B decay anomalies at LHCb

Arantza Oyanguren
(IFIC – U. Valencia/CSIC)

(On behalf of the LHCb collaboration)

XIIIth Quark Confinement and the hadron Spectrum
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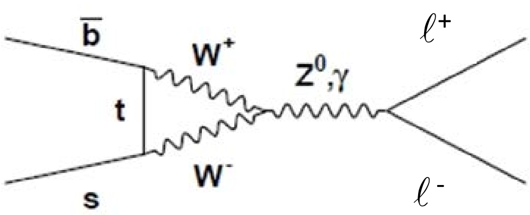
Outline

- Introduction
- The LHCb experiment
- Branching fraction measurements in $b \to s\ell\ell$
- Angular analyses
- Lepton Flavour Universality tests
- Conclusions

Introduction

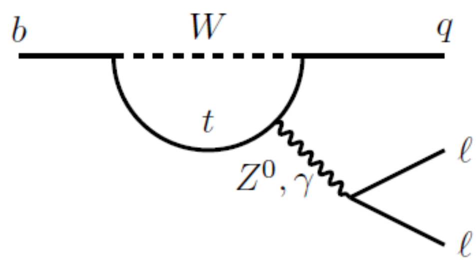
- ***b→s,d*** quark transitions are **Flavor Changing Neutral Currents (FCNCs)**,
  → in the SM they only can occur through loops (*penguin and box diagrams*)
  → very sensitive to new physics

leptonic



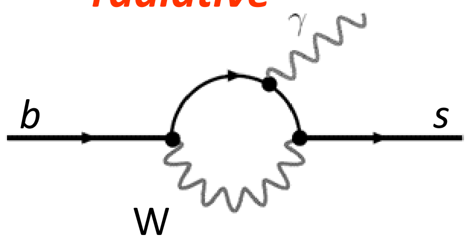
BR ~ 10^{-9}

semileptonic



BR ~ 10^{-7}

radiative



BR ~ 10^{-5}

Experimentally → leptons/photons with high transverse momenta

Theoretically → observables can be calculated by using effective theories

In this talk I will focus on b → s $\ell\ell$ transitions

Introduction

- The amplitude of a hadron decay process can be described using OPE:

$$A(M \to F) = \langle F|\mathcal{H}_{eff}|M\rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle F|O_i(\mu)|M\rangle$$

CKM couplings — Wilson Coefficients (μ = scale) — Hadronic Matrix Elements

$\rightarrow$ a series of effective vertices multiplied by effective coupling constants C_i .

Electroweak scale ~ $1/M_W$

New Physics scale ~ $1/M_{NP}$

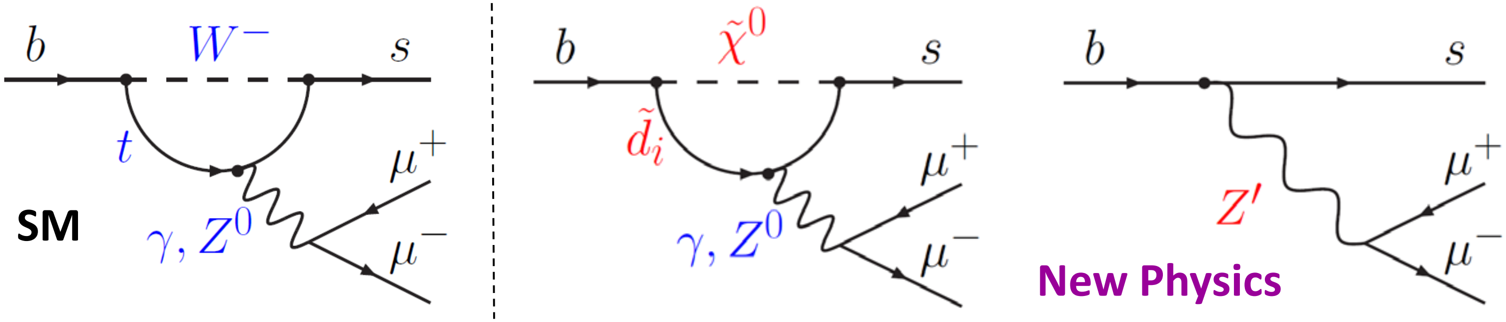
$C_i = C_i^{SM} + C_i^{NP}$

$C'_i = C_i'^{SM} + C_i'^{NP}$

Primed $C'_i \rightarrow$ right handed currents: suppressed in SM

Introduction

- $b \to s \ell^+ \ell^-$ is mainly sensitive to $\mathbf{C_7}$, $\mathbf{C_9}$ and $\mathbf{C_{10}}$ Wilson coefficients



Observables that can be affected:

- **Differential branching fractions**
  ($B^0 \to K^{(*)0}\mu^+\mu^-$, $B^+ \to K^{(*)+}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $B^+ \to \pi^+\mu^+\mu^-$ and $\Lambda_b \to \Lambda\mu^+\mu^-$)
  $\to$ Affected by hadronic uncertainties in the theory predictions

- **Angular distributions**
  ($B^0 \to K^{(*)0}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$ $B^0 \to K^{*0}e^+e^-$ and $\Lambda_b \to \Lambda\mu^+\mu^-$)
  $\to$ Observables with smaller theory uncertainties

- **Ratios testing Lepton Flavour Universality**
  ($B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$)
  $\to$ Hadronic uncertainties in theory predictions cancel in ratios

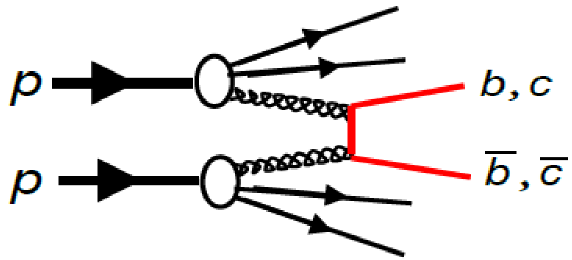
The LHCb experiment

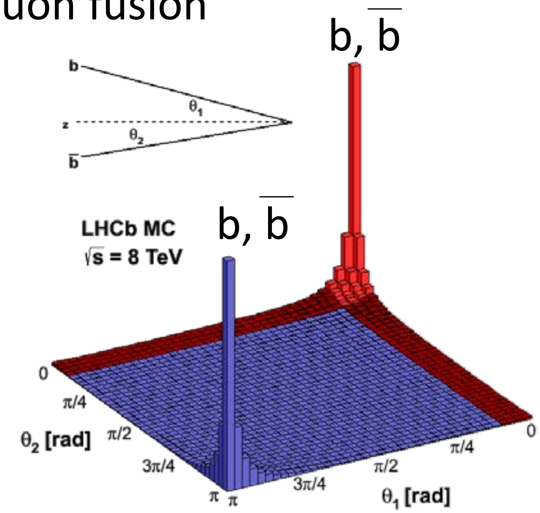
- The $b\bar{b}$ cross section in pp collisions is large, mainly from gluon fusion

  ~ 300 μb @ √s=7 TeV

  ~ 600 μb @ √s=13 TeV

  [PRL 118 (2017) 052002]





The *b* quarks hadronize in B, B_s, $B^*_{(s)}$, *b*-baryons…

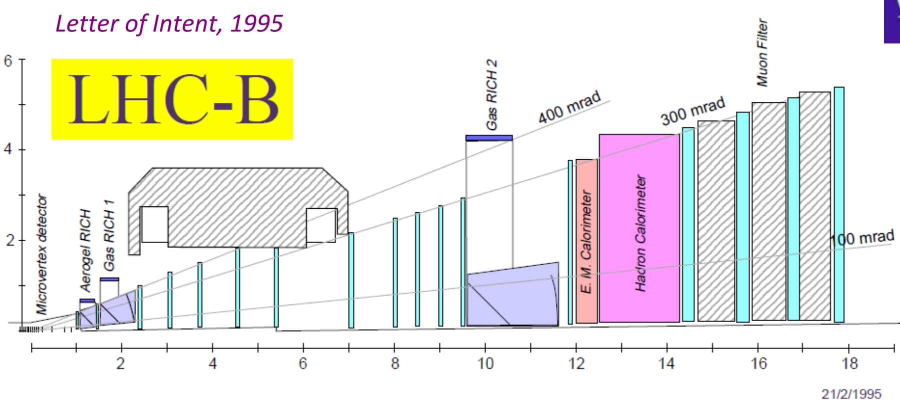
→ average B meson momentum ~ 80 GeV

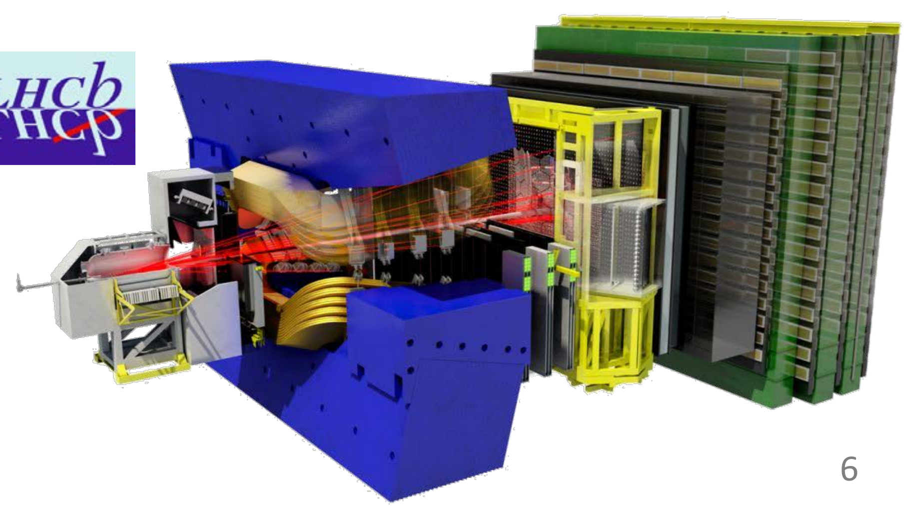
- The LHCb idea: to build a single-arm forward spectrometer:

  ~ 4% of the solid angle (2 < η < 5),

  ~30% of the *b* hadron production

Letter of Intent, 1995

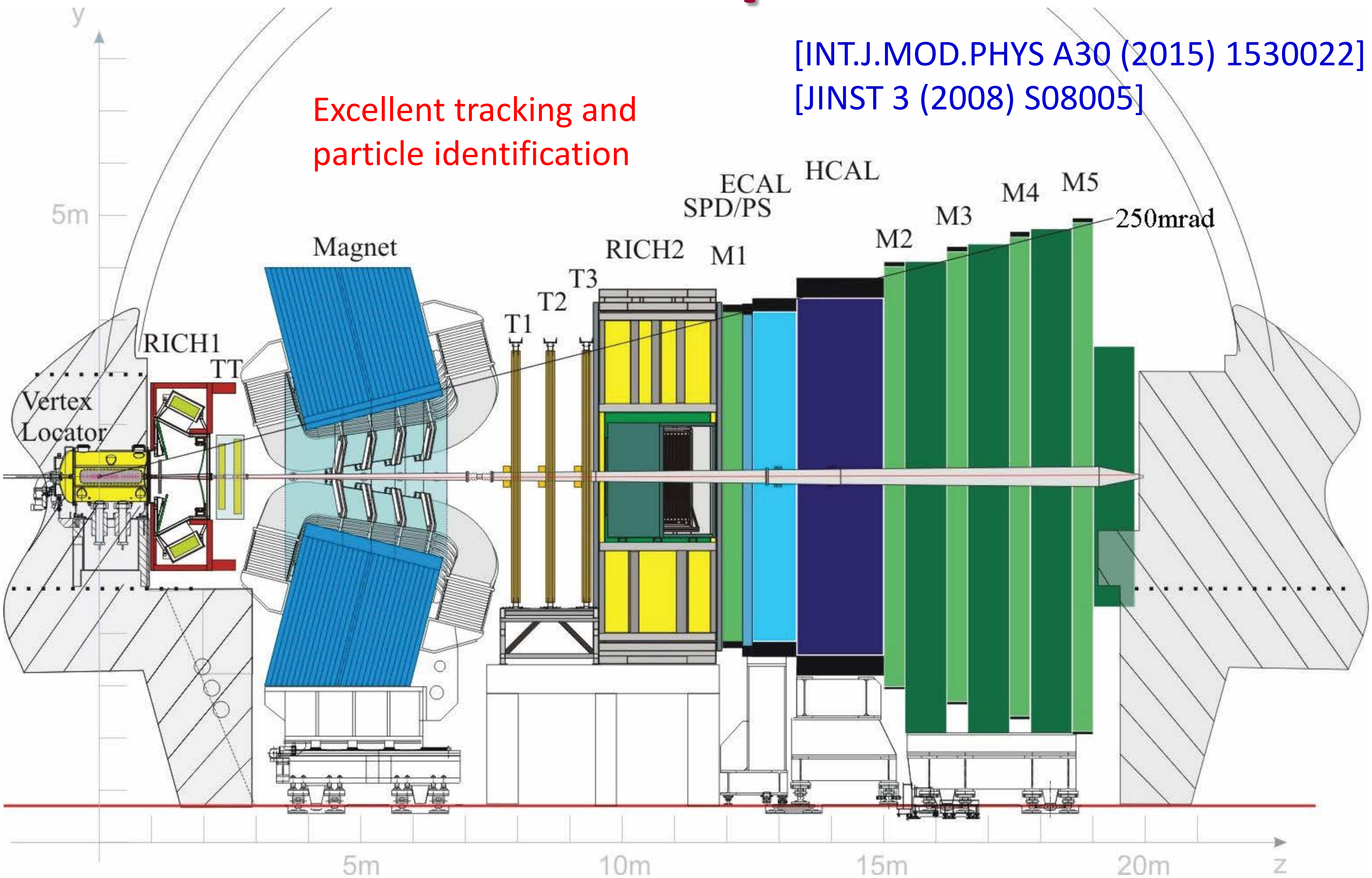




The LHCb experiment

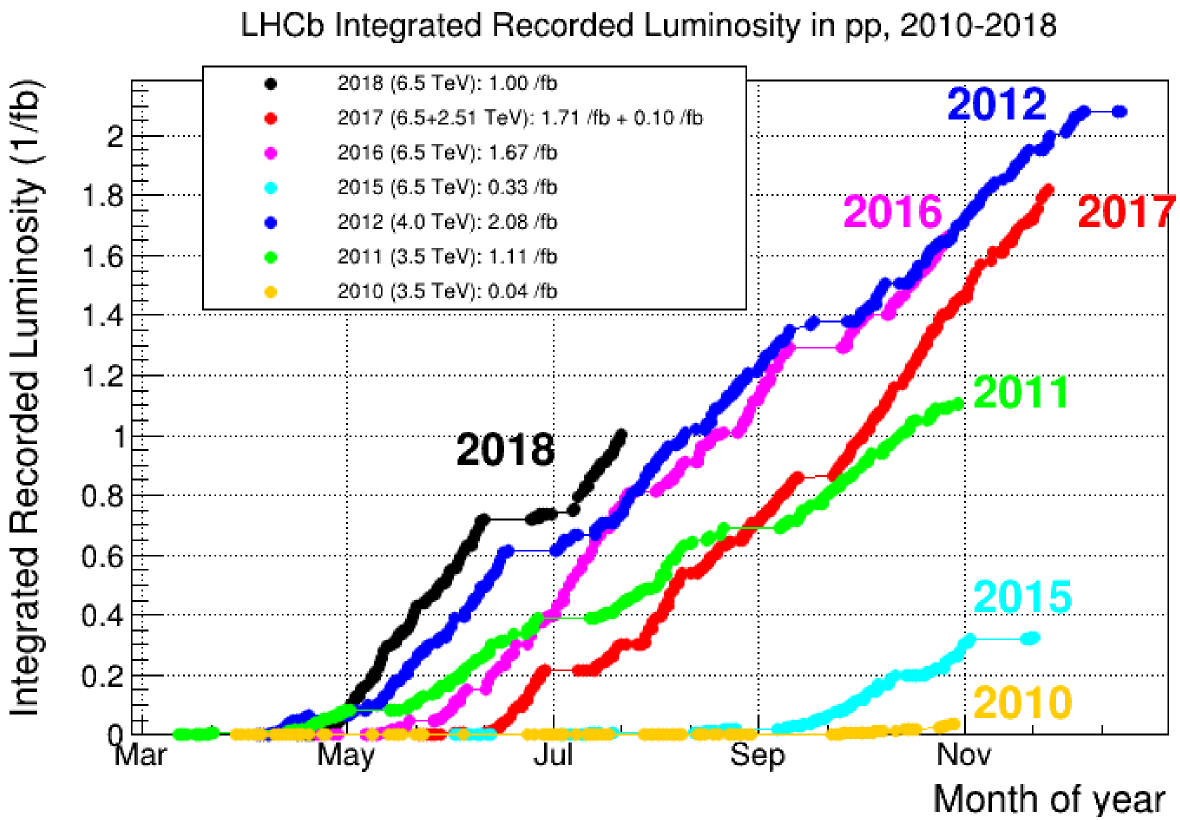
[INT.J.MOD.PHYS A30 (2015) 1530022]
[JINST 3 (2008) S08005]

Excellent tracking and
particle identification



The LHCb experiment

Very good performace: 3 fb^{-1} in Run1, more than 5fb^{-1} in Run2



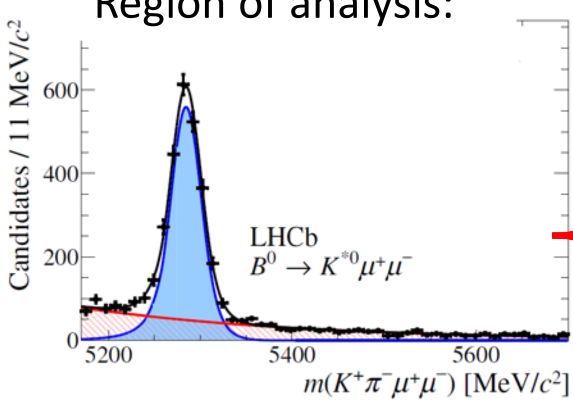
Analysis of b→sℓℓ events

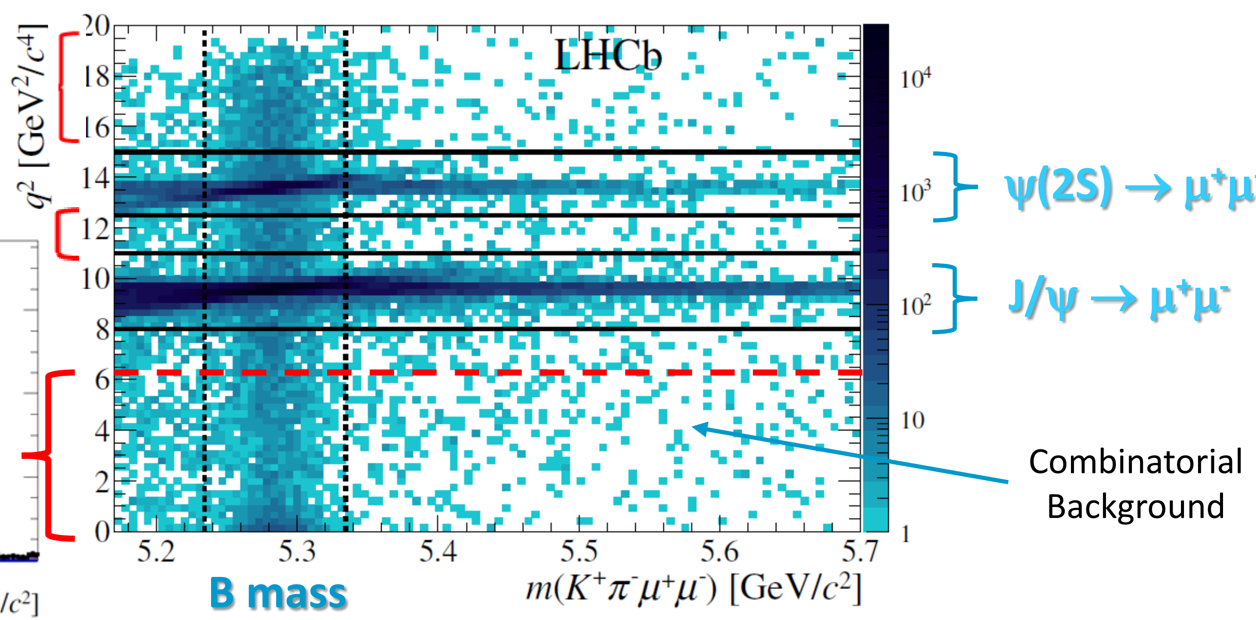
- *b*-hadron mass is reconstructed from final hadron decays and two energetic leptons
- Background events suppressed by requiring displaced vertices
- The decay width is expressed in terms of **q²** = invariant mass of the dilepton system (differential BR, ratios of BRs) and **decay angles** (angular analysis)
- Tree level decays involving **J/ψ** and **ψ(2S)** resonances are used as control samples and the q^2 regions are generally removed from the analyses of b→sℓℓ decays

Ex: B → K μ⁻μ⁺*

[JHEP02(2016)104]

Region of analysis:

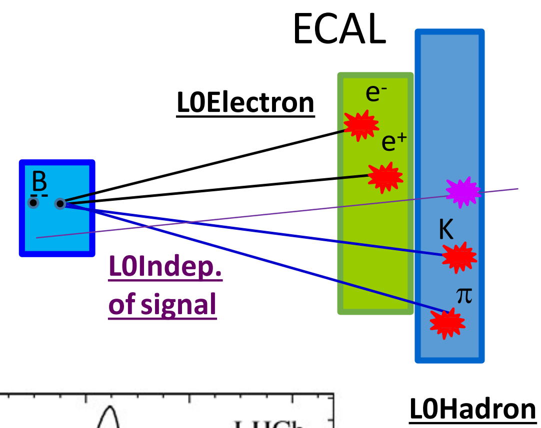


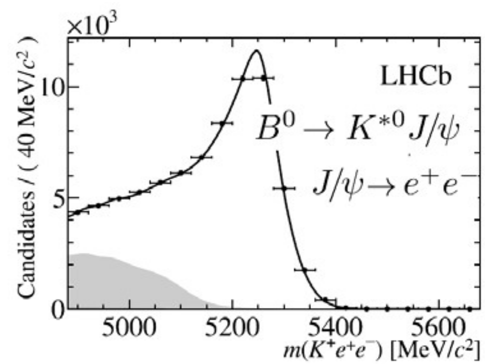


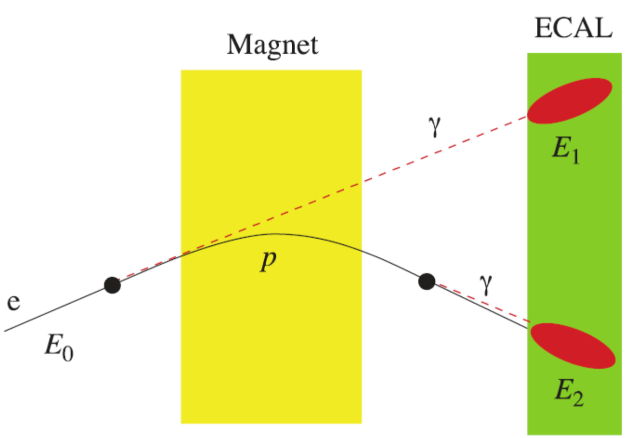
Analysis of b→sℓℓ events

Decays involving electrons:

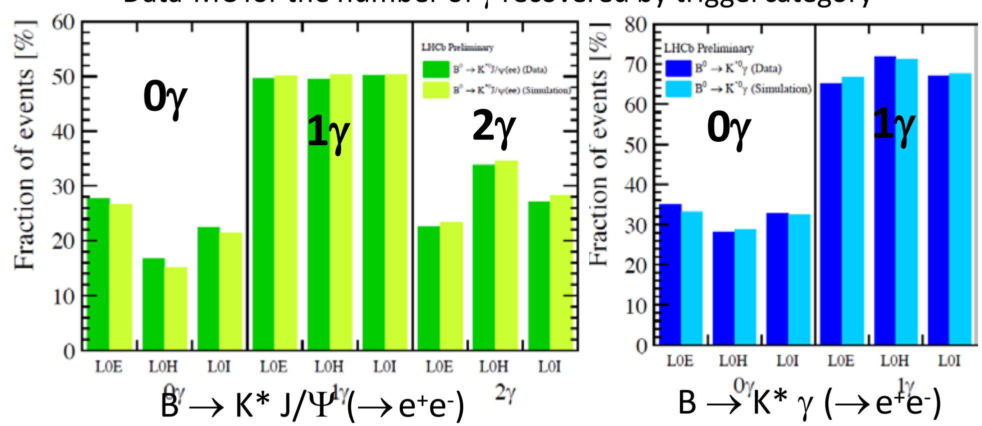
- LHCb is far better with muons than electrons
- *Trigger*, reconstruction, selection and particle identification are harder with electrons
- Mass resolution affected by *e bremsstrahlung* → need energy recovery
- Mass shape modelled according to the number of *bremsstrahlung* recovered





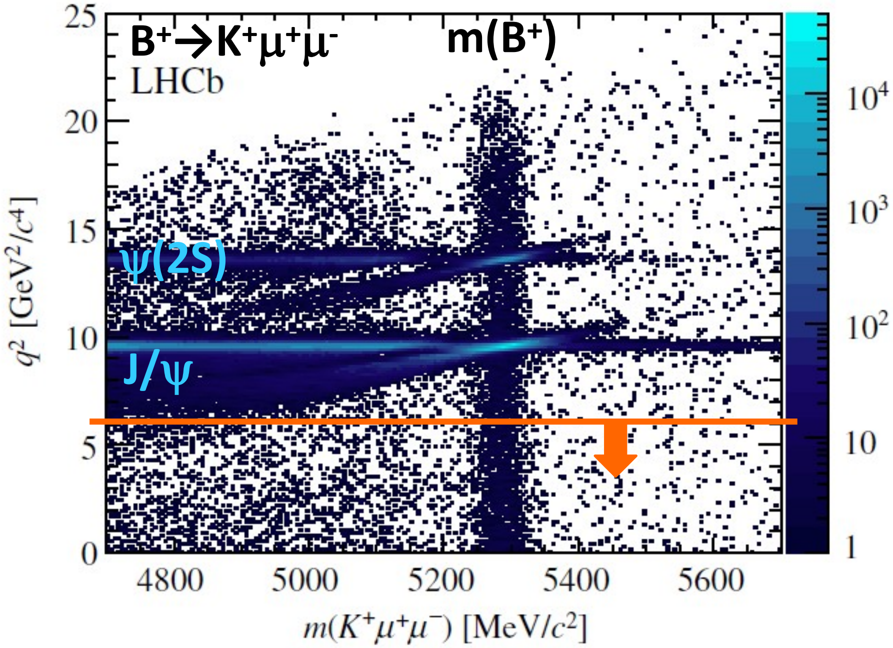


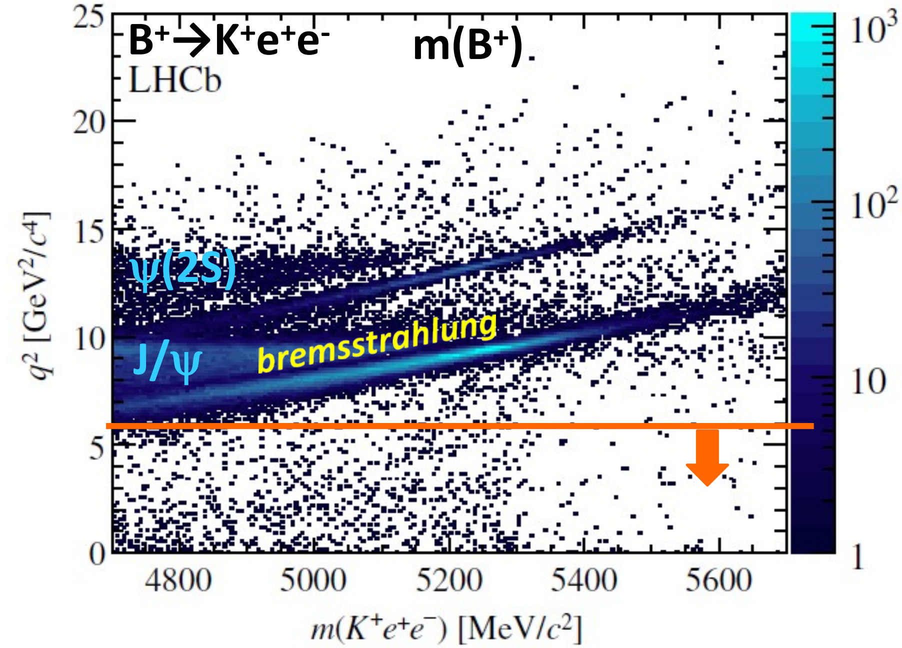
Data-MC for the number of γ recovered by trigger category

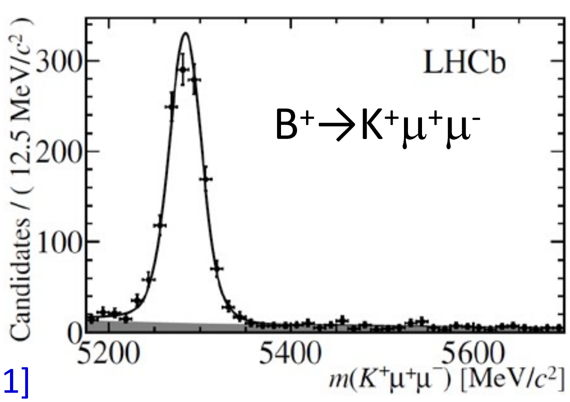


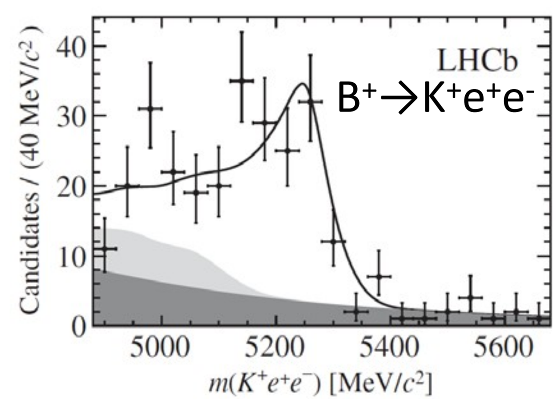
Analysis of b→sℓℓ events

B mass vesus q^2 for $B^+ \to K^+ \ell^+ \ell^-$









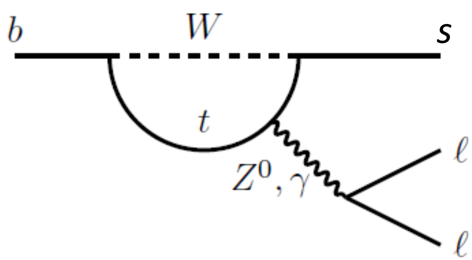
[PRL 113 (2014) 151601]

Branching fractions

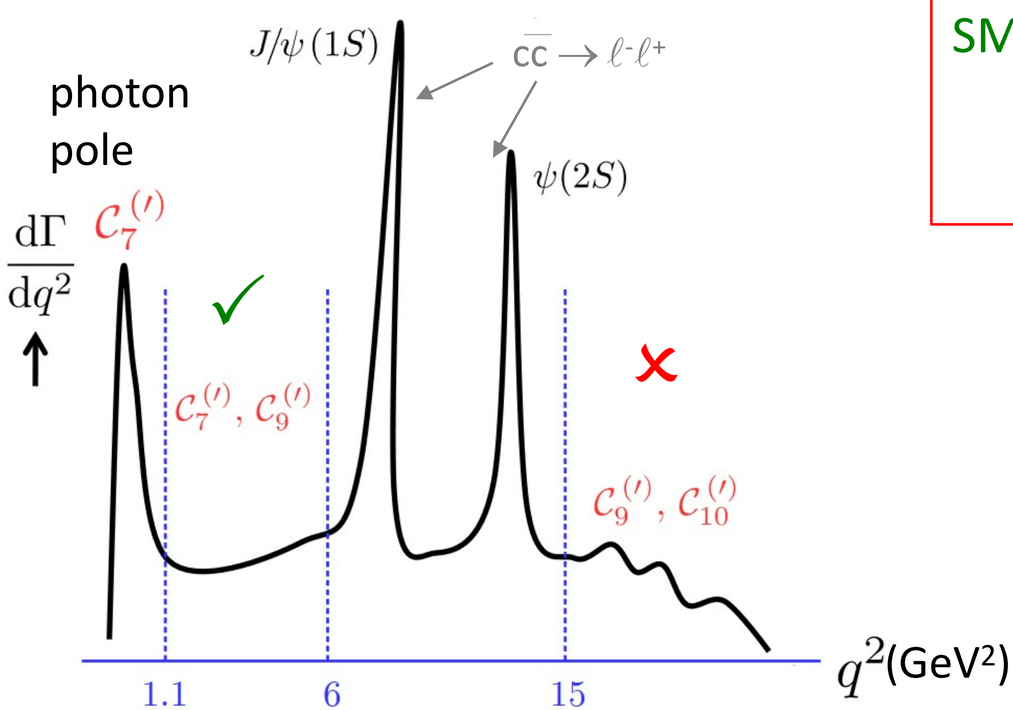
Differential branching fraction: $d\Gamma/dq^2$

Each q^2 region probes different processes

$B \rightarrow K^* \ell^- \ell^+$



$q^2 = (p_{\ell^+} + p_{\ell^-})^2$



SM values (μ=m_b): $C_7 \sim -0.33$, $C_9 \sim 4.27$, $C_{10} \sim -4.17$

(Everything else small or negligible)

Branching fractions

In a q^2 range, the differential branching fraction can be obtained:

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2} = \frac{R_\epsilon}{(q^2_{\mathrm{max}} - q^2_{\mathrm{min}})} \frac{(1 - F_{\mathrm{S}}|^{1200}_{644}) n_{K^{*0}\mu^+\mu^-}}{(1 - F_{\mathrm{S}}^{J/\psi\, K^{*0}}) n_{J/\psi\, K^{*0}}} \mathcal{B}(B^0 \to J/\psi\, K^{*0}) \mathcal{B}(J/\psi \to \mu^+\mu^-)$$

→ Normalized to the J/ψ mode

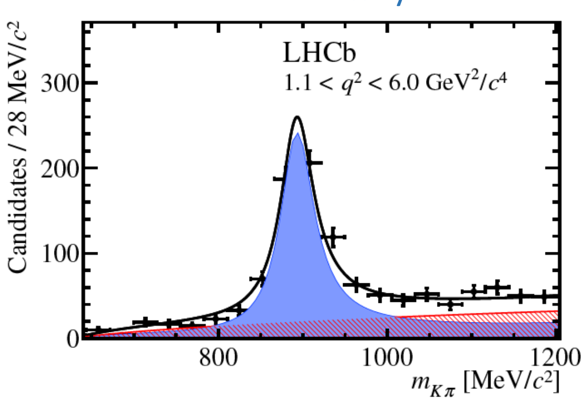
→ **$n_{channel}$** is the yield for the signal and normalization decay modes

→ **R_ε** is the ratio of efficiencies for signal and normalization decay modes

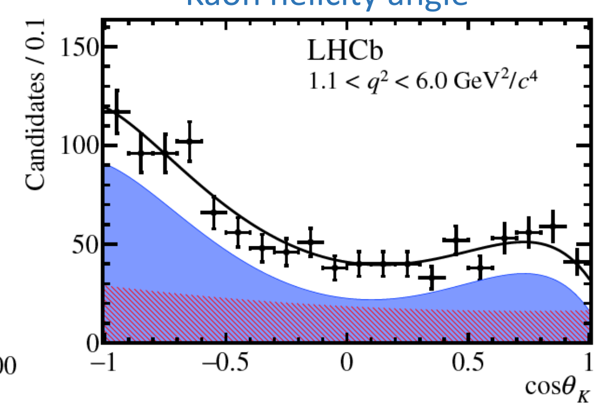
→ **F_S** is the fraction of a S-Wave interfering with the P-wave (for signal and normalization), in a specific $m_{K\pi}$ range (use LASS parameterization to describe the S-wave)

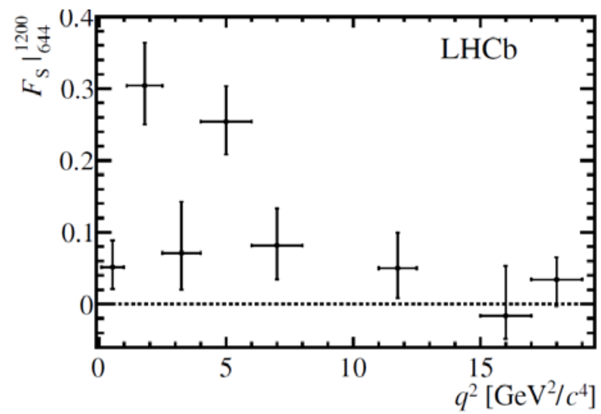
LHCb, [JHEP11 (2016) 047]

Mass of the Kπ system



Kaon helicity angle

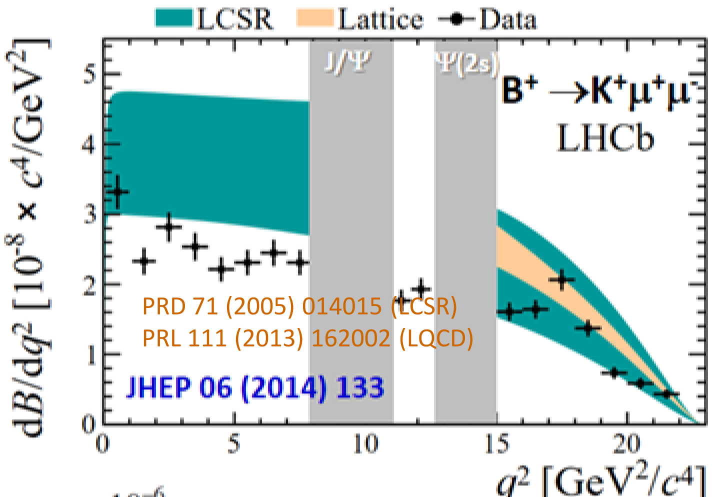


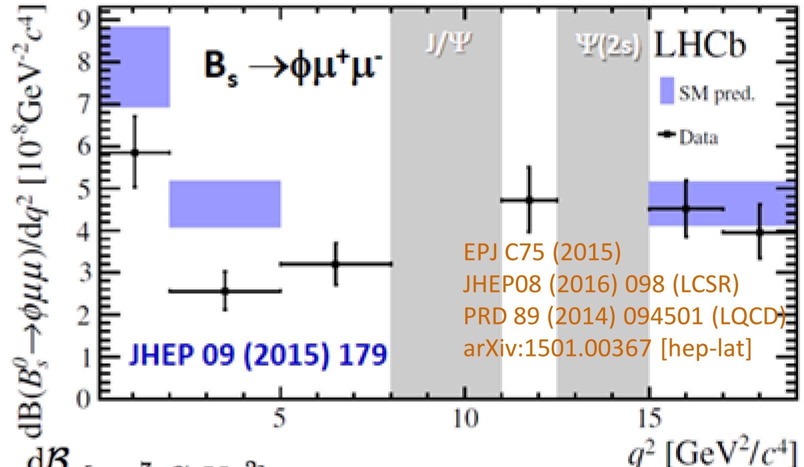


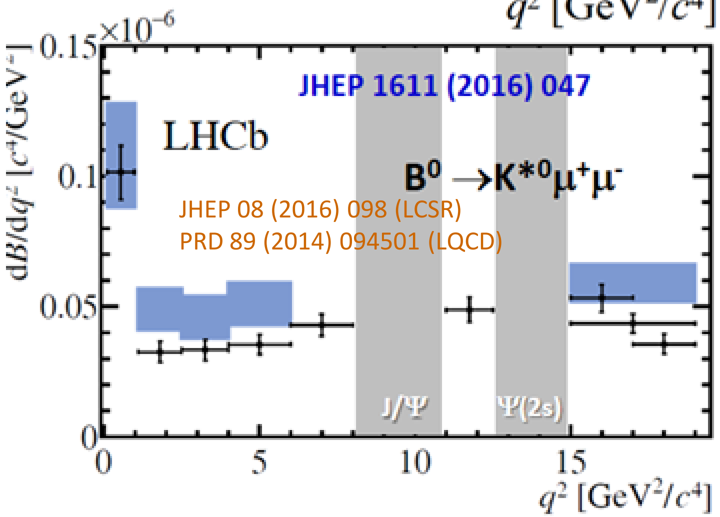
→ S-wave contribution found to be small, < 10%

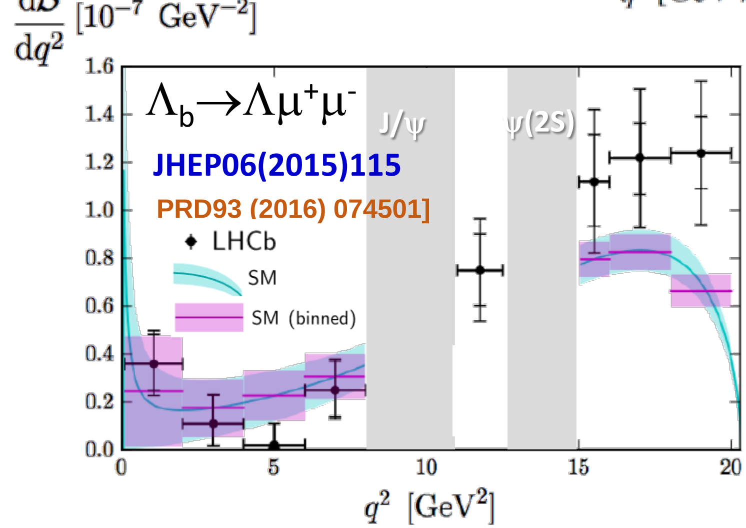
Branching fractions

- Differential decay width as function of $q^2 = m^2_{\mu\mu}$ at **LHCb**, using $3fb^{-1}$





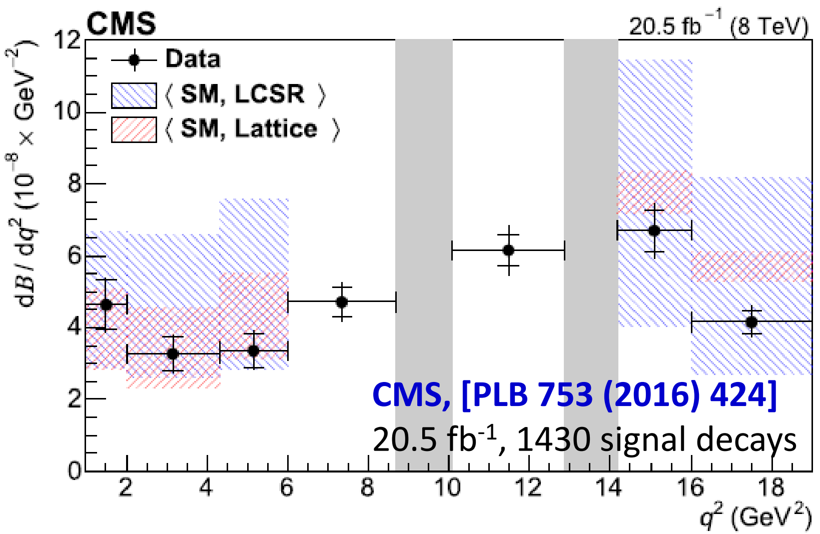


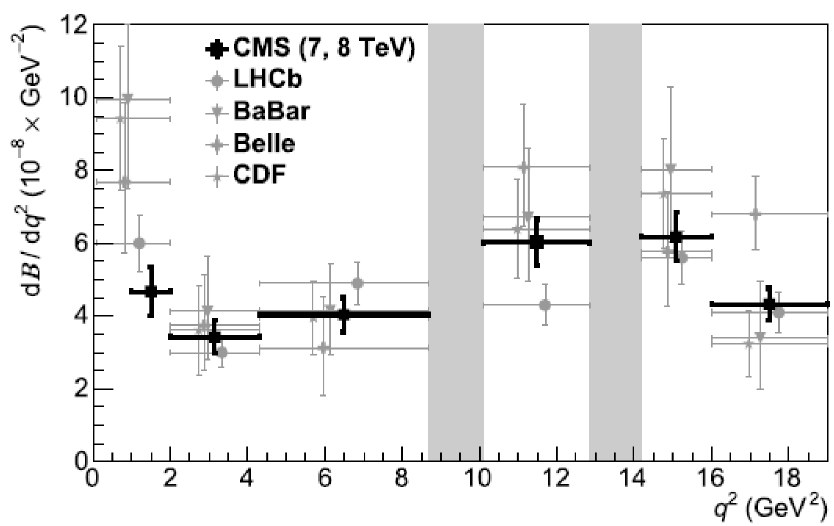


→ Smaller branching fractions than the SM predictions

Branching fractions

- Also measured by other experiments in the $B \to K^* \ell^+ \ell^-$ channel:





→ Smaller branching fractions than the SM predictions?

→ Results dominated by statistical uncertainties (including the BR of the normalization channels)

→ Caveat: theory affected by hadronic uncertainties (LQCD +LCSR)

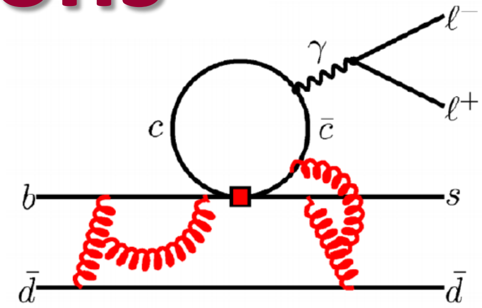
→ And what about the charm resonances contribution?

Branching fractions

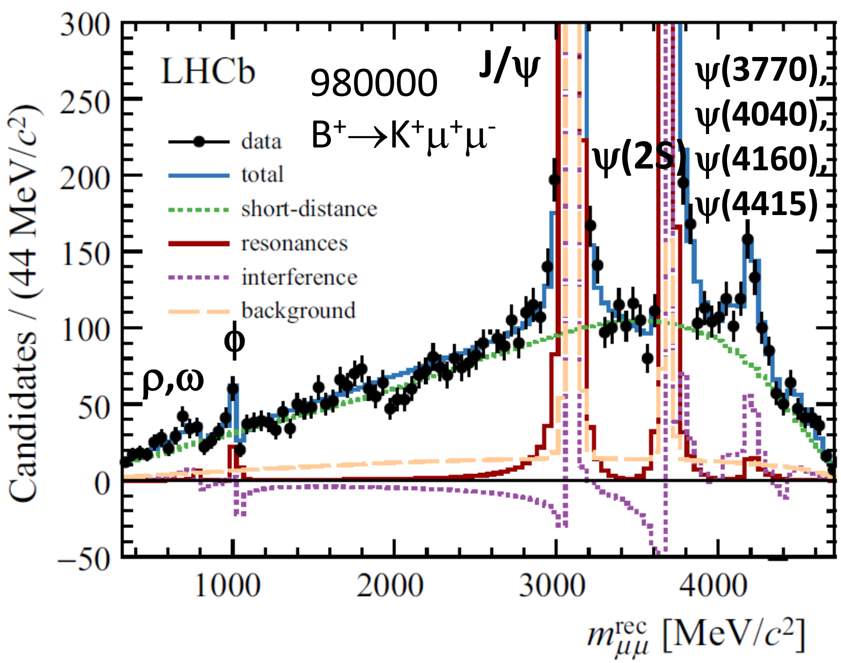
Understanding effects from charm at LHCb:

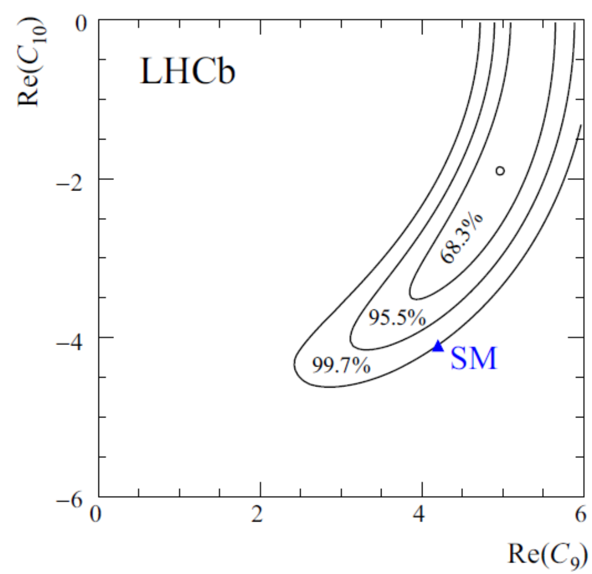
• Phase difference between short- and long-distance amplitudes in the $B^+ \to K^+\mu^+\mu^-$ decay **LHCb, [EPJ C(2017) 77]**

→ $d\Gamma/dm_{\mu\mu}$ is a function of form factors and $\mathbf{C_i}$
→ $\mathbf{C_i^{eff}}$ expressed as a sum of relativistic Breit-Wigner amplitudes: **magnitudes and phases extracted from data**
→ Form factors from FNAL & MILC [PRD 93(2016)025026]



$$\mathcal{C}_9^{\rm eff} = \mathcal{C}_9 + \sum_j \eta_j e^{i\delta_j} A_j^{\rm res}(q^2)$$

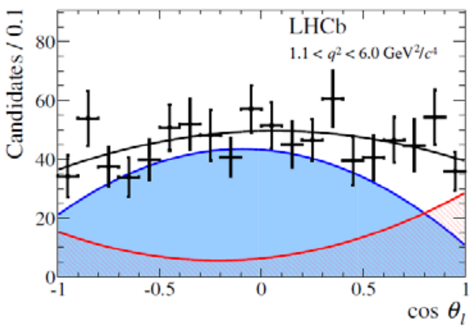


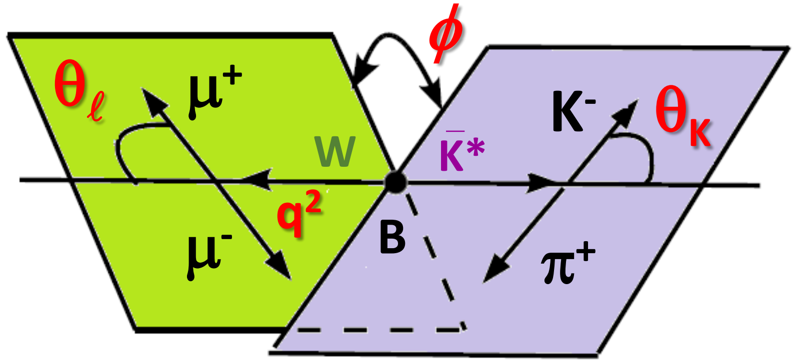


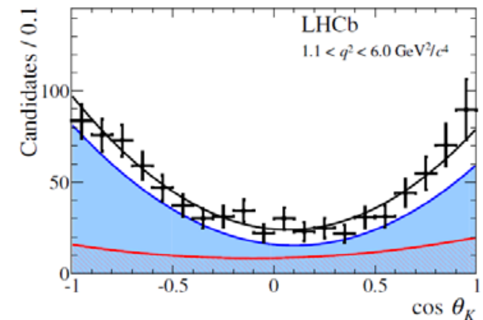
→ **Small effect of hadronic resonances in Wilson coefficients**

Angular analyses

- Angular distribution in B$\rightarrow$ K*$\ell^-\ell^+$: q^2 and three angles







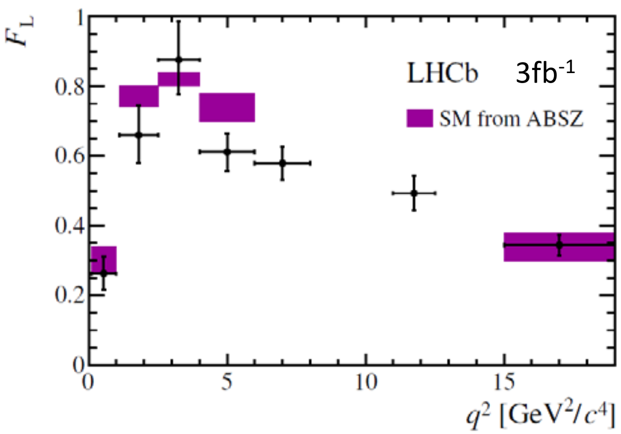
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\ \mathrm{d}\cos\theta_K\ \mathrm{d}\phi\ \mathrm{d}q^2}=\frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K+F_L\cos^2\theta_K+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$-F_L\cos^2\theta_K\cos 2\theta_\ell+S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+S_5\sin 2\theta_K\sin\theta_\ell\cos\phi+S_6\sin^2\theta_K\cos\theta_\ell+S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi+S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

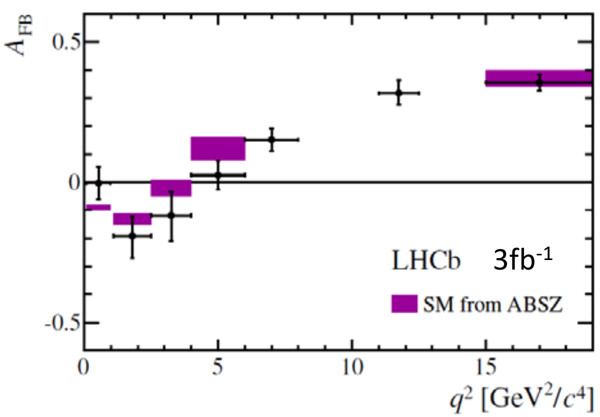
$\rightarrow$ In the lepton massless limit there are **eight** independent observables:

F_L = fraction of the longitudinal polarization of the K*
S_6 = 4/3 A_{FB}, the forward-backward asymmetry of the dimuon system
$S_{3,4,5,7,8,9}$ are the remaining CP-averaged observables

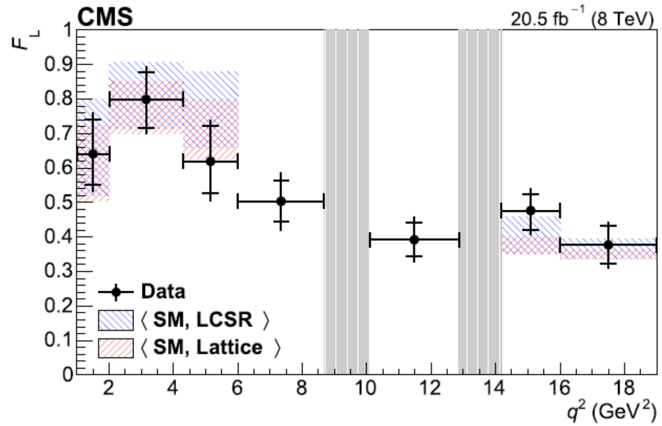
Angular analyses

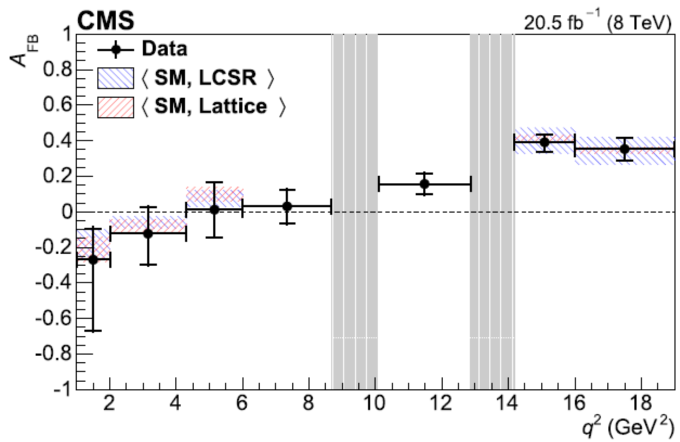
LHCb
[JHEP02(2016)104]



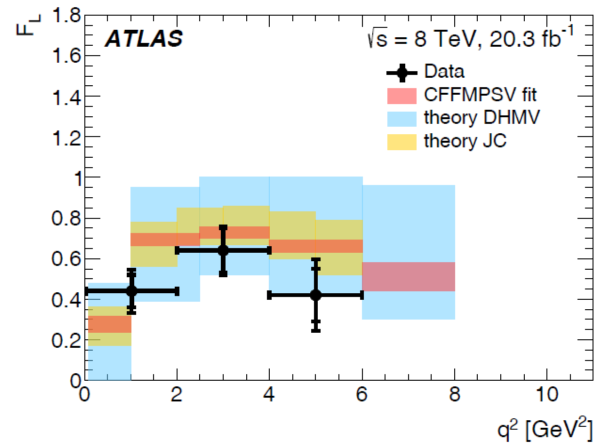


CMS
[PLB 753 (2016) 424]





ATLAS
[arXiv:1805.04000]



SM predictions based on
[Altmannshofer & Straub, EPJC 75 (2015) 382]
[LCSR f.f. from Bharucha, Straub & Zwicky, JHEP 08 (2016) 98]
[Lattice f.f. from Horgan, Liu, Meinel & Wingate arXiv:1501.00367]

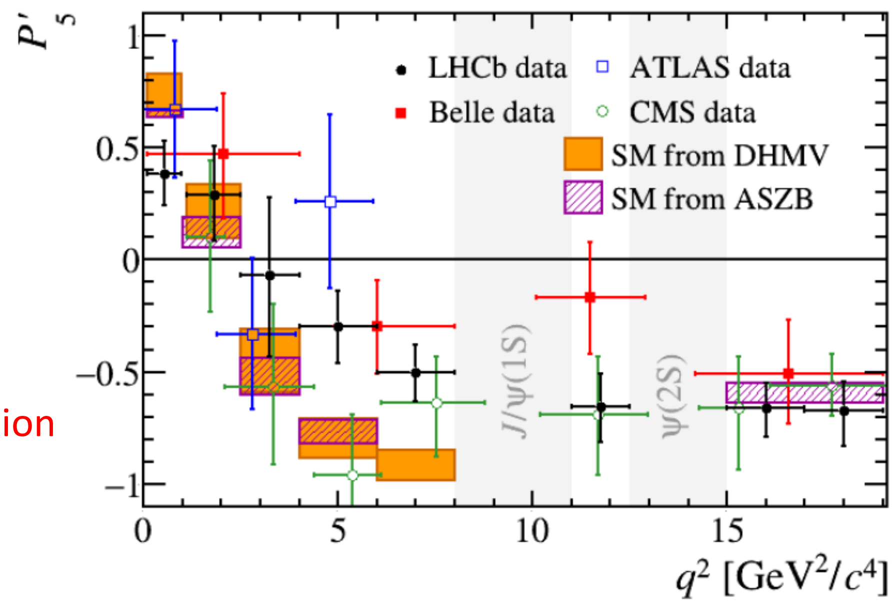
Angular analyses

- These observables are also affected by hadronic uncertainties
- A new set of "optimized observables", with form factor cancellations can be defined: [Descotes-Genon et al, JHEP 05 (2013) 137]

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

- These observable are functions of q^2 and the Wilson coefficients $\mathbf{C_i}$

Example: P'_5



3σ local deviation

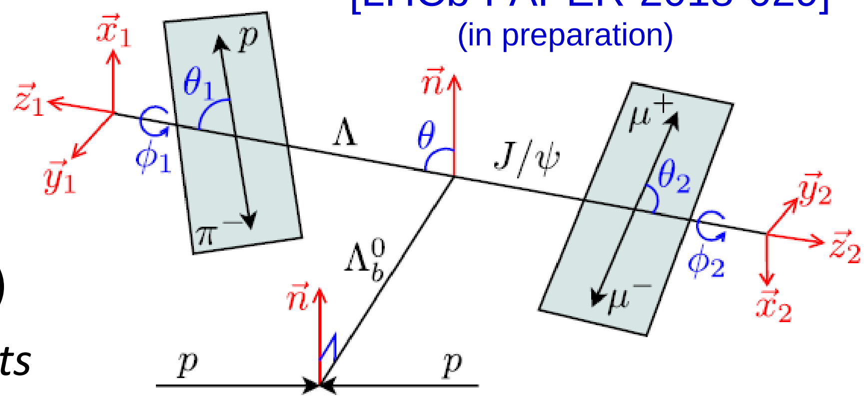
- JHEP 02 (2016) 104
- PRL 118 (2017) 111801
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

Angular analyses

→ **New**: results from **LHCb** in the $\Lambda_b \to \Lambda\mu^+\mu^-$ decay channel **Run1 + Run2 data: 5fb^{-1}**

[LHCb-PAPER-2018-029]
(in preparation)

$$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2}\sum_i^{34} K_i(q^2) f_i(\vec{\Omega})$$

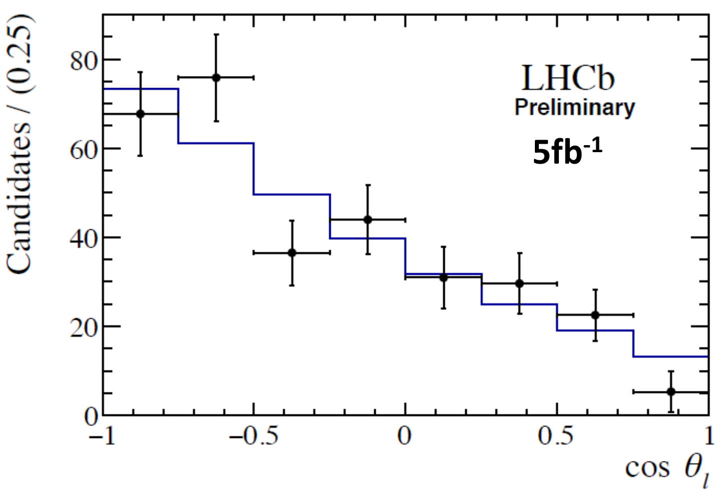


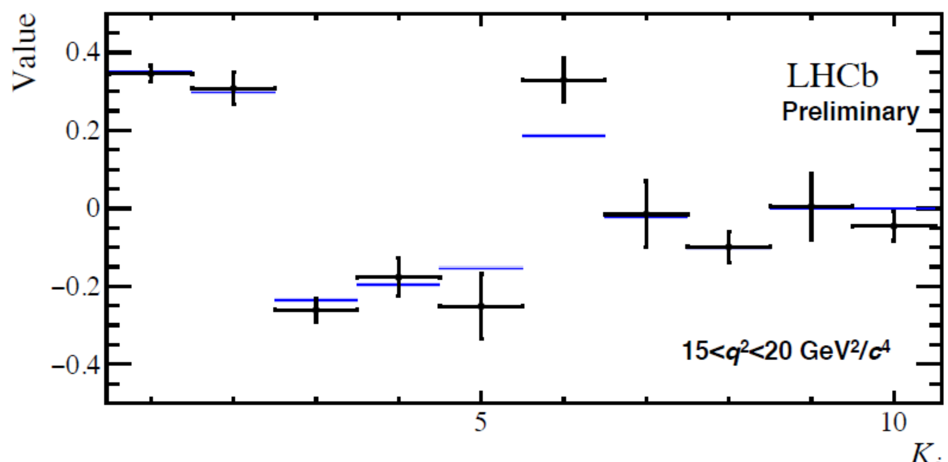
5 angles and 1 normal vector $\vec{n}$

Depends on many observables (K_i)

Obtained from *method of moments*

$15 < q^2 < 20\,\mathrm{GeV}^2$





In general compatible with SM predictions
[Boër et al, JHEP 01 (2015) 155],
[Detmold et al. Phys.Rev. D93 (2016) 074501]

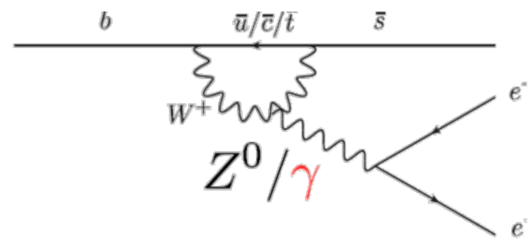
Angular analyses

- What about electrons? (sensitive to $C_7^{(\prime)}$)

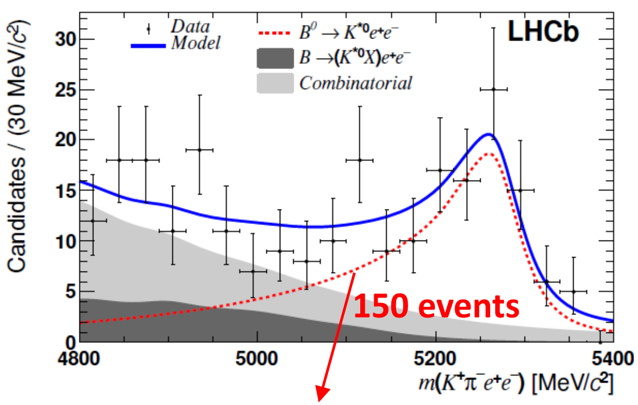
Angular observables of the $B^0 \to K^* e^- e^+$ at **LHCb** in the low $q^2 <$ 1GeV^2

→ Virtual γ decaying in an observable $\ell^- \ell^+$ pair

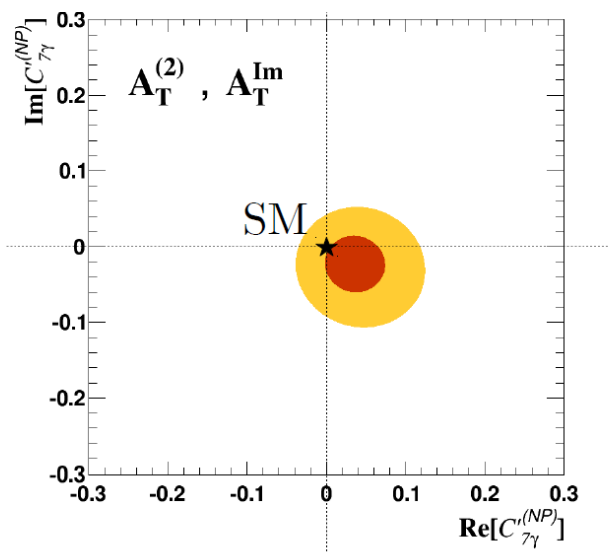
→ Requires to go very low in the q^2 region

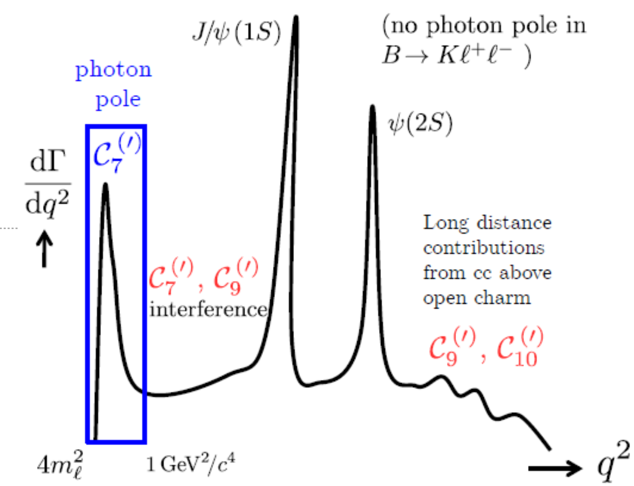


[JHEP04(2015)064] **(3fb^{-1})**



Long radiative tail in the B mass distribution: controlled from $B \to K^*\gamma$ events ($\gamma \to e^- e^+$, with bremsstrahlung emission)





→ **Compatible with the SM predictions***

[Adapted from Jäger and Camalich arXiv:1412.3183]

*leading order estimation, 5% accuracy for SM value

Lepton Flavour Universality

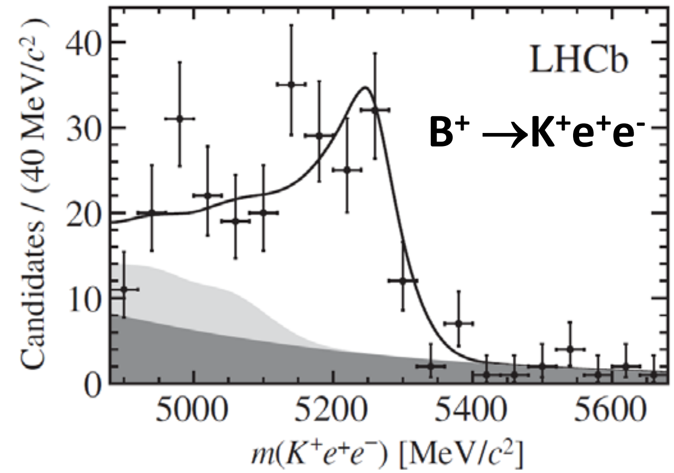
- In the SM all leptons are expected to behave in the same way:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 1.000 + O(m_\mu^2/m_b^2) \text{ (SM)}$$

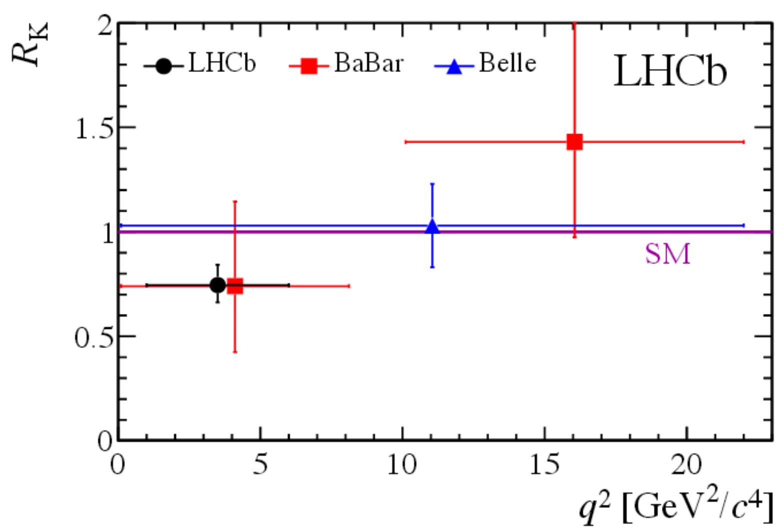
[PRL 113 (2014) 151601]

- Experimentally, use the $B^+ \to K^+ J/\psi(\to e^+e^-)$ and $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ to perform a double ratio

- Precise theory prediction due to cancellation of hadronic form factor uncertainties



1 GeV < q^2 < 6 GeV



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

→ Consistent, but lower, than the SM at **2.6σ**

Lepton Flavour Universality

- Measurement in the $B \to K^* \mu^+ \mu^-$ channel, R_{K^*}:

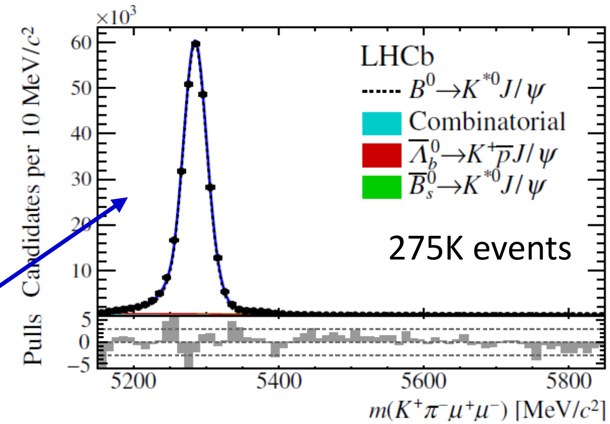
LHCb, JHEP08(2017)055

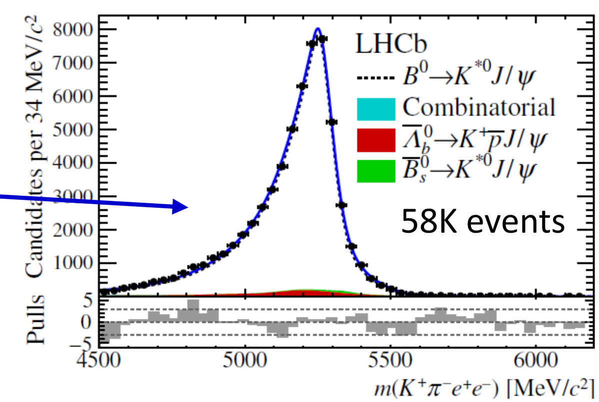
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$

- Precise theoretical calculations due to the cancellation of form factors

- Double ratio using J/ψ modes to cancel systematics:

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





- Several trigger categories with different efficiencies

- Blinded analysis, many checks performed before unblinding:

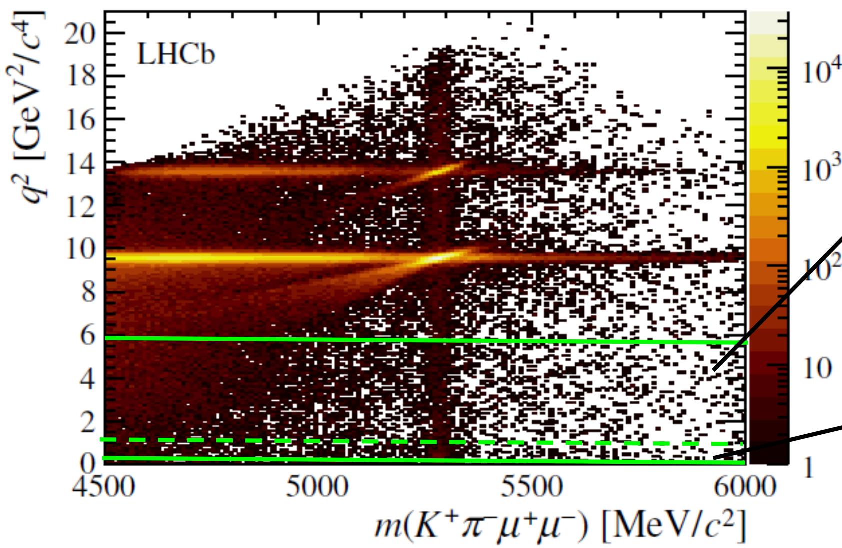
  → $r_{J/\psi}$ = $\mathcal{B}(B \to K^* J/\psi(\to \mu^+\mu))/\mathcal{B}(B \to K^* J/\psi(\to e^+e^-))$=1.04 (0.05)
  → $R\psi_{(2S)}$ = muon/electron ratio for $\mathcal{B}(B \to K^* \psi(2s)/\mathcal{B}(B \to K^* J/\psi)$ = 1 (0.02)
  → $\mathcal{B}(B \to K^* \mu^+\mu^-)$ ✓; $\mathcal{B}(B \to K^* \gamma (\to e^+e^-))$ ✓

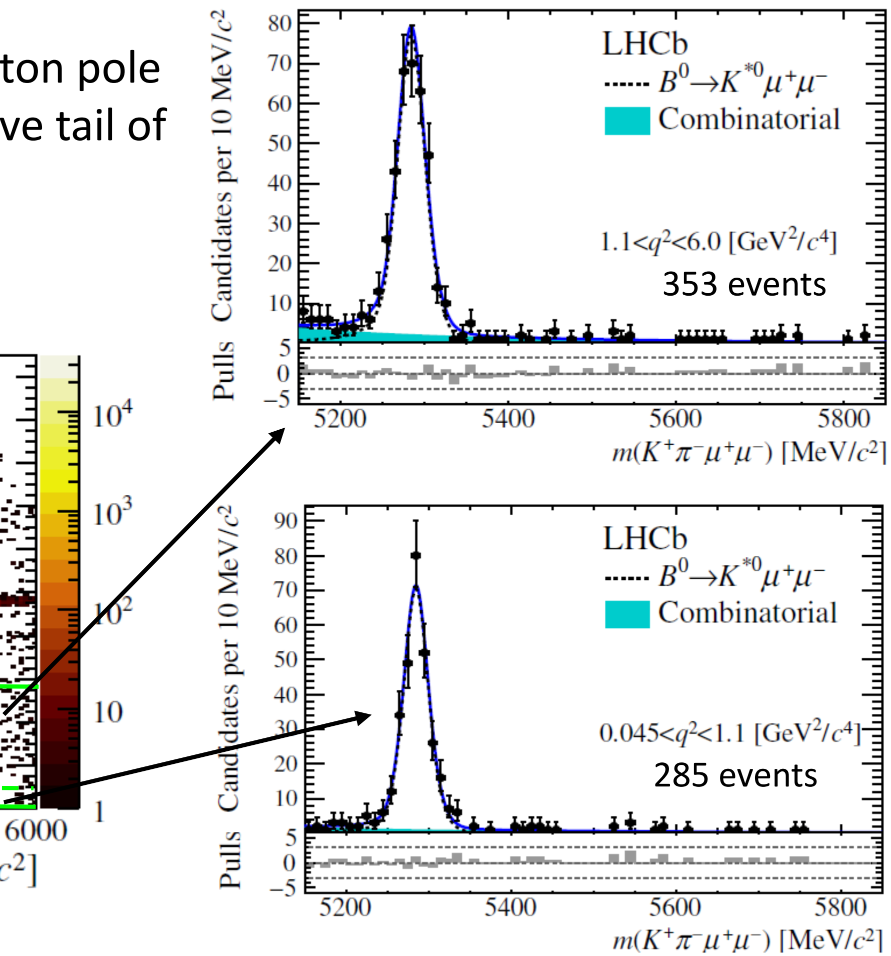
Lepton Flavour Universality

LHCb, JHEP08(2017)055

- Computed in two bins of q^2
  - [0.045, 1.1 GeV^2] avoiding the photon pole
  - [1.1, 6.0 GeV^2] avoiding the radiative tail of J/ψ modes

- Decay mode with muons:



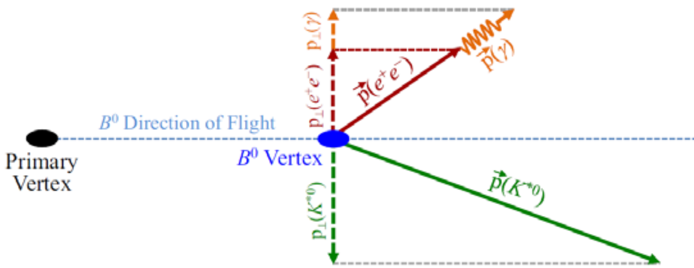


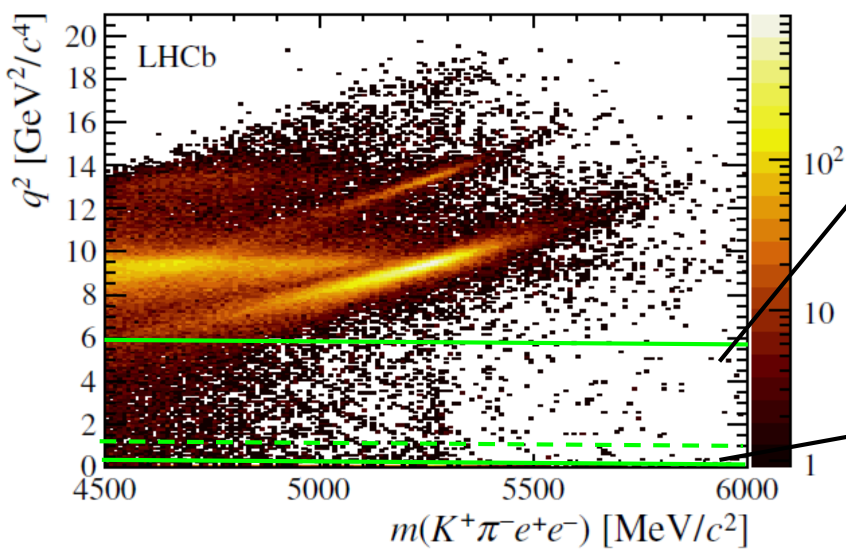
Lepton Flavour Universality

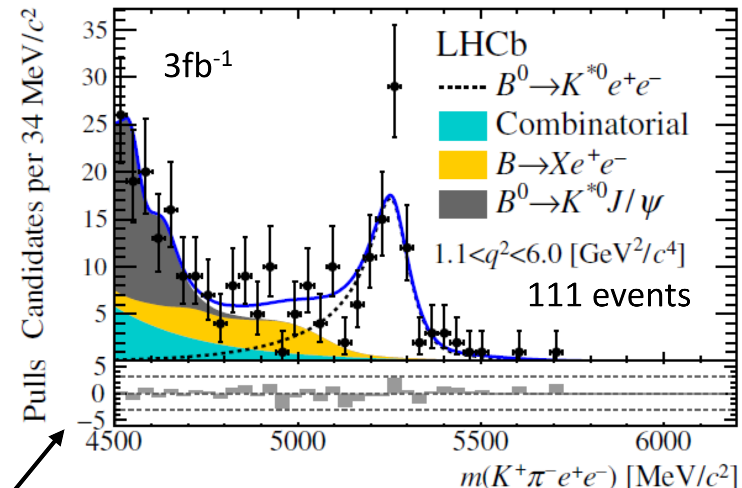
- Decay mode with electrons:

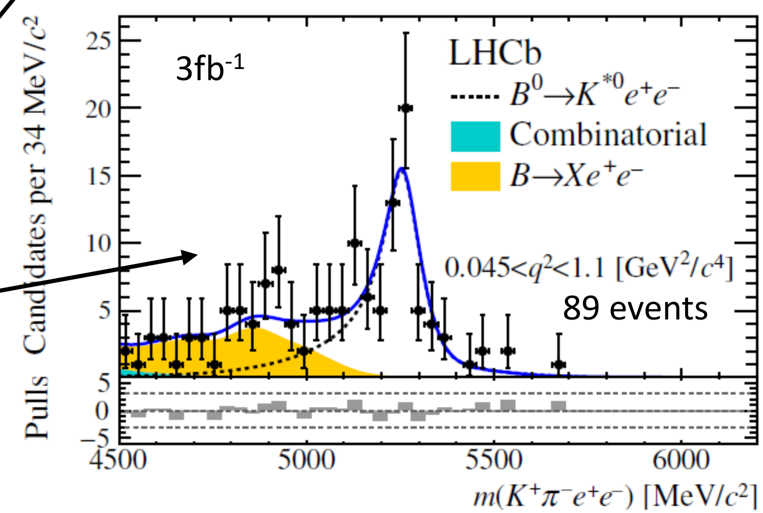
LHCb, JHEP08(2017)055

exploiting kinematics in case of unrecovered bremsstrahlung photons





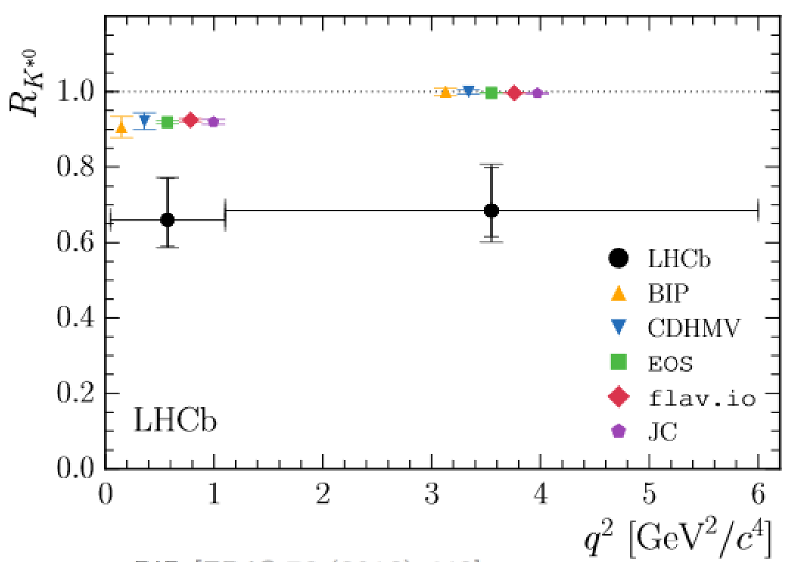


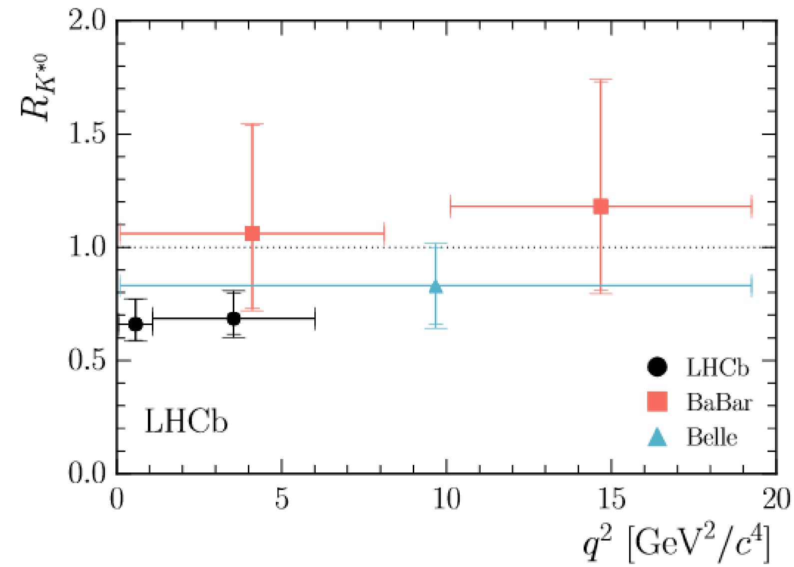


Lepton Flavour Universality

- Results:

LHCb, JHEP08(2017)055





▲ BIP [EPJC 76 (2016) 440]
▼ CDHMV [JHEP 04 (2017) 016]
■ EOS [PRD 95 (2017) 035029]
◆ flav.io [EPJC 77 (2017) 377]
⬟ JC [PRD 93 (2016) 014028]

● LHCb [PRL 113 (2014) 151601]
▲ Belle [PRL 103 (2009) 171801]
■ BaBar [PRD 86 (2012) 032012]

Low q^2 [0.045-1.1 GeV^2]: SM▼ = 0.922(22)

$$R_{K^{*0}} = 0.66 \,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst})$$

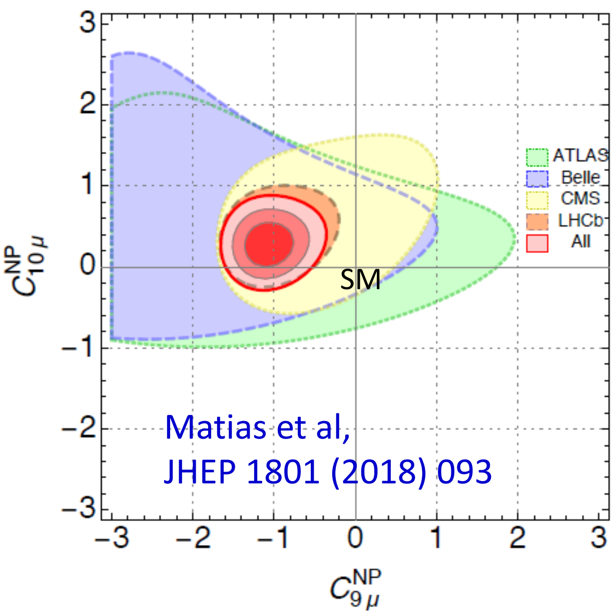
Central q^2: [1.1-6 GeV^2]: SM▼ = 1.000(6)

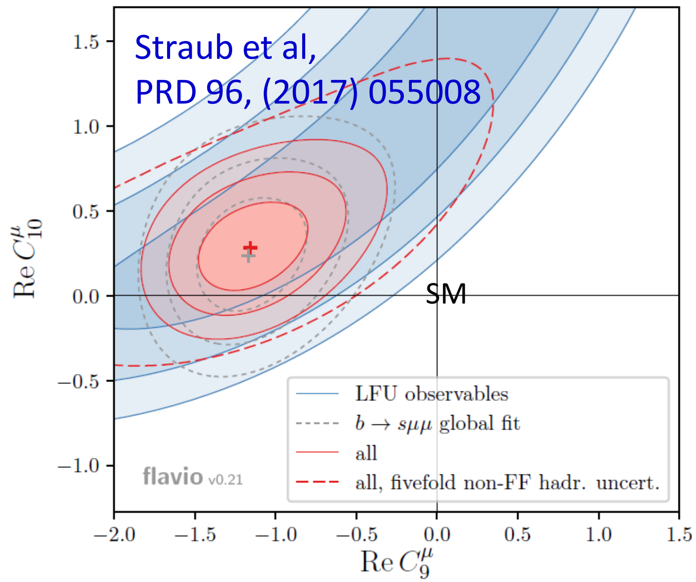
$$R_{K^{*0}} = 0.69 \,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst})$$

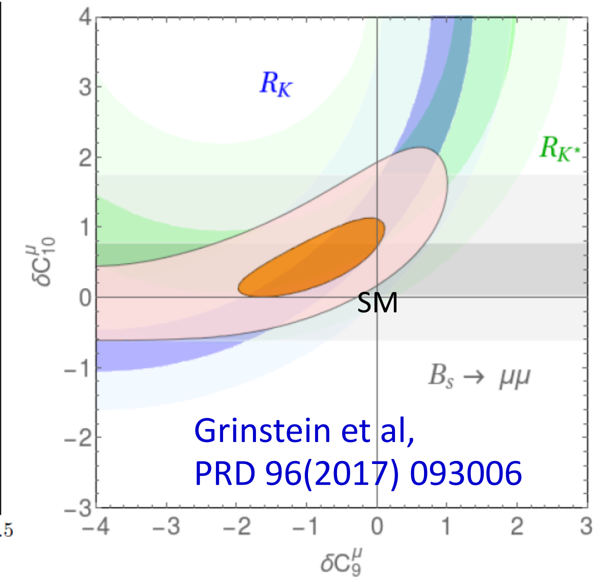
→ Consistent, but lower than the SM at **2.1-2.3σ** (low q^2) and **2.4-2.5σ** (central q^2)

Interpretation

- Global fits (some cases with more than 100 observables)







New Physics hypothesis preferred over SM by more than 4 - 5σ
Main effect on the $C_{9\mu}$ coefficient: **4.27^{SM}** **-1.1^{NP}**

Triggered models with Z', leptoquarks (LQ), and composite Higgs

Conclusions

• Measurements on rare $b \to s \ell\ell$ decays present a consistent pattern of anomalies in some observables, observed by several experiments:

* **Differential branching fractions:** $B^0 \to K^{(*)0}\mu^+\mu^-$, $B^+ \to K^{(*)+}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, and $\Lambda_b \to \Lambda\mu^+\mu^-$
* **Angular analyses:** $B^0 \to K^{(*)0}\mu^+\mu^-$, $B^0 \to K^{*0}e^+e^-$ and $\Lambda_b \to \Lambda\mu^+\mu^-$
* **Test of Lepton Flavour Universality:** $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$

• Particular interest is in ratios testing LFV since they are not affected by hadronic uncertainties

• These deviations from SM predictions point to new physics in the Wilson coefficient $C_{9\mu}$, affecting differently to lepton families.

$\to$ **Difficult to be explained by just experimental effects.**

$\to$ **Difficult to be explained by just QCD effects…**

• Most of results here are from Run1 and are limited by statistics… measurements on Run2 data ongoing!

Thanks !