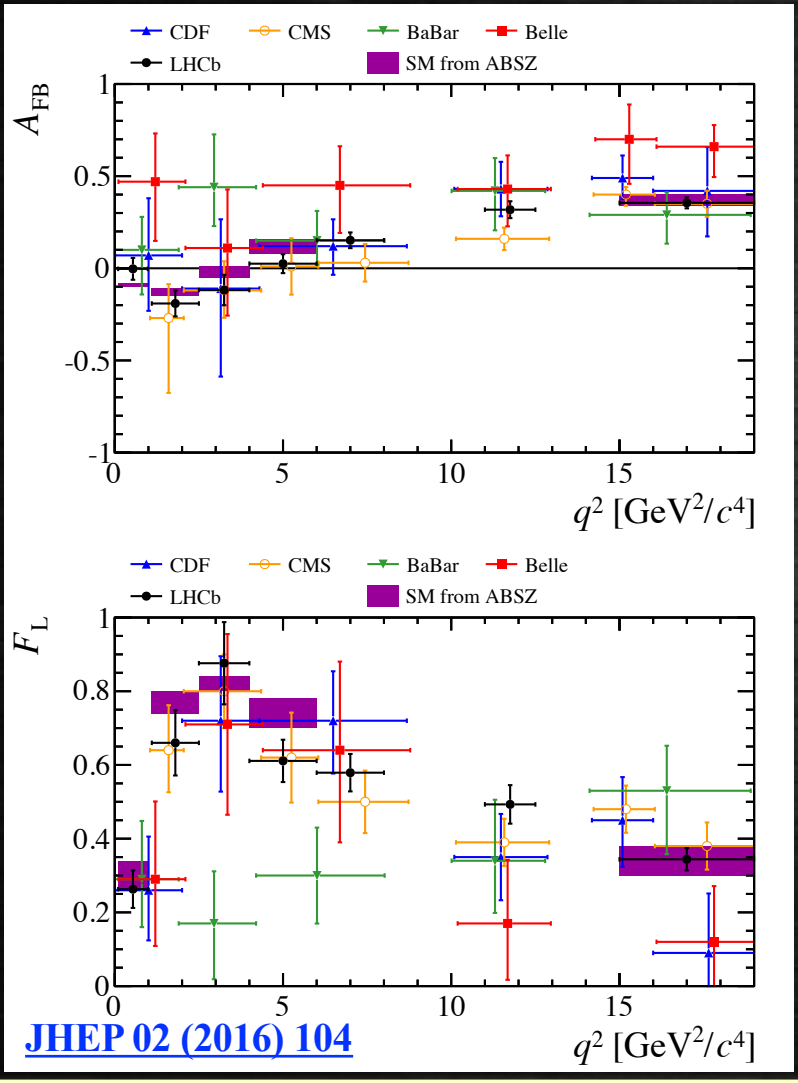

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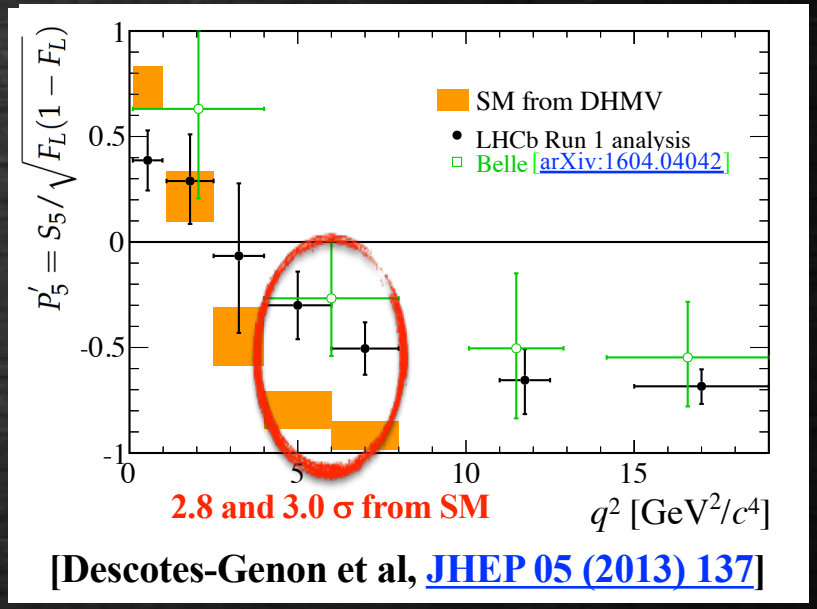
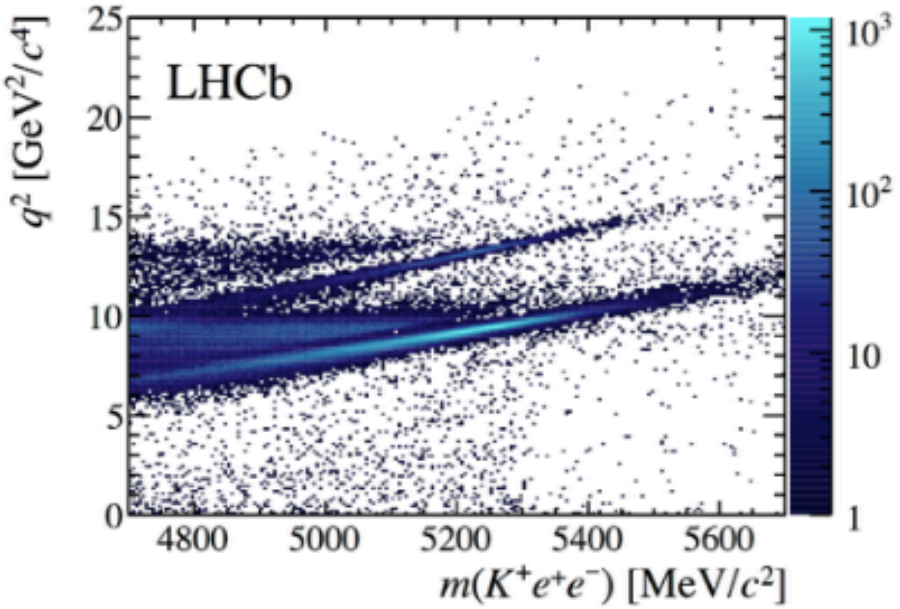


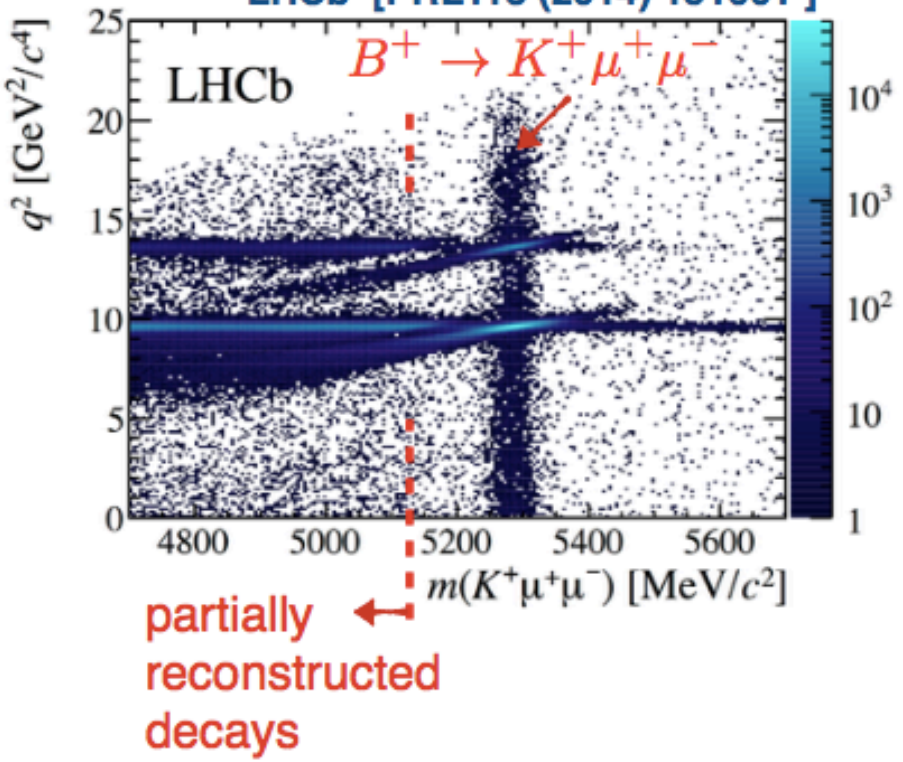
New Belle result consistent with LHCb

Tests of LFU

- Even after Bremsstrahlung recovery there are significant differences between dielectron and dimuon final states:

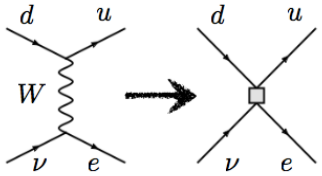


LHCb [PRL113 (2014) 151601]



Theoretical Framework

- In the Fermi model of the weak interaction, the full electroweak Lagrangian (which was unknown at the time) is replaced by the low-energy theory (QED) plus a single operator with an effective coupling constant.



$$\mathcal{L}_{\rm EW} \to \mathcal{L}_{\rm QED} + \frac{G_{\rm F}}{\sqrt{2}}(\bar{u}d)(e\bar{\nu})$$

- Can write a Hamiltonian for the effective theory as

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i(\mu)\mathcal{O}_i(\mu),$$

Wilson coefficient (integrating out scales above μ)

Local operator with different Lorentz structure (vector, axial vector current etc)

Operators

SM operators

photon penguin

$$\mathcal{O}_7 = \frac{m_b}{e}\bar{s}\sigma^{\mu\nu}P_R b F_{\mu\nu}\,,$$

$$\mathcal{O}_8 = g_s\frac{m_b}{e^2}\bar{s}\sigma^{\mu\nu}P_R T^a b G^a_{\mu\nu}\,,$$

$$\mathcal{O}_9 = \bar{s}\gamma_\mu P_L b\,\bar{\ell}\gamma^\mu \ell\,,$$

$$\mathcal{O}_{10} = \bar{s}\gamma_\mu P_L b\,\bar{\ell}\gamma^\mu\gamma_5\ell\quad,$$

vector and axial-vector currents

Beyond SM operators

$$\mathcal{O}'_7 = \frac{m_b}{e}\bar{s}\sigma^{\mu\nu}P_L b F_{\mu\nu}\,,$$

$$\mathcal{O}'_8 = g_s\frac{m_b}{e^2}\bar{s}\sigma^{\mu\nu}P_L T^a b G^a_{\mu\nu}\,,$$

$$\mathcal{O}'_9 = \bar{s}\gamma_\mu P_R b\,\bar{\ell}\gamma^\mu \ell\,,$$

$$\mathcal{O}'_{10} = \bar{s}\gamma_\mu P_R b\,\bar{\ell}\gamma^\mu\gamma_5\ell\,.$$

right handed currents (suppressed in SM)

Angular Analyses

- Complex angular distribution:

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

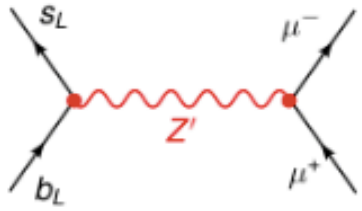
fraction of longitudinal polarisation of the K*

forward-backward asymmetry of the dilepton system

The observables depend on form-factors for the $B \to K^*$ transition plus the underlying short distance physics (Wilson coefficients).

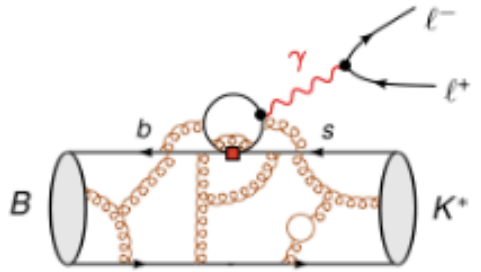
Interpretation of Global Fits

Optimist's view point



Vector-like contribution could come from new tree level contribution from a Z' with a mass of a few TeV

Pessimist's view point

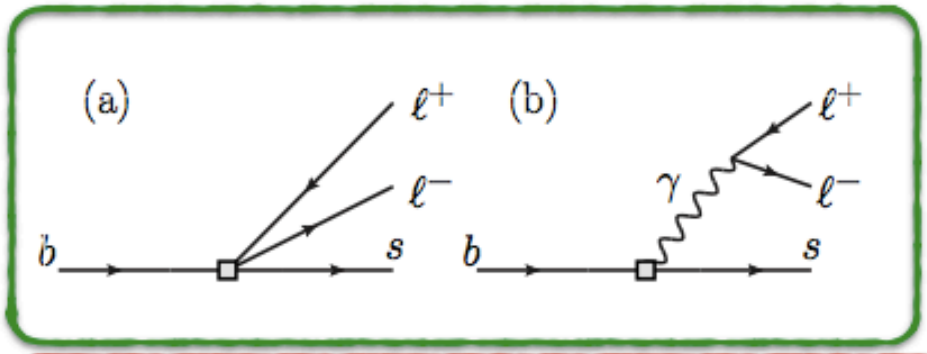


Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon.

More work needed from experiment/theory to disentangle the two

Interpretation of Global Fits

- This is the physics we are interested in.
- We also get long-distance hadronic contributions. Included in the SM but are the predictions correct?



Short distance part integrates out (as a Wilson coefficient)