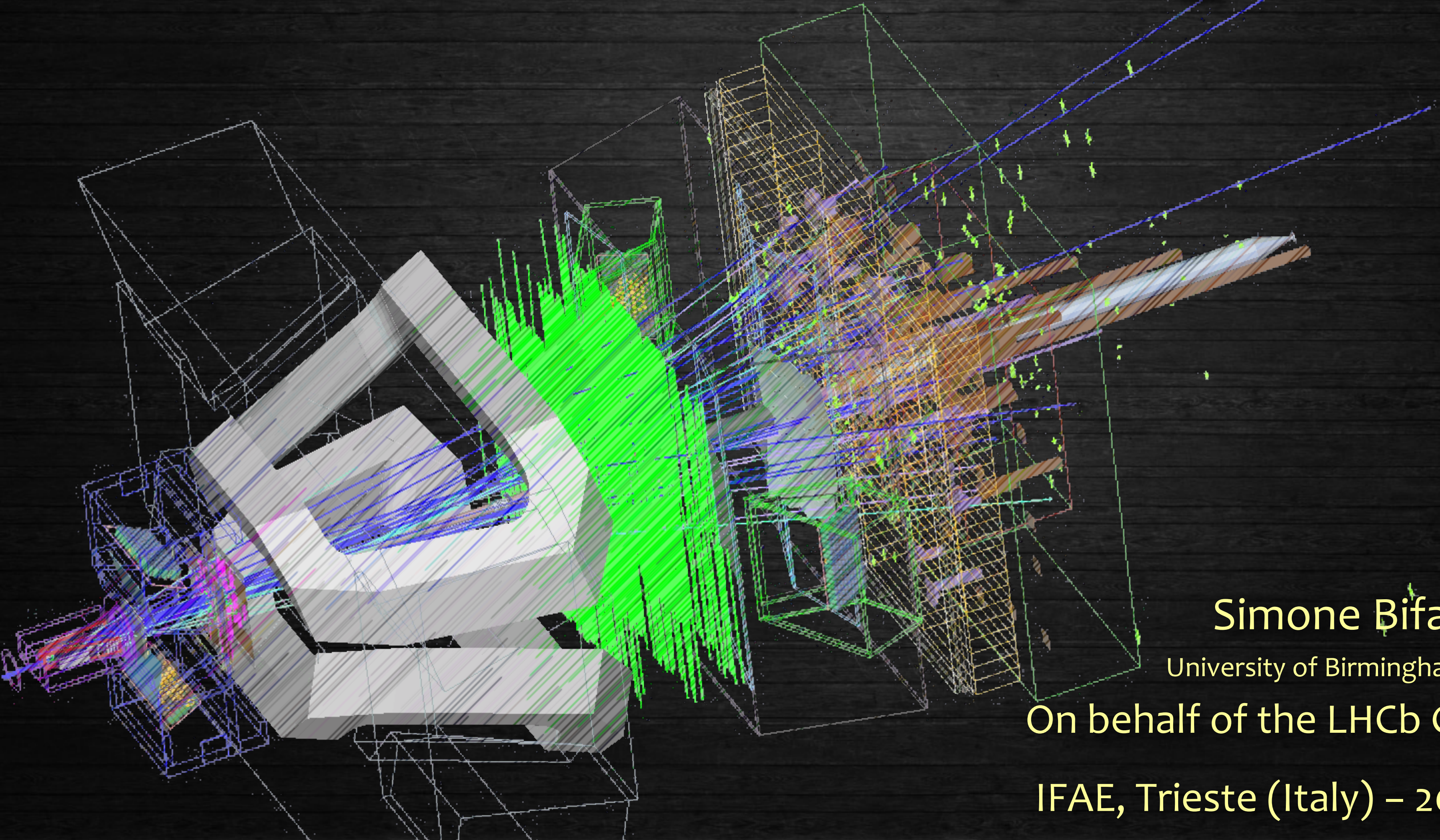
Search for New Physics with $b \to sll$ decays @ LHCb

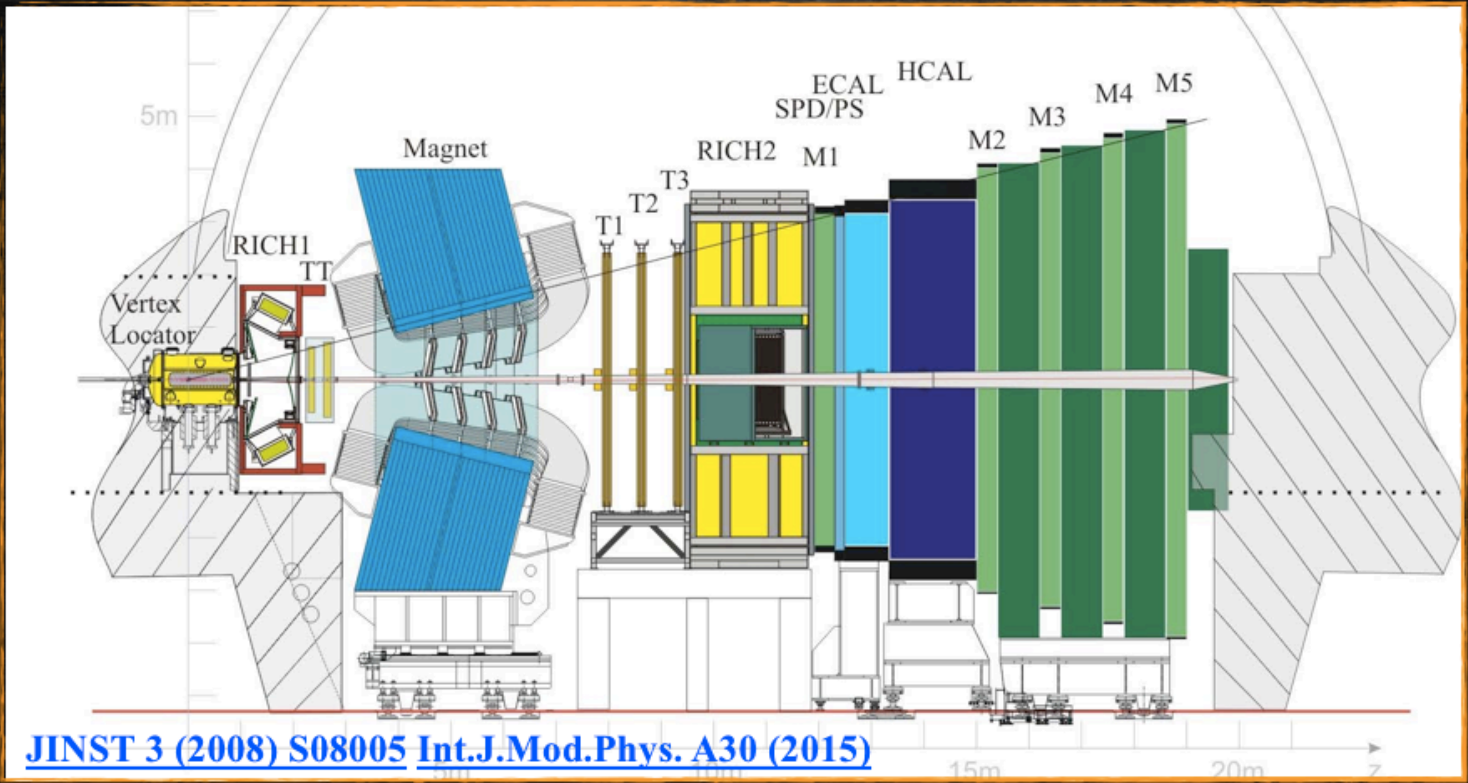


Simone Bifani
University of Birmingham (UK)
On behalf of the LHCb Collaboration

IFAE, Trieste (Italy) – 20^{th} April 2017

A Forward Spectrometer

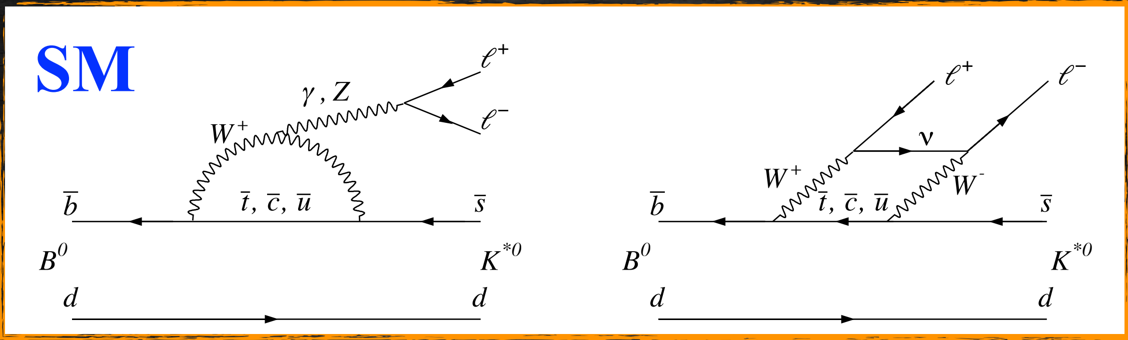
- Optimized for beauty and charm physics at large pseudorapidity ($2<\eta<5$)
  - **Trigger**: >95% (60-70%) efficient for muons (electrons)
  - **Tracking**: σ_p/p 0.4%–0.6% (p from 5 to 100 GeV), $\sigma_{IP} < 20\ \mu m$
  - **Calorimeter**: $\sigma_E/E \sim 10\% / \sqrt{E} \oplus 1\%$
  - **PID**: 97% μ,e ID for 1–3% $\pi\rightarrow\mu$,e misID



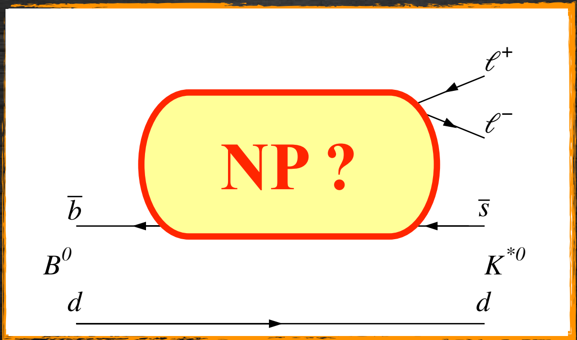
JINST 3 (2008) S08005 Int.J.Mod.Phys. A30 (2015)

Why Rare b Decays?

- b→sll decays proceed via **FCNC transitions** that only occur at loop order (or beyond) in the SM



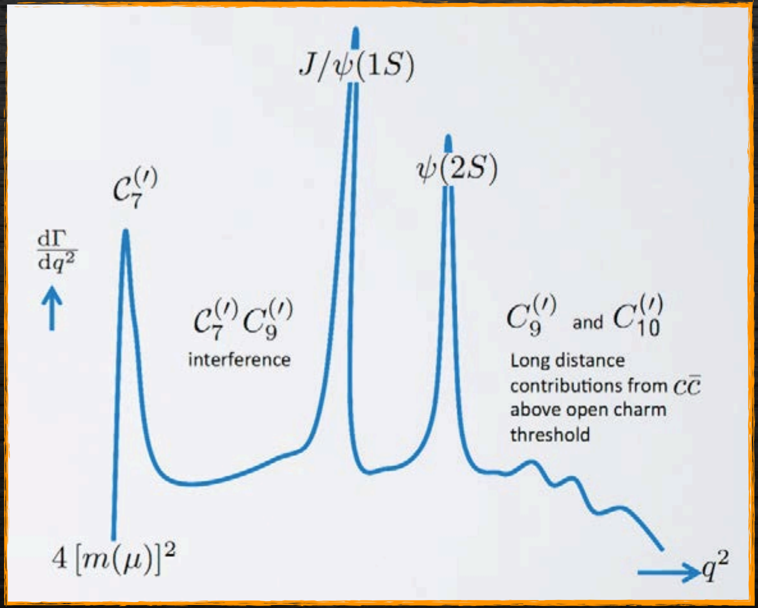
- New particles can for example contribute to loop or tree level diagrams by enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of the final-state particles



- **Rare b decays place strong constraints on many NP models by probing energy scales higher than direct searches**

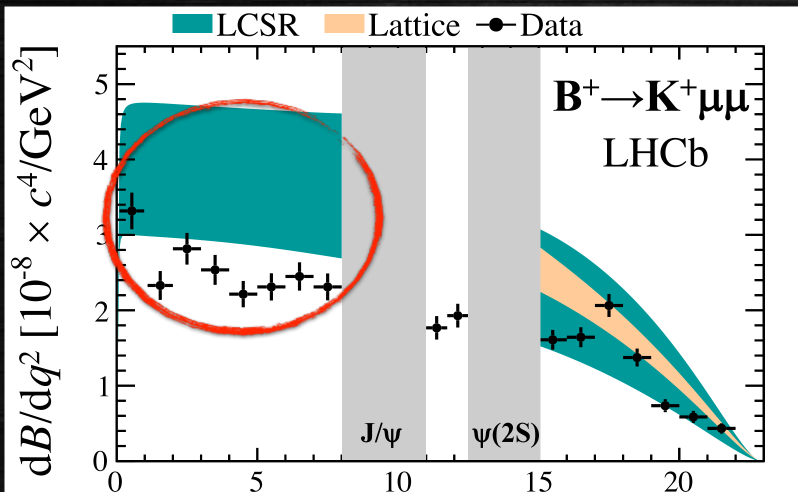
Shopping List

- **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 $\Lambda_b \to \Lambda\mu\mu$
  - » Presence of 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 smaller theory uncertainties
- **Test of Lepton Flavour Universality** in $B^+ \to K^+ll$ and $B^0 \to K^{*0}ll$
  - » Cancellation of hadronic uncertainties in theory predictions

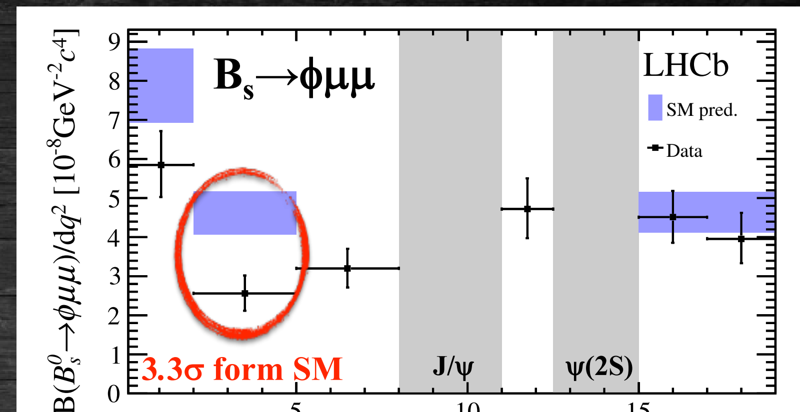


Differential Branching Fractions

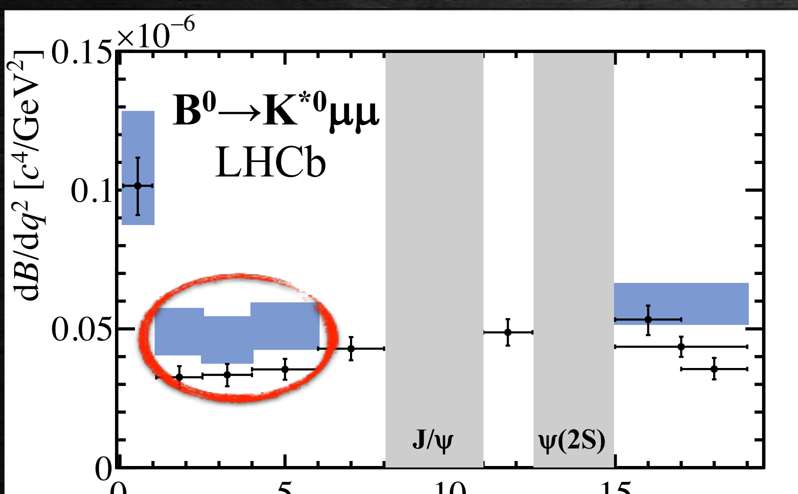
› Results **consistently lower than SM predictions**



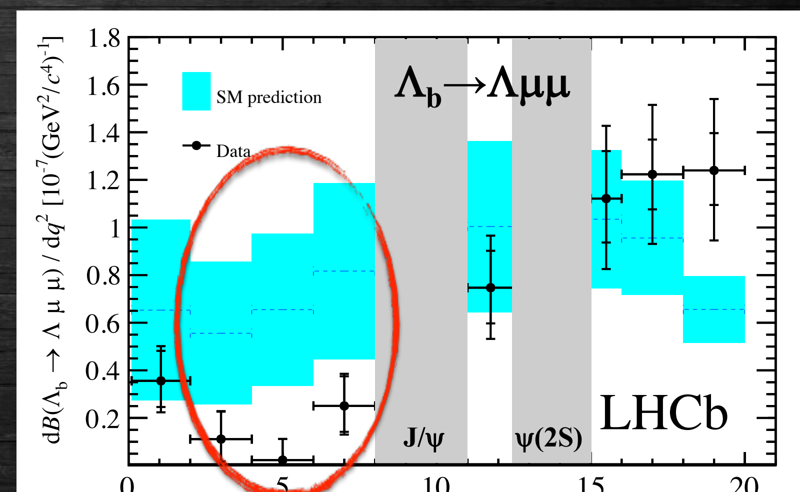
JHEP 06 (2014) 133



JHEP 09 (2015) 179



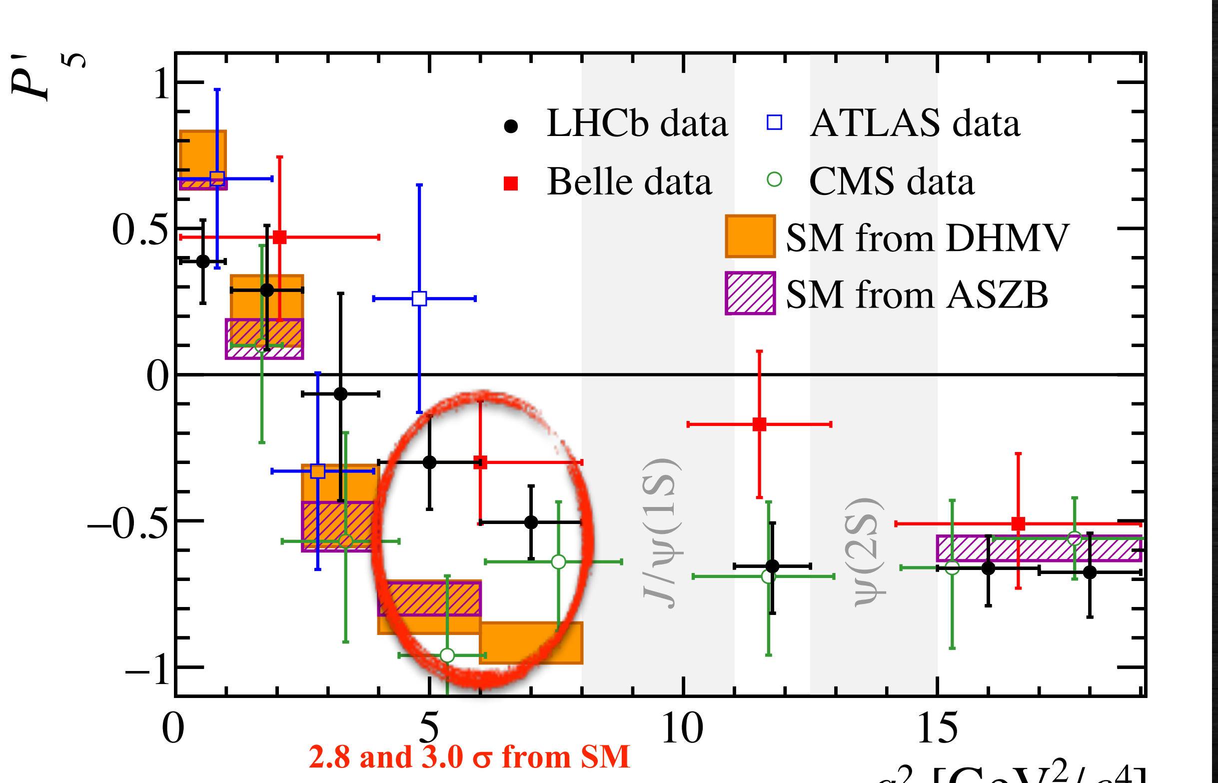
arXiv:1606.04731



JHEP 06 (2015) 115

Angular Analyses

- First **full angular analysis** of $B^0 \to K^{*0}\mu\mu$: measured all CP-averaged angular terms and CP-asymmetries
- Can construct **less form-factor dependent ratios of observables**

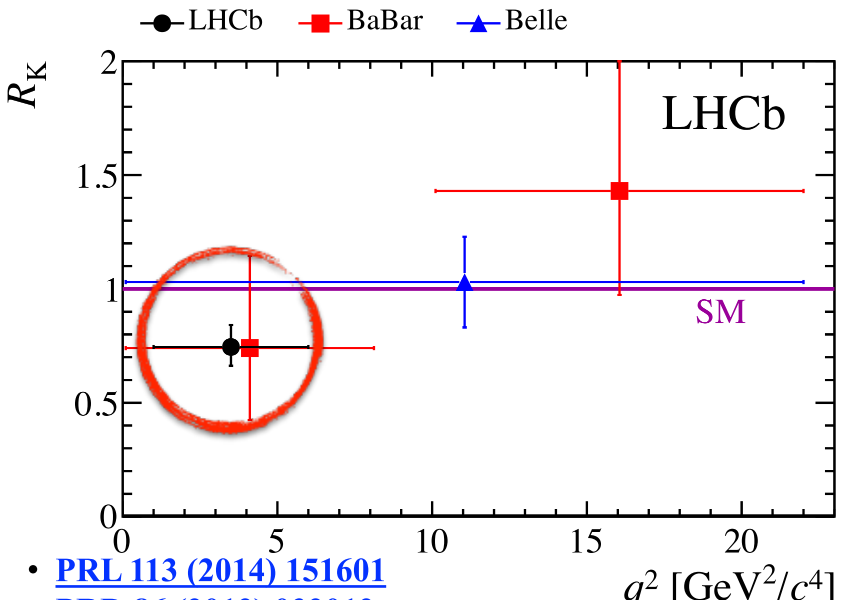


- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

Lepton Flavour Universality

› LHCb tested Lepton Flavour Universality using **$B^+ \to K^+ll$** decays and observed a **tension with the SM at 2.6σ**

$$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\to e^+e^-))}$$



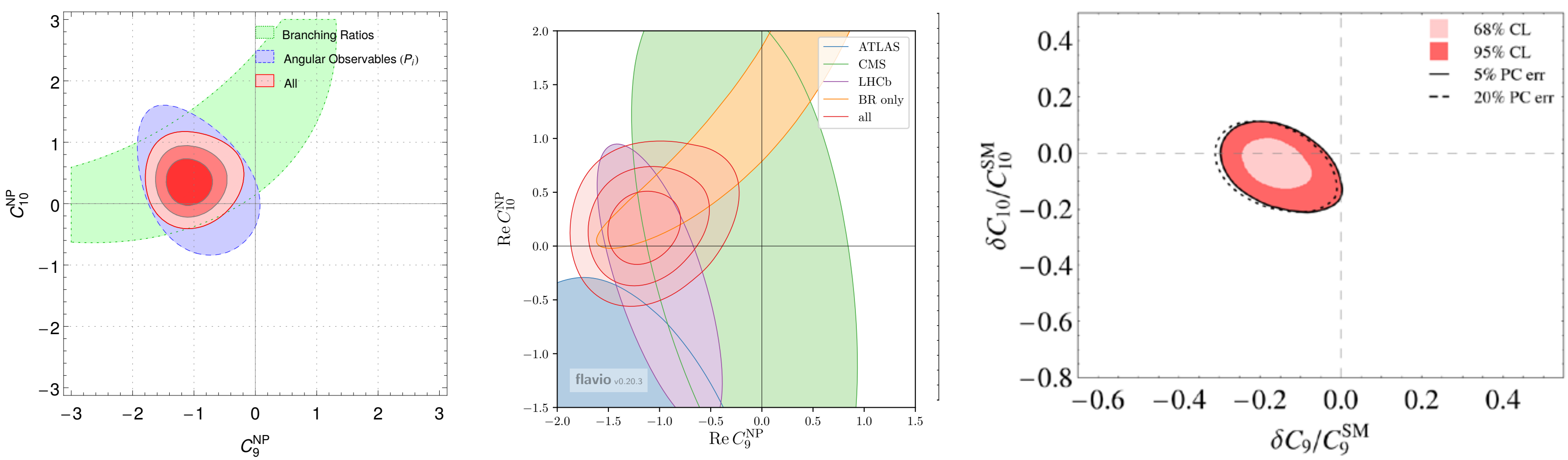
- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

› Consistent with observed BR($B^+ \to K^+\mu\mu$) if NP does not couple to electrons

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

Global Fits

- Several attempts to interpret results by performing **global fits to data**

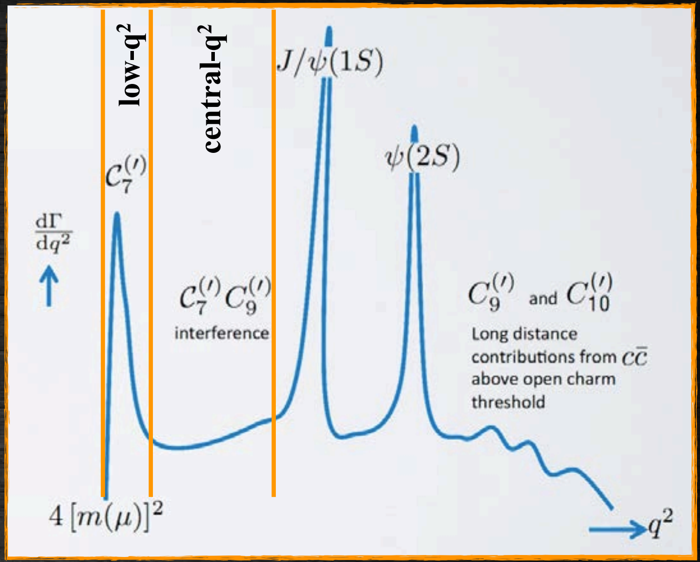


arXiv:1510.04239 arXiv:1703.09189 arXiv:1611.05060

- Take into account ~90 observables from different experiments, including $B\to\mu\mu$ and $b\to sll$ 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 the understanding of QCD?**
  (e.g. correctly estimating the contribution from charm loops?)

$R_{K^{*0}}$

› Test of LFU with **$B^0 \to K^{*0}\mu\mu$** and **$B^0 \to K^{*0}ee$**



› **Two regions of q^2**

» Low [0.045-1.1] GeV^2/c^4

» Central [1.1-6.0] GeV^2/c^4

› Measured relative to **$B^0 \to K^{*0} J/\psi(ll)$** in order to reduce systematics

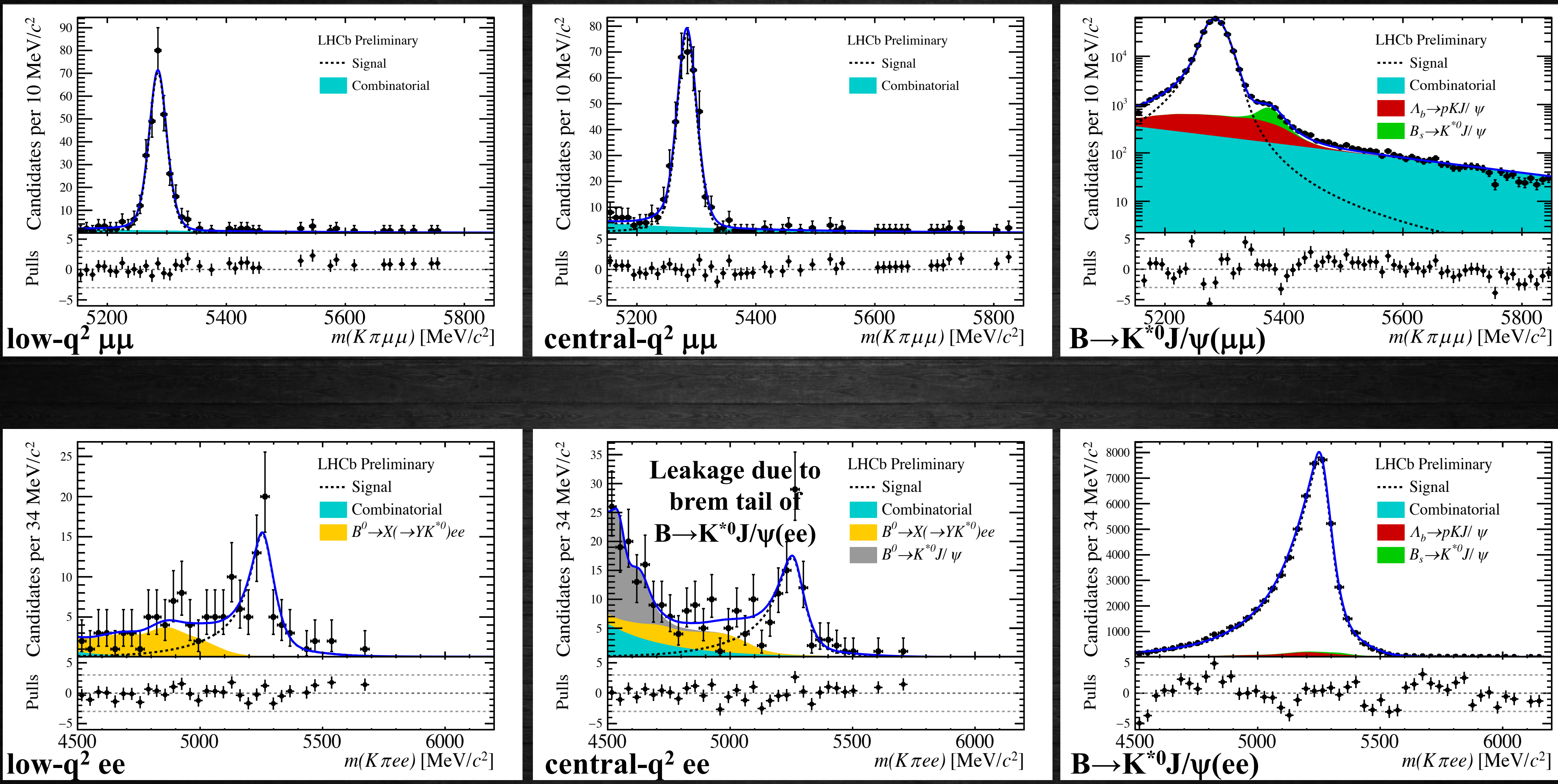
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

› K^{*0} reconstructed as **$K^+\pi^-$** within 100MeV from the $K^*(892)^0$

› **Blind analysis** to avoid experimental biases

› Extremely challenging due to significant differences in the way muons and electrons "interact" with the detector (bremsstrahlung and trigger)

Fit Results



› In total, about 290 (90) and 350 (110) $B^0 \to K^{*0}\mu\mu$ ($B^0 \to K^{*0}ee$) candidates at low- and central-q^2, respectively

Systematics

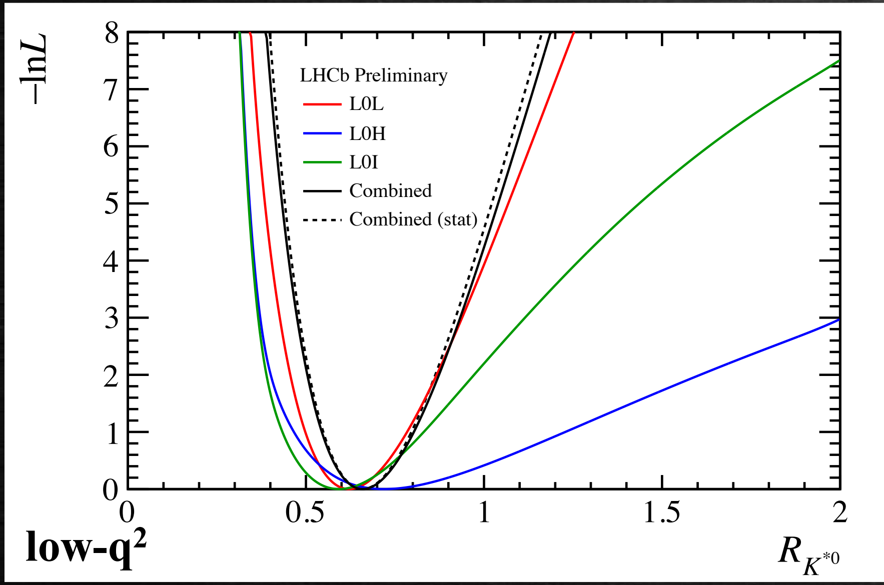
- $R_{K^{*0}}$ **determined as a double ratio**
  - Many experimental systematic effects cancel
  - Statistically dominated (~15%)

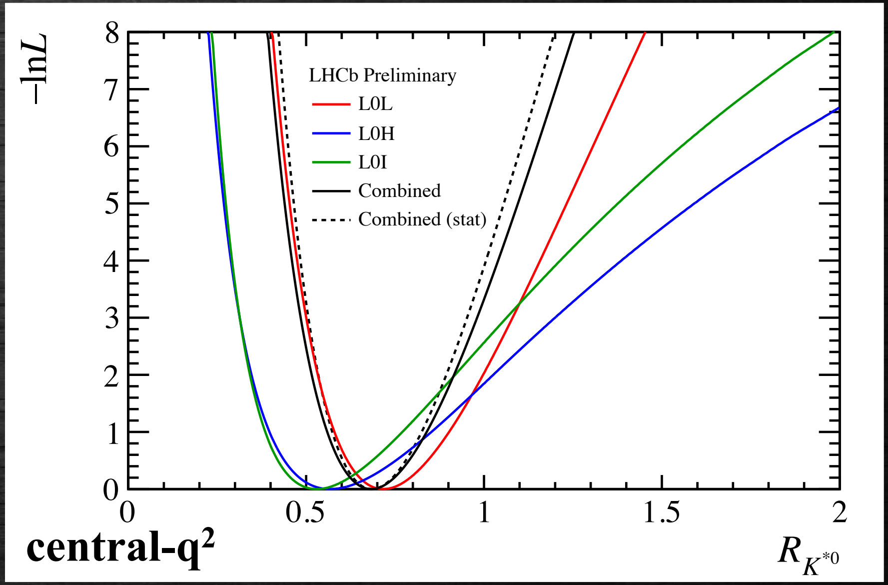
	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ **flatness**	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

- Total systematic uncertainty of 4-6% and 6-8% in the low- and central-q^2

Results – I

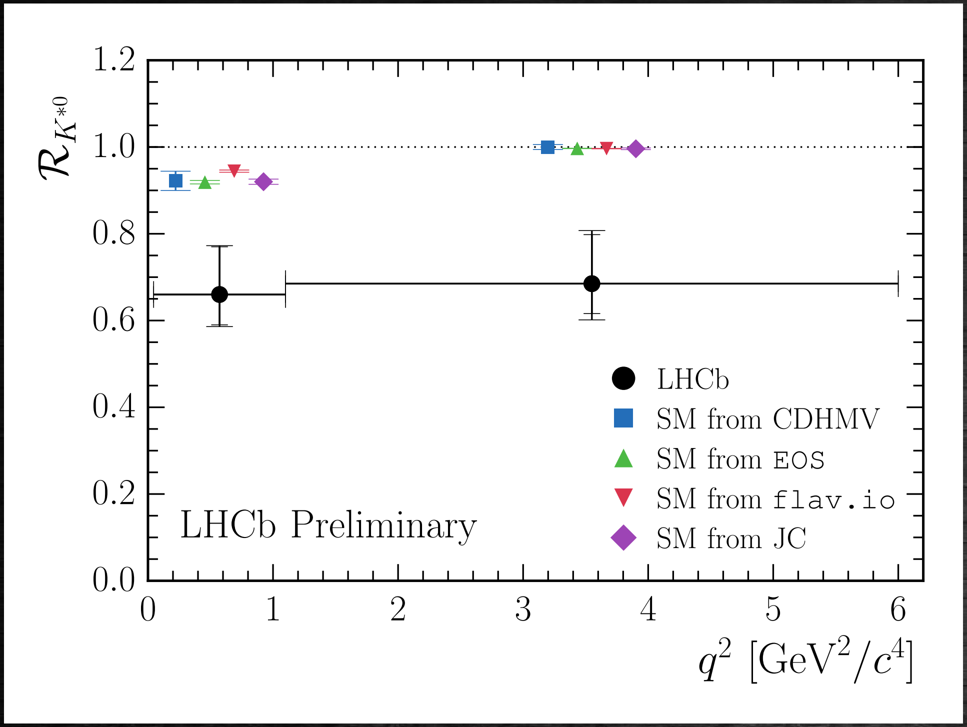
LHCb Preliminary	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\ 0.110}_{-\ 0.070} \pm 0.024$	$0.685\ ^{+\ 0.113}_{-\ 0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]

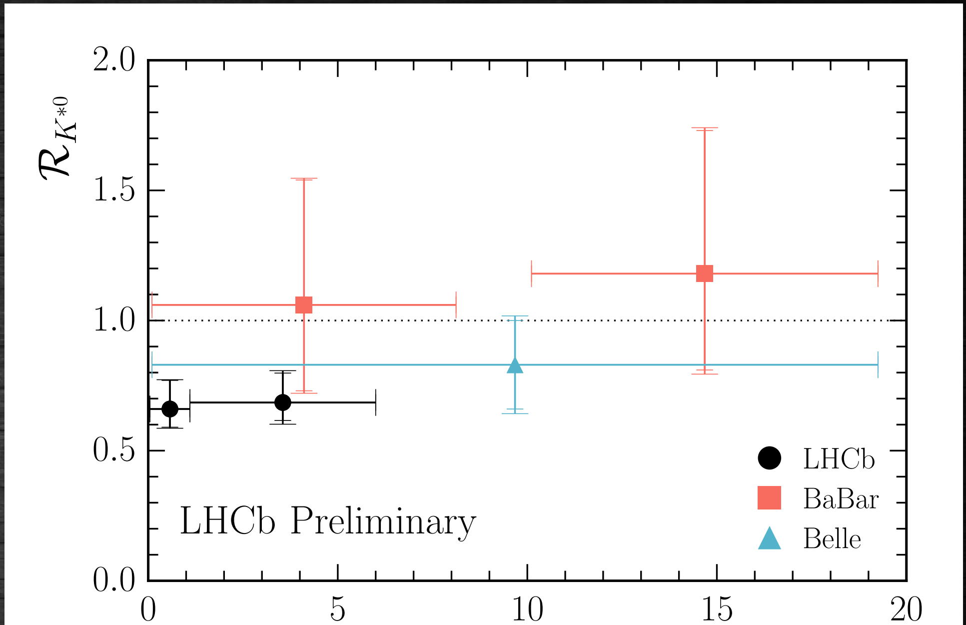




› The measured values of $R_{K^{*0}}$ are found to be in good agreement among the three trigger categories in both q^2 regions

Results – II





- [PRD 86 (2012) 032012](#)
- [PRL 103 (2009) 171801](#)

› The compatibility of the result in the **low-q²** with respect to the SM prediction(s) is of **2.2-2.4** standard deviations

› The compatibility of the result in the **central-q²** with respect to the SM prediction(s) is of **2.4-2.5** standard deviations

The Day After…

Patterns of New Physics in $b \to s\ell^+\ell^-$ transitions in the light of recent data

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(Dated: April 19, 2017)

The $b \to s\ell^+\ell^-$ processes observed by the LHCb collaboration at 1 and 3 fb^{-1} have exhibited a coherent set of deviations from the Standard Model (SM) predictions, i.e., anomalies, most remarkably in the angular analysis of the $B \to K^*\mu^+\mu^-$ decay and in the Lepton Flavour Universality (LFU) violating ratios R_K and (very recently) R_{K^*}. All these anomalies are analysed consistently by fitting the Wilson coefficients of effective operators which encode the short-distance contributions to $b \to s\ell^+\ell^-$ transitions, pointing towards specific patterns of New Physics (NP). We include recent data presented by LHCb, CMS, ATLAS and Belle in our framework, finding several hypotheses with NP in one and two Wilson coefficients preferred at the 5 σ level compared to the SM. One of the most prominent patterns consist of large contributions to the coefficients $\mathcal{C}_{9\mu}$ ($\mathcal{C}_{10\mu}$) involving a left-handed quark current and a vector (axial) muon current while the effect in electrons is small, confirming the indications for LFU violation. We also perform an analysis allowing for New Physics in six Wilson coefficients (SM-like and chirally flipped), obtaining a pull for the SM at the level of 5 σ. Dedicated fits restricted to LFU-violating observables are also presented. We find that LFU violation is favoured with respect to LFU at 3.3σ level in the case of NP contributions to $\mathcal{C}$… and $\mathcal{C}_{9\mu}$. Finally, we consider the implications of the… possible correlations to the LFU-violating ratios…

arXiv:1704.05340

Interpreting Hints for Lepton Flavor Universality Violation

Wolfgang Altmannshofer,[1,*] Peter Stangl,[2,†] and David M. Straub[2,‡]

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[2] *Excellence Cluster Universe, Boltzmannstr. 2, 85748 Garching, Germany*

We interpret the recent hints for lepton flavor universality violation in rare B meson decays. Based on a model-independent effective Hamiltonian approach, we determine regions of new physics parameter space that give a good description of the experimental data on R_K and R_{K^*}, which is in tension with Standard Model predictions. We suggest further measurements that can help narrowing down viable new physics explanations. We stress that the measured values of R_K and R_{K^*} are fully compatible with new physics explanations of other anomalies in rare B meson decays based on the $b \to s\mu\mu$ transition. If the hints for lepton flavor universality violation are… perturbative unitarity implies new phenomena be… TeV.

arXiv:1704.05435

R_K and R_{K^*} beyond the Standard Model

Gudrun Hiller[1,*] and Ivan Nišandžić[1,†]

[1] *Institut für Physik, Technische Universität Dortmund, D-44221 Dortmund, Germany*

Measurements of the ratio of $B \to K^*\mu\mu$ to $B \to K^*ee$ branching fractions, R_{K^*}, by the LHCb collaboration strengthen the hints from previous studies with pseudoscalar kaons, R_K, for the breakdown of lepton universality, and therefore the Standard Model (SM), to $\sim 3.5\sigma$. Complementarity between R_K and R_{K^*} allows to pin down the Dirac structure of the new contributions to be predominantly SM-like chiral, with possible admixture of chirality-flipped contributions of up to $\mathcal{O}$(few10%). Scalar and vector leptoquark representations (S_3, V_1, V_3) plus possible $(\tilde{S}_2, V_2)$ admixture can explain R_{K,K^*} via tree level exchange. Flavor models naturally predict leptoquark masses not exceeding a few TeV, with couplings to third generation quarks at $\mathcal{O}(0.1)$, implying that this scenario can be directly tested at the LHC.

arXiv:1704.05444

Towards the discovery of new physics with lepton-universality ratios of $b \to s\ell\ell$ decays

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[2] *Dept. Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0319, USA*
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Tests of lepton-universality as rate ratios in $b \to s\ell\ell$ transitions can be predicted very accurately in the Standard Model. The deficits with respect to expectations reported by the LHCb experiment in muon-to-electron ratios of the $B \to K^{(*)}\ell\ell$ decay rates thus point to genuine manifestations of lepton non-universal new physics. In this paper, we analyse these measurements in the context of effective field theory. First, we discuss the interplay of the different operators in R_K and R_{K^*} and provide predictions for R_{K^*} in the Standard Model and in new-physics scenarios that can explain R_K. We also provide approximate numerical formulas for these observables in bins of interest as functions of the relevant Wilson coefficients. Secondly, we perform frequentist fits to R_K and R_{K^*}. The SM disagrees with these measurements at 3.7σ significance. We find excellent fits in scenarios with combinations of $\mathcal{O}^{\ell}_{9(10)} = \bar{s}\gamma^\mu b_L\, \ell\gamma_\mu(\gamma_5)\ell$ operators, with pulls relative to the Standard Model in the region of 4σ. An important conclusion of our analysis is that a lepton-specific contribution to $\mathcal{O}_{10}$ is essential to understand the data. Under the hypothesis that new-physics couples selectively to the muons, we also present fits to other $b \to s\mu\mu$ data with a conservative error assessment, and comment on more general scenarios. Finally, we discuss new lepton universalit… discrepancy, should contribute to the statistically sign… physics in the near future.

arXiv:1704.05446

Flavour anomalies after the R_{K^*} measurement

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Abstract

The LHCb measurement of the μ/e ratio R_{K^*} indicates a deficit with respect to the Standard Model prediction, supporting earlier hints of lepton universality violation observed in the R_K ratio. We show that the R_K and R_{K^*} ratios alone constrain the chiralities of the states contributing to these anomalies, and we find deviations from the Standard Model at the 4σ level. This conclusion is further corroborated by hints in the theoretically challenging $b \to s\mu^+\mu^-$ distributions. Theoretical interpretations in terms of Z', lepto-quarks, loop mediators, and composite dynamics are discussed. We highlight their distinctive features in terms of chiralities and flavour structure relevant for the observed anomalies.

arXiv:1704.05438

On Flavourful Easter eggs for New Physics hunger and Lepton Flavour Universality violation

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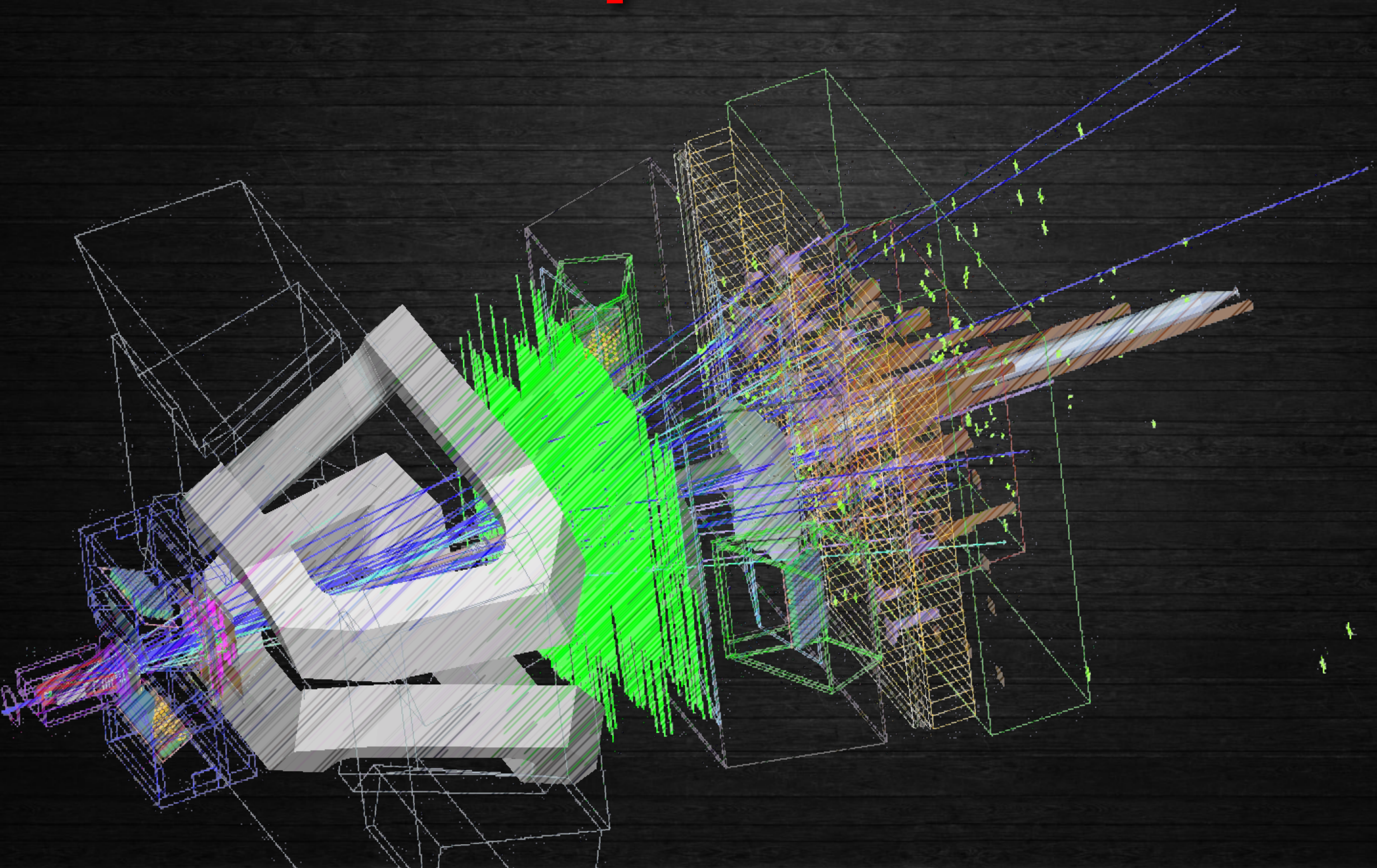
ABSTRACT: In the world of media, Easter eggs are commonly associated to the internal jokes and/or secret messages usually hidden e.g. in computer gaming and hi-tech software. In this work, we take advantage of this terminology to motivate the search for New Physics Beyond the Standard Model of Particle Physics in the radiative and (semi-)leptonic channels of rare B meson decays. Within the standard approach of effective field theory of weak interactions for $\Delta B = 1$ transitions, we look for possibly unexpected subtle NP effects, aka "flavourful Easter eggs". We perform a Bayesian analysis that takes into account the state-of-the-art of the experimental information concerning these processes, including the suggestive measurements from LHCb of R_K and R_{K^*}, the latter available only very recently. We parametrize NP contributions to $b \to s$ transitions in terms of shifts of Wilson coefficients of the electromagnetic dipole and semileptonic operators, assuming CP-conserving effects, but allowing in general for violation of lepton flavour universality. We show how the optimistic/conservative hadronic estimates can impact quantitatively the size of NP extracted from the fit.

arXiv:1704.05447

Summary and Outlook

- Using the full Run 1 data set the $R_{K^{*0}}$ ratio has been measured by LHCb with the best precision to date in two q^2 bins
- The compatibility of the result with respect to the SM prediction(s) is of 2.2-2.5 standard deviations in each q^2 bin
- The result is particularly interesting given a similar behaviour in R_K
- Rare decays will largely benefit from the increase of energy (cross-section) and collected data (~5 fb^{-1} expected in LHCb) in Run 2
- LHCb has a wide programme of LU tests based on similar ratios
- Future measurements will be able to clarify whether the tantalising hints we are observing are a glimpse of NP

Backup



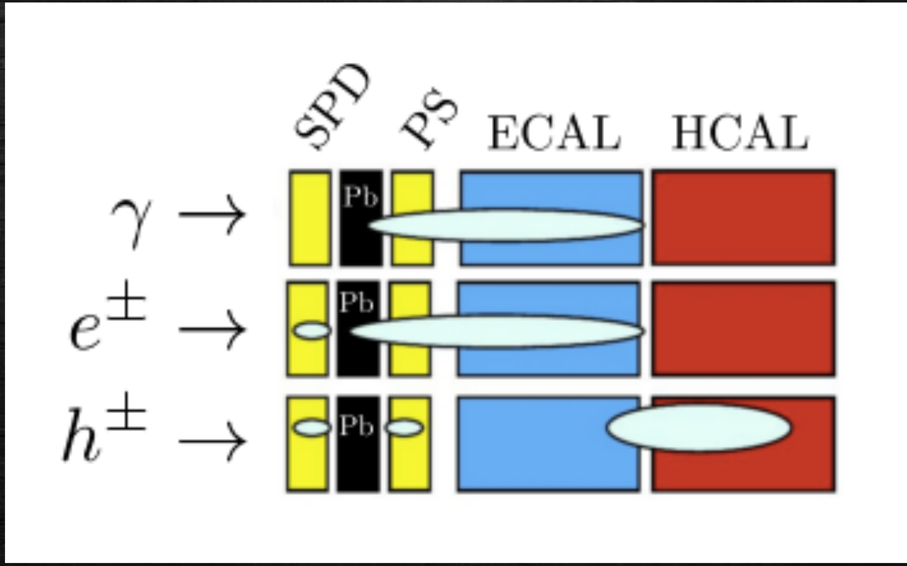
Calorimeter System

› Composed of a Scintillating Pad Detector (SPD), a Preshower (PS), an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL)

› The SPD and the PS consist of a plane of scintillator tiles (2.5 radiation lengths, but to only ~6% hadronic interaction lengths)

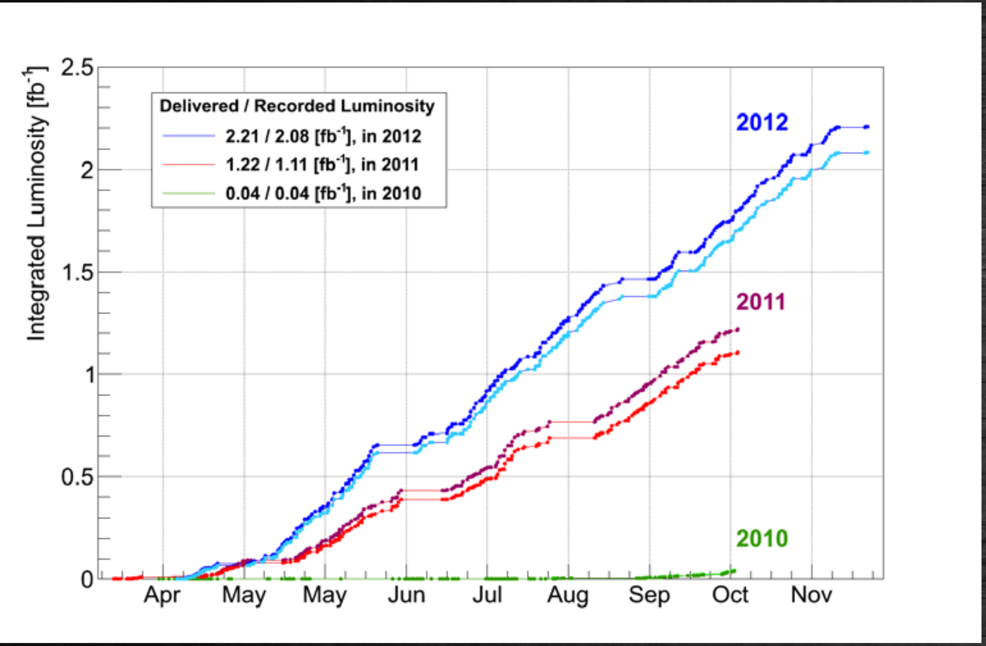
› The ECAL has shashlik-type construction, i.e. a stack of alternating slices of lead absorber and scintillator (25 radiation lengths)

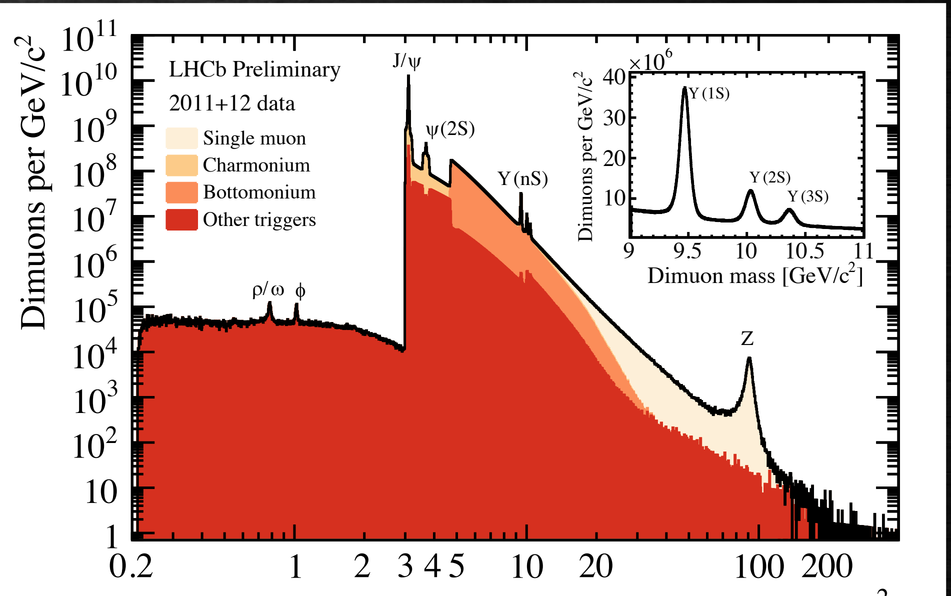
› The HCAL is a sampling device made from iron and scintillator tiles being orientated parallel to the beam axis (5.6 interaction lengths)



Datasets

› Analysis presented today based on the full **Run 1** dataset





[LHCB-CONF-2016-005]

› Due to luminosity levelling, same running conditions throughout fills

Bremsstrahlung – I

› Electrons emit a large amount of bremsstrahlung that results in degraded momentum and mass resolutions

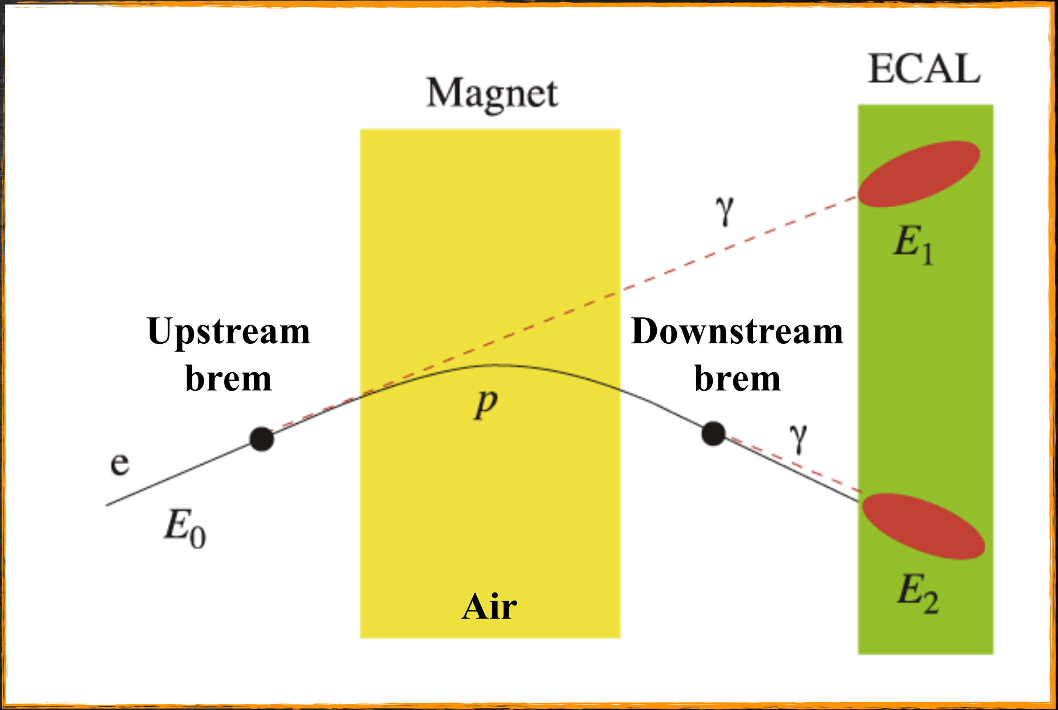
› **Two types of bremsstrahlung**

» **Downstream of the magnet**

- photon energy in the same calorimeter cell as the electron
- momentum correctly measured

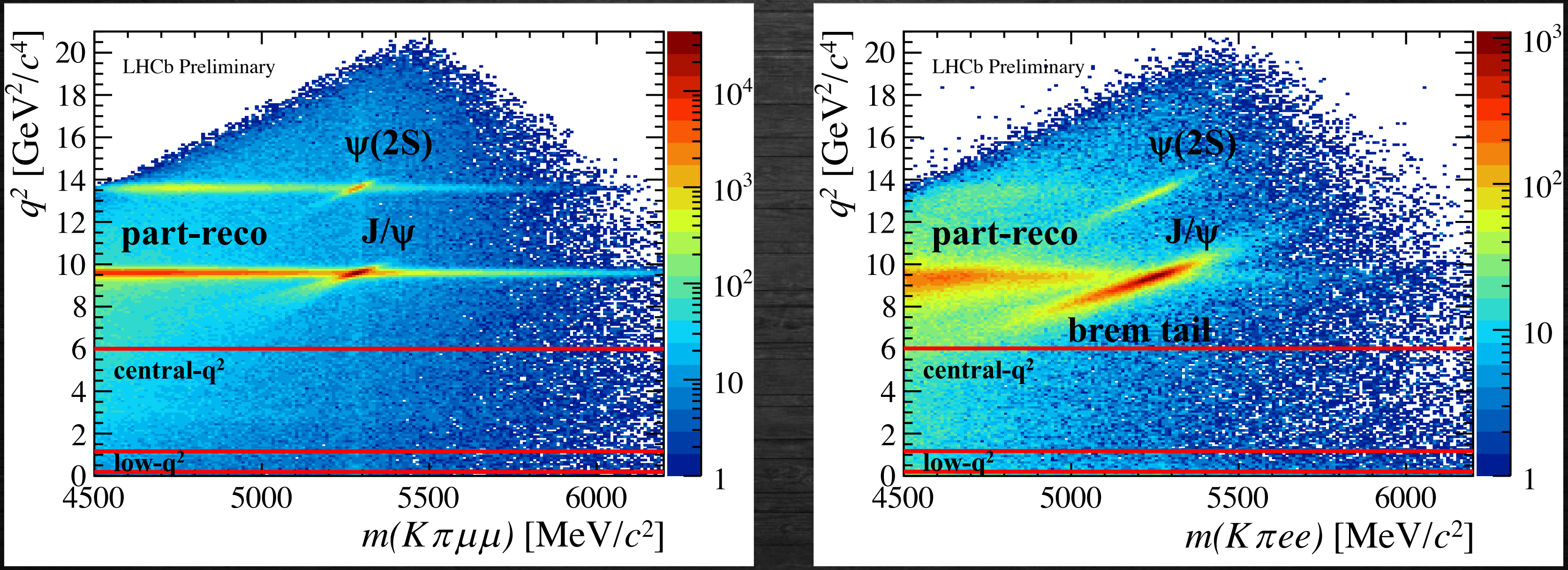
» **Upstream of the magnet**

- photon energy in different calorimeter cells than electron
- momentum evaluated after bremsstrahlung



Bremsstrahlung – II

- A **recovery procedure** is in place to improve the momentum reconstruction
- Events are categorised depending on the number of recovered photon clusters
- Incomplete recovery due to
  - Energy threshold of the bremsstrahlung photon ($E_T > 75$ MeV)
  - Calorimeter acceptance
  - Presence of energy deposits mistaken as bremsstrahlung photons



- Incomplete recovery causes the reconstructed B mass to shift towards lower values and events to migrate in and out of the q^2 bins

Trigger

› Trigger system split in hardware (L0) and software (HLT) stages

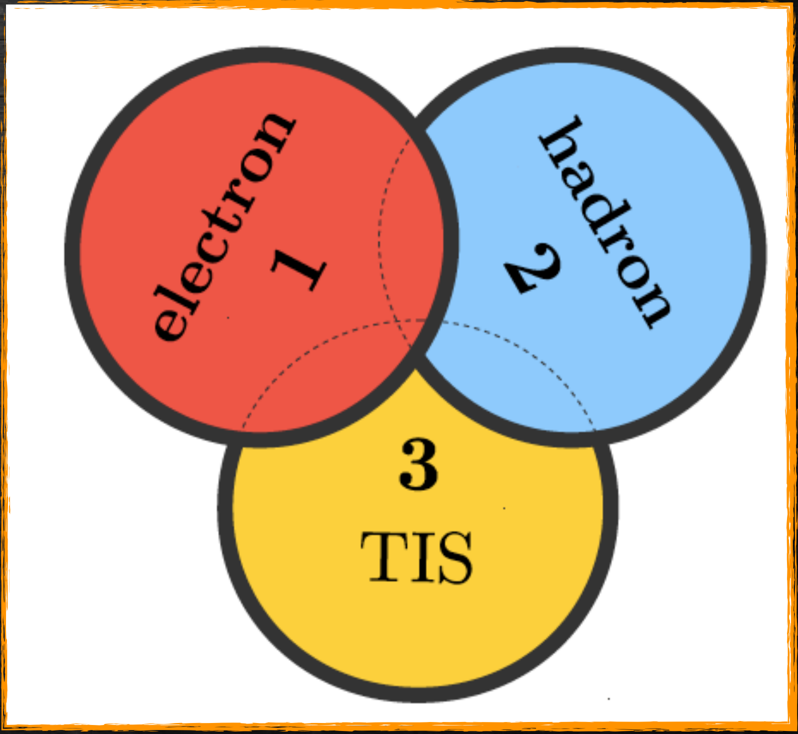
› Due to higher occupancy of the calorimeters compared to the muon stations, hardware thresholds on the electron E_T are higher than on the muon p_T (**L0 Muon**, p_T>1.5,1.8 GeV)

› To partially mitigate this effect, **3 exclusive trigger categories** are defined

» **L0 Electron**: electron hardware trigger fired by clusters associated to at least one of the two electrons (E_T > 2.5 GeV)

» **L0 Hadron**: hadron hardware trigger fired by clusters associated to at least one of the K^{*0} decay products (E_T > 3.5 GeV)

» **L0 TIS**: any hardware trigger fired by particles in the event not associated to the signal candidate



Strategy

› $R_{K^{*0}}$ determined as double ratio to reduce systematic effects

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

› Selection as similar as possible between μμ and ee

» Pre-selection requirements on trigger and quality of the candidates

» Cuts to remove the peaking backgrounds

» Particle identification to further reduce the background

» Multivariate classifier to reject the combinatorial background

» Kinematic requirements to reduce the partially-reconstructed backgrounds

» Multiple candidates randomly rejected (1-2%)

› Efficiencies

» Determined using simulation, but tuned using data

Corrections to Simulation

› Four-step procedure largely based on tag-and-probe technique

1. **Particle identification**
   » PID response of each particle species tuned using dedicated calibration samples

2. **Generator**
   » Event multiplicity and B^0 kinematics matched to data using $B^0 \to K^{*0} J/\psi(\mu\mu)$ decay

3. **Trigger**
   » Hardware and software trigger responses tuned using $B^0 \to K^{*0} J/\psi(ll)$ decays

4. **Data/MC differences**
   » Residual discrepancies in variables entering the MVA reduced using $B^0 \to K^{*0} J/\psi(ll)$ decays

› After tuning, very good data/MC agreement in all key observables

Fit Procedure

- Fit signal MC to extract initial parameters
- Simultaneous fit to resonant and non-resonant modes
- Electron data split in three trigger categories

- **Signal**
  - $\mu\mu$ — Hypatia [NIM A, 764, 150 (2014)]
  - ee — Crystal-Ball (Crystal-Ball and Gaussian)
  - Free parameters — mass shift and width scale

- **Backgrounds**
  - **Combinatorial** — exponential
  - $\Lambda_b \to pK^- J/\psi(ll)$ — simulation & data, constrained using muons ($B^0 \to K^{*0} J/\psi$ only)
  - $B_s \to K^{*0} J/\psi(ll)$ — same as signal but shifted by m_{Bs}-m_{B0}, constrained using muons ($B^0 \to K^{*0} J/\psi$ only)
  - $B^0 \to K^{*0} J/\psi$ **Leakage** — simulation, yield constrained using data ($B^0 \to K^{*0} ee$ only)
  - **Part-Reco** — simulation & data ($B^0 \to K^{*0} ee$ only)

Fit Procedure – μμ

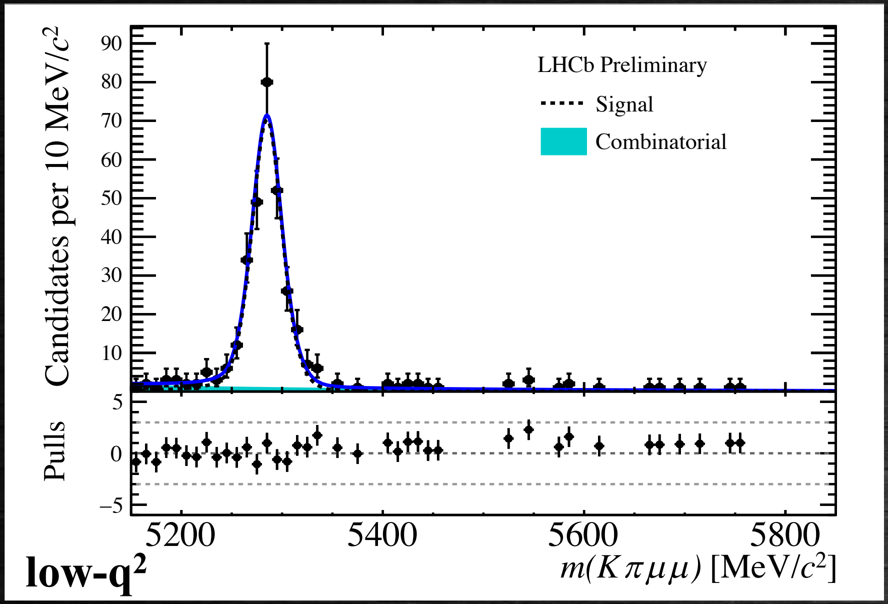
- Fit signal MC to extract initial parameters
- Simultaneous fit to resonant and non-resonant data allowing (some) parameters to vary

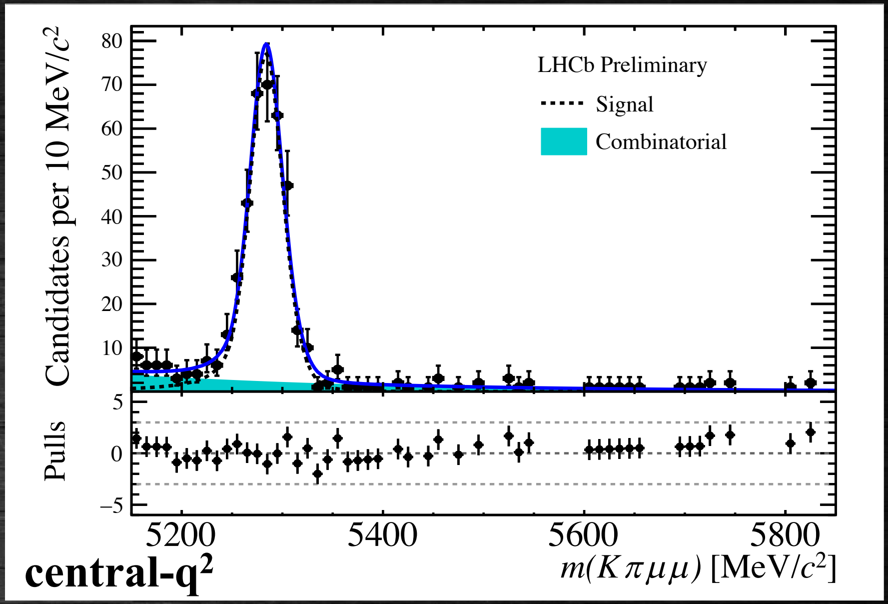
- **Signal**
  - Hypatia [NIM A, 764, 150 (2014)]
  - Free parameters mass shift and width scale

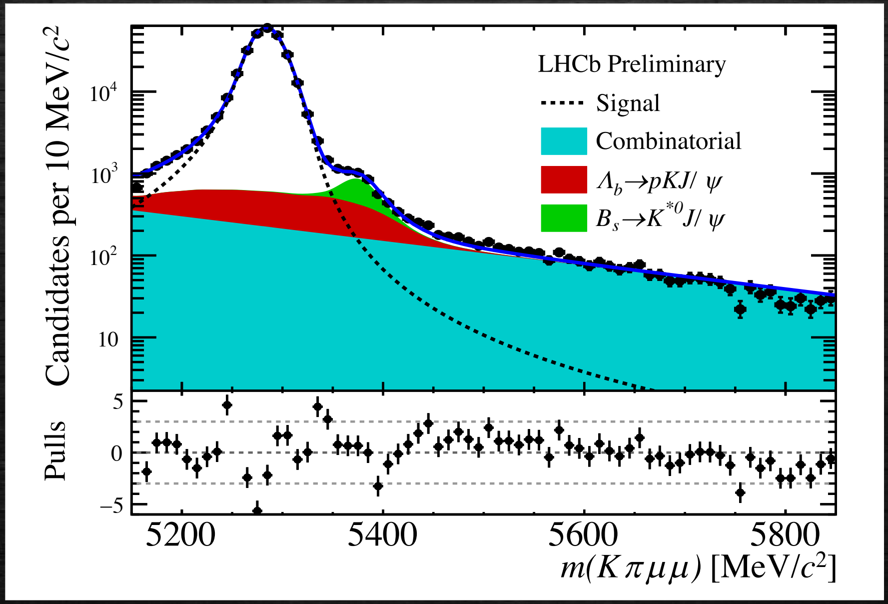
- **Backgrounds**
  - **Combinatorial** exponential
  - $\Lambda_b \rightarrow pK^- J/\psi(\mu\mu)$ simulation & data
  - $B_s \rightarrow K^{*0} J/\psi(\mu\mu)$ same as signal but shifted by m_{Bs}-m_{B0}

$B^0 \rightarrow K^{*0} J/\psi$ only

Fit Results – μμ







Fit Procedure – ee

- Fit signal MC to extract initial parameters
- Simultaneous fit to resonant and non-resonant data split in trigger categories allowing (some) parameters to vary (bremsstrahlung fractions fixed from MC)

- **Signal**
  - Crystal-Ball (Crystal-Ball and Gaussian)
  - Free parameters mass shift and width scale

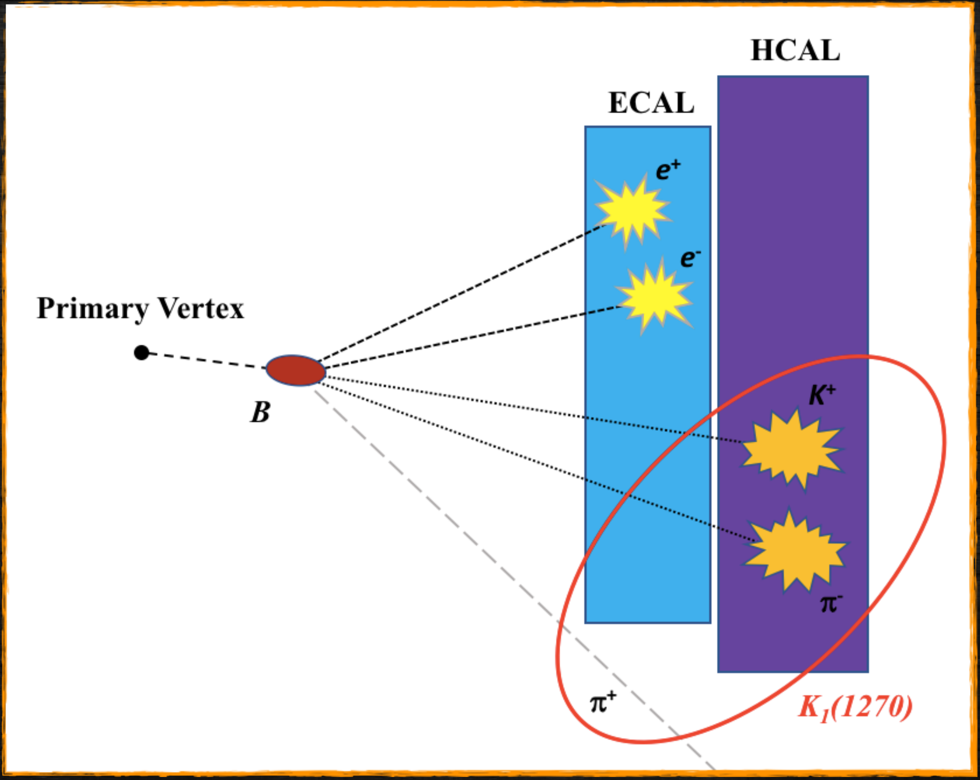
- **Backgrounds**
  - **Combinatorial** exponential
  - $\Lambda_b \to pK^- J/\psi(ee)$ simulation & data, constrained using muons
  - $B_s \to K^{*0} J/\psi(ee)$ same as signal but shifted by m_{Bs}-m_{B0}, constrained using muons

    (Λ_b and B_s items: $B^0 \to K^{*0} J/\psi$ only)
  - $B^0 \to K^{*0} J/\psi$ **Leakage** simulation, yield constrained using data
  - **Part-Reco** simulation & data

    (Leakage and Part-Reco items: $B^0 \to K^{*0}ee$ only)

Part-Reco Background – I

- Partially-reconstructed backgrounds arise from decays involving **higher K resonances** with one or more decay products in addition to a $K\pi$ pair that are not reconstructed
- Large variety of decays, most abundant due to **$B \to K_1(1270)ee$** and **$B \to K_2^*(1430)ee$**

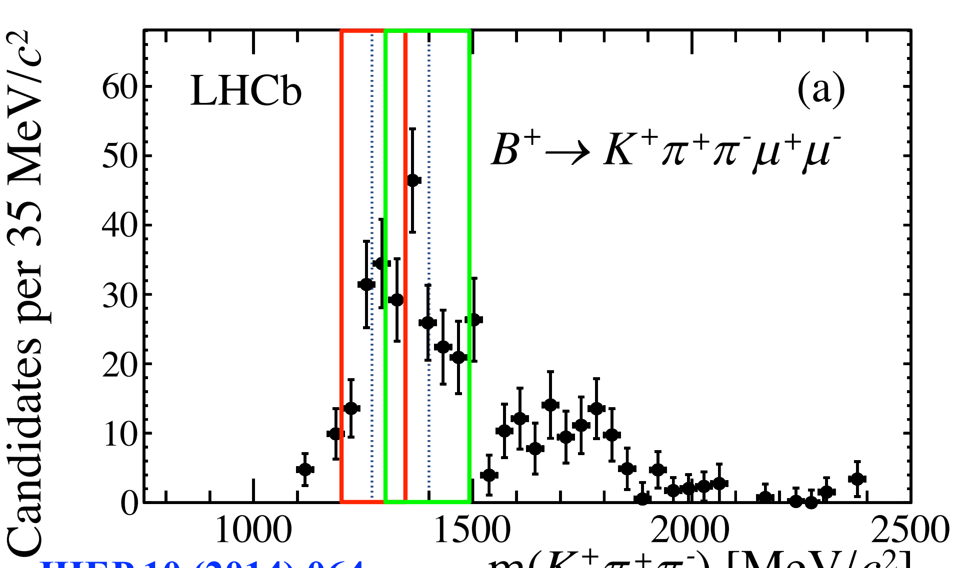


Part-Reco Background – II

› Modelled using two independent methods

» Create a K_1+K_2 cocktail from simulation and use $B \to XJ/\psi(ee)$ data to determine their relative fraction

» Re-weight $B^+ \to K^+\pi^+\pi^- ee$ simulated events using background subtracted $B^+ \to K^+\pi^+\pi^-\mu\mu$ data



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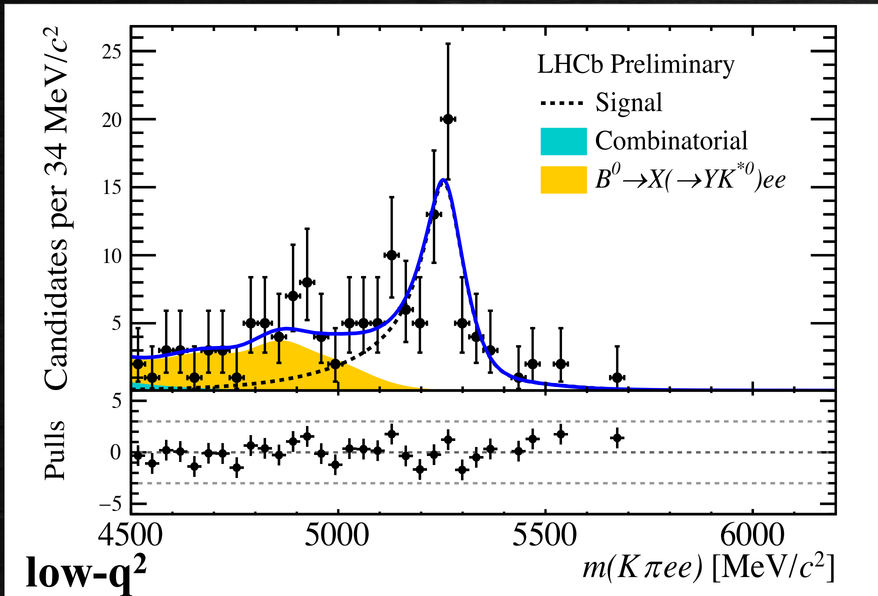
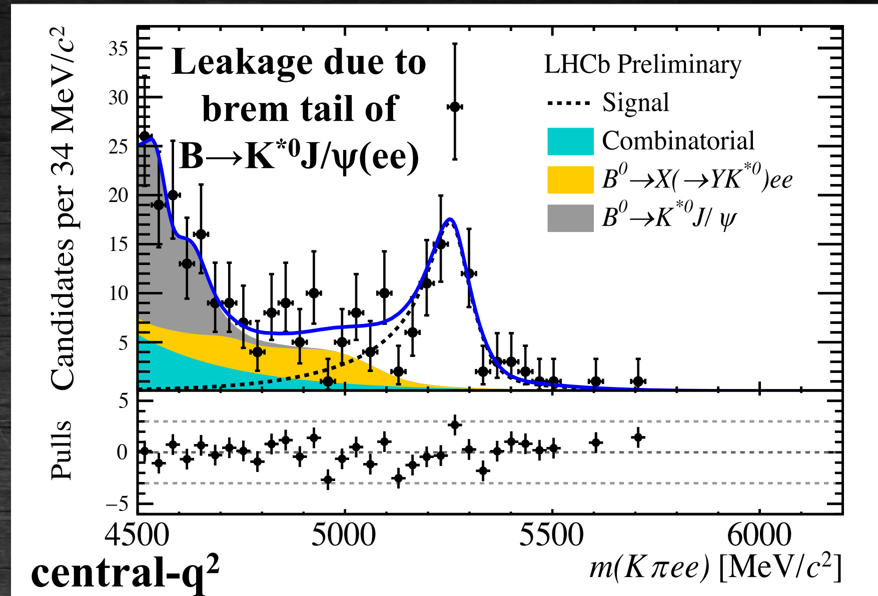
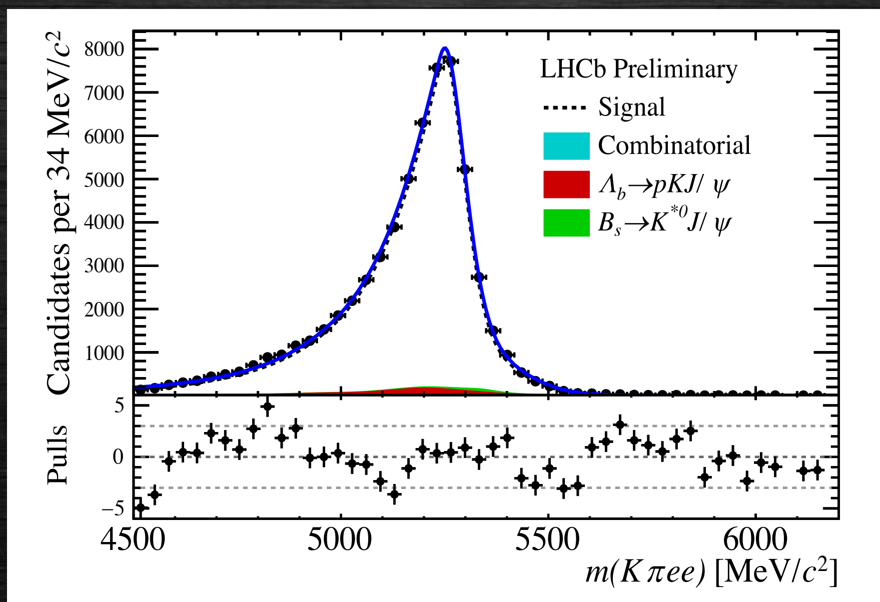
Fit Results – ee







Yields

› Precision of the measurement driven by the statistics of the electron samples

	$B^0 \to K^{*0}\ell^+\ell^-$		$B^0 \to K^{*0}J/\psi\,(\to \ell^+\ell^-)$
	low-q^2	central-q^2	
$\mu^+\mu^-$	$285\,^{+\,18}_{-\,18}$	$353\,^{+\,21}_{-\,21}$	$274416\,^{+\,602}_{-\,654}$
e^+e^- (L0E)	$55\,^{+\,9}_{-\,8}$	$67\,^{+\,10}_{-\,10}$	$43468\,^{+\,222}_{-\,221}$
e^+e^- (L0H)	$13\,^{+\,5}_{-\,5}$	$19\,^{+\,6}_{-\,5}$	$3388\,^{+\,62}_{-\,61}$
e^+e^- (L0I)	$21\,^{+\,5}_{-\,4}$	$25\,^{+\,7}_{-\,6}$	$11505\,^{+\,115}_{-\,114}$

› In total, about 90 and 110 $B^0 \to K^{*0}ee$ candidates at low- and central-q^2, respectively

Cross-Checks

› **Control of the absolute scale of the efficiencies** via the ratio

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

which is expected to be unity and measured to be

$$1.043 \pm 0.006\,(\mathrm{stat}) \pm 0.045\,(\mathrm{syst})$$

› Result observed to be reasonably flat as a function of the decay kinematics and event multiplicity

› **BR($B^0 \to K^{*0}\mu\mu$)** in good agreement with [arXiv:1606.04731]

› If **corrections to simulations** are not accounted for, the ratio of the efficiencies changes by less than 5%

Cross-Checks – II

› **BR($B^0 \to K^{*0}\mu\mu$)** in good agreement with [arXiv:1606.04731]

› If **corrections to simulations** are not accounted for, the ratio of the efficiencies changes by less than 5%

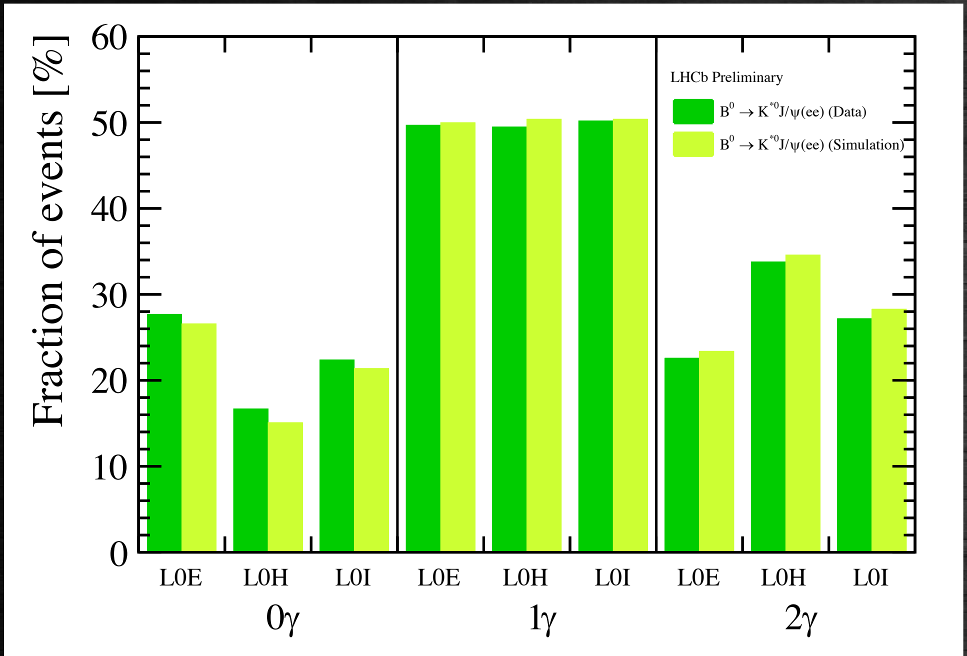
› **Further checks** performed by measuring the following ratios

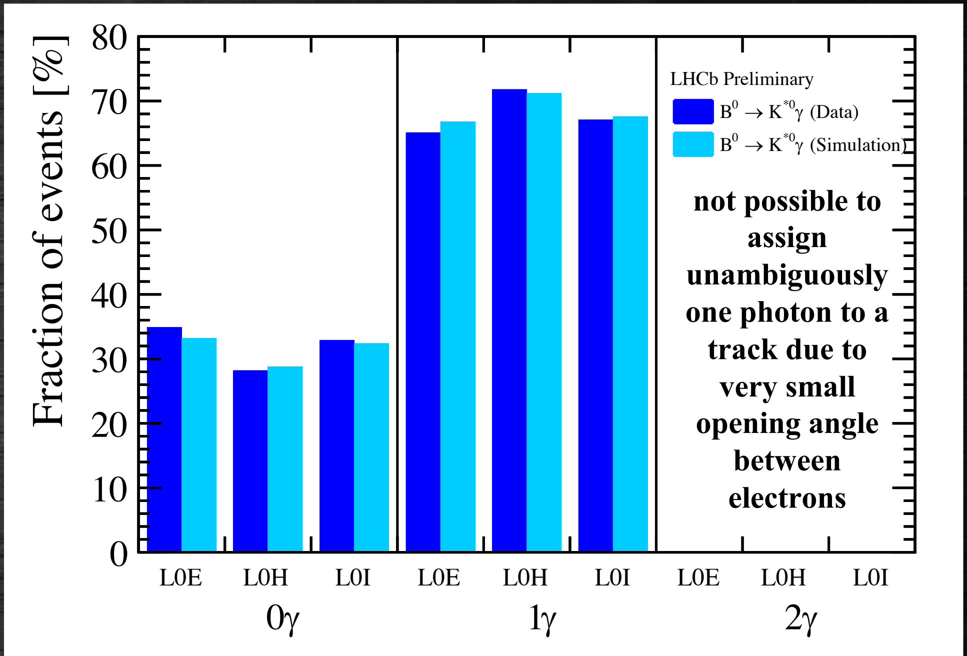
$$\mathcal{R}_{\psi(2S)} = \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

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

which are found to be compatible with the expectations

› Relative population of **bremsstrahlung categories** compared between data and simulation using $B^0 \to K^{*0} J/\psi(ee)$ and $B^0 \to K^{*0}\gamma(ee)$ events

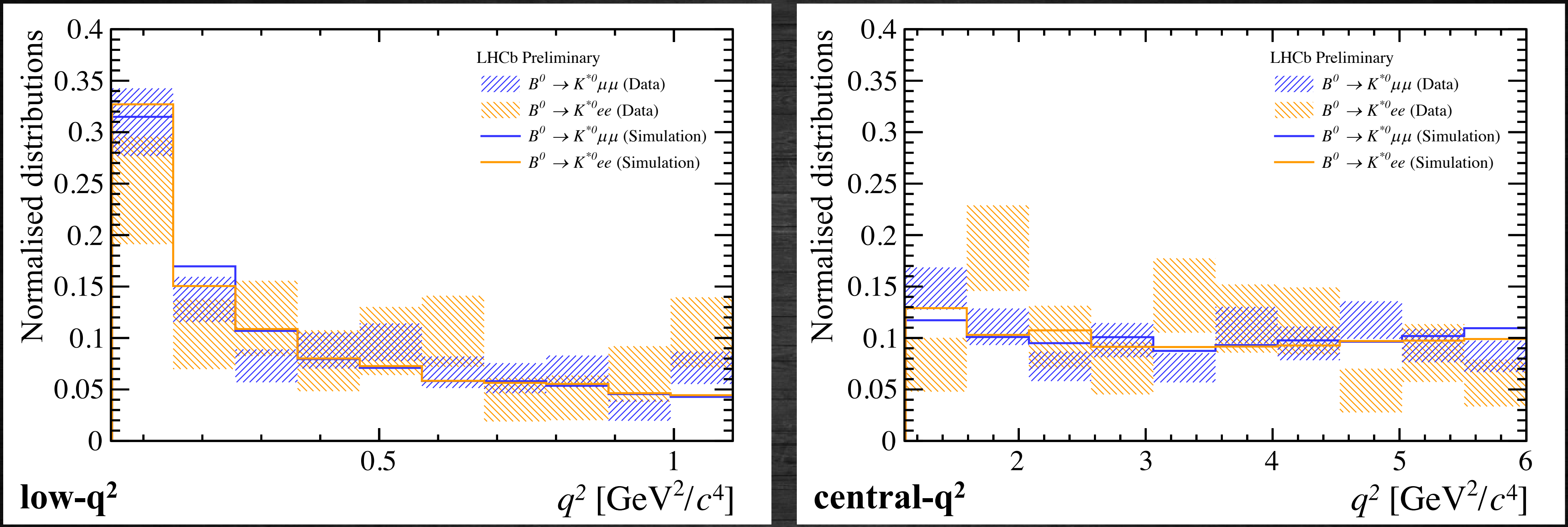




› A good agreement is observed

Cross-Checks – IV

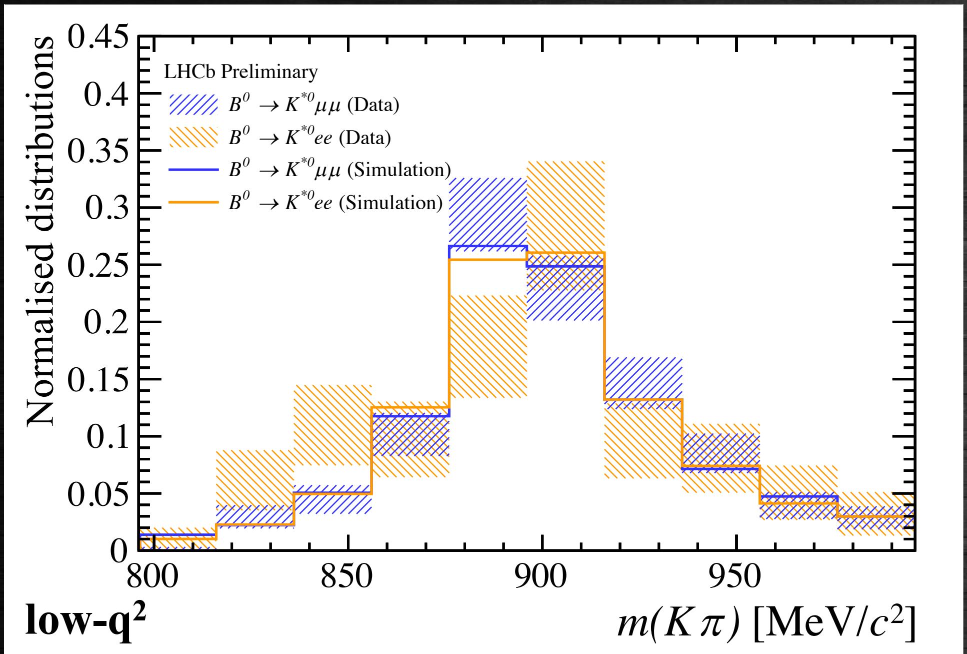
› The sPlot technique is used to statistically subtract the background from the selected data [NIM A555, 356-369 (2005)]

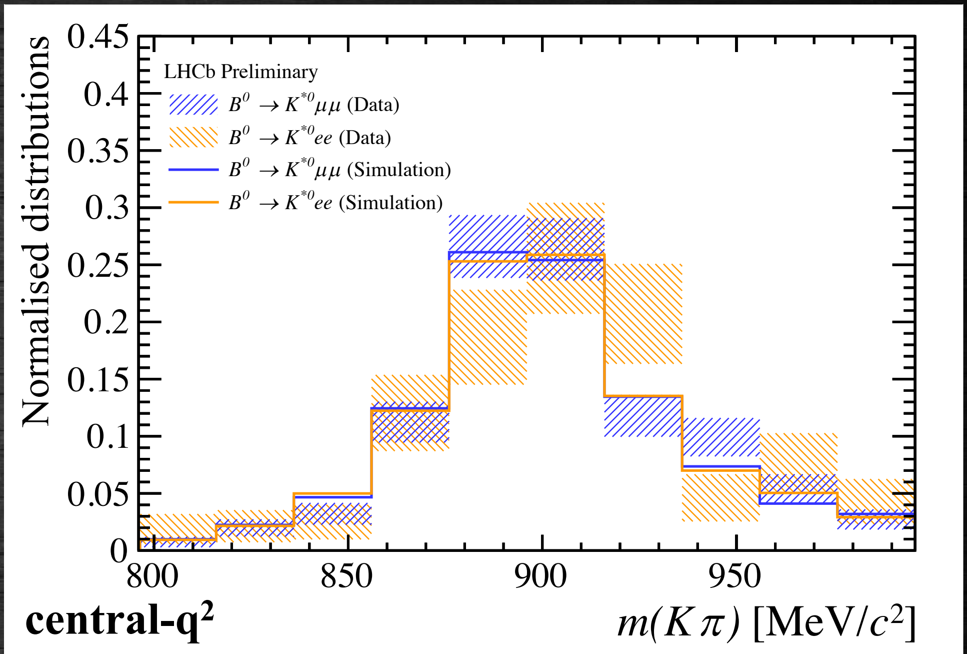


› A good agreement is observed in both q² regions between muons and electrons, data and simulation

Cross-Checks – V

- No attempt is made to separate the K^{*0} meson from S-wave or other broad contributions present in the mass peak region

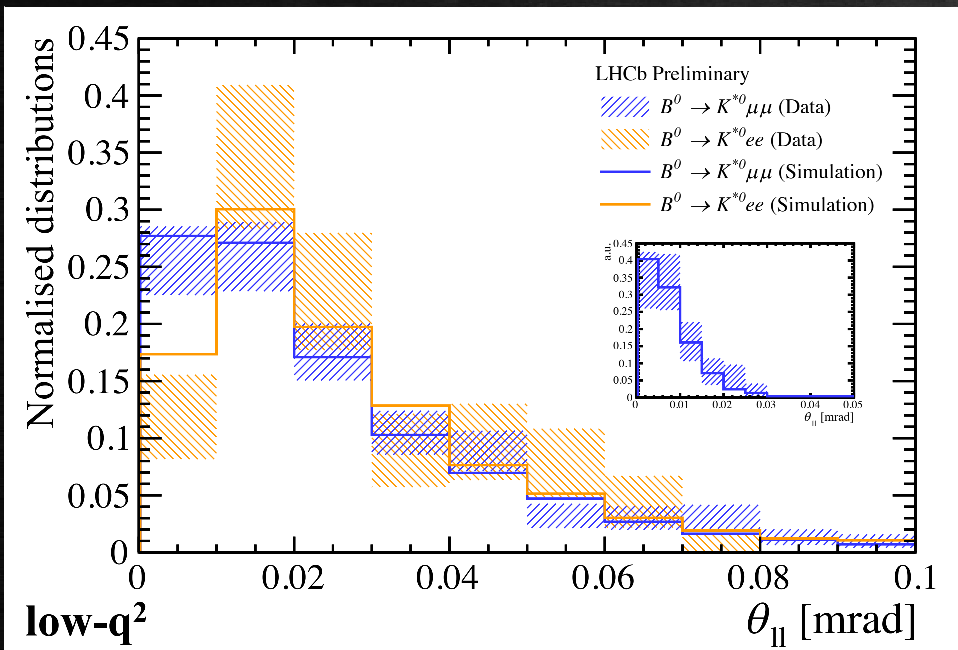


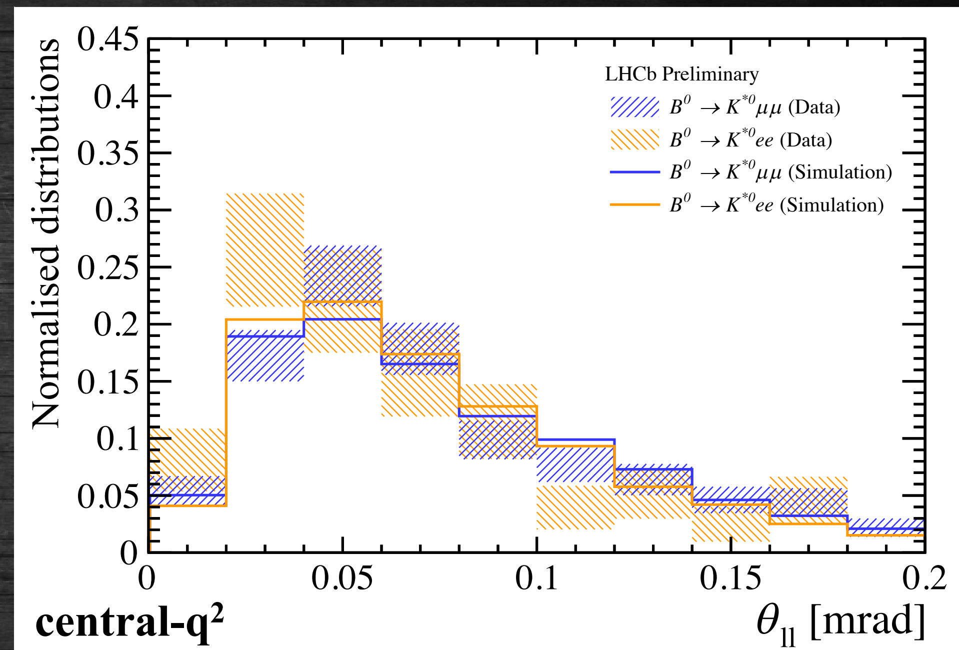


- A clear K^{*0} mass peak is visible, and the muon and electron channels manifest a very good agreement

Cross-Checks – VI

› The opening angle between the two leptons





› The distribution is different between muons and electrons at low-q^2 because of the difference in the lepton masses

› Even very close to threshold a good description is observed (insert, $0.045<q^2<0.1$ GeV^2/c^4)

Systematics – II

- **Corrections to simulation**: besides the uncertainty due to the size of the samples, an additional systematic is determined using different parameterisations of the corrections
- **Kinematic selection**: a systematic uncertainty for Data/MC differences in the description of the bremsstrahlung tail and the MVA classifier is determined by comparing simulation and background subtracted $B^0 \to K^{*0} J/\psi(ll)$ data
- **Residual background**: both data and simulation are used to assess a systematic uncertainty for residual background contamination due to $B^0 \to K^{*0} J/\psi(ee)$ events with a $K \leftrightarrow e$ or $\pi \leftrightarrow e$ swap

	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ flatness	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

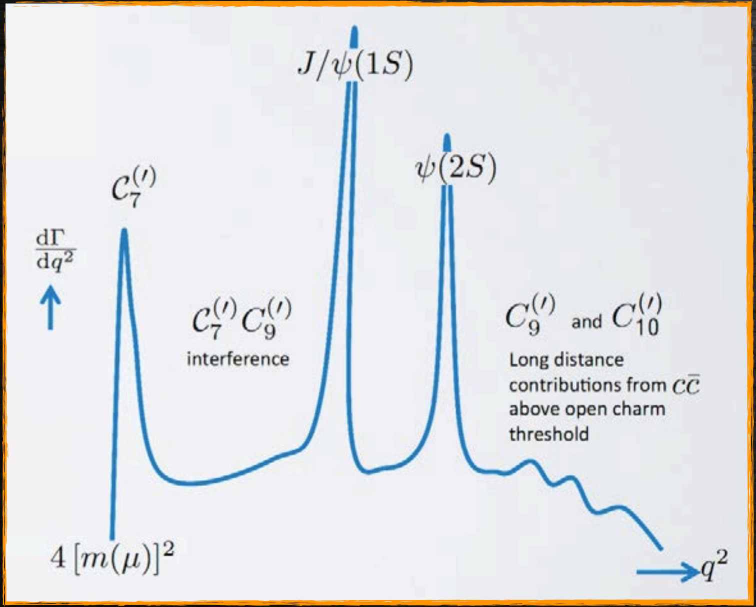
Systematics – III

- **Mass fit**: a systematic uncertainty is determined by running pseudo-experiments with different descriptions of the signal and background fit models
- **Bin migration**: the effect of the model dependence and description of the q^2 resolution in simulation are assigned as a systematic uncertainty
- **$r_{J/\psi}$ flatness**: the ratio is studied as a function of several properties of the event and decay products, and the observed residual deviations from unity are used to assign a systematic uncertainty

	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ flatness	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

Shopping List

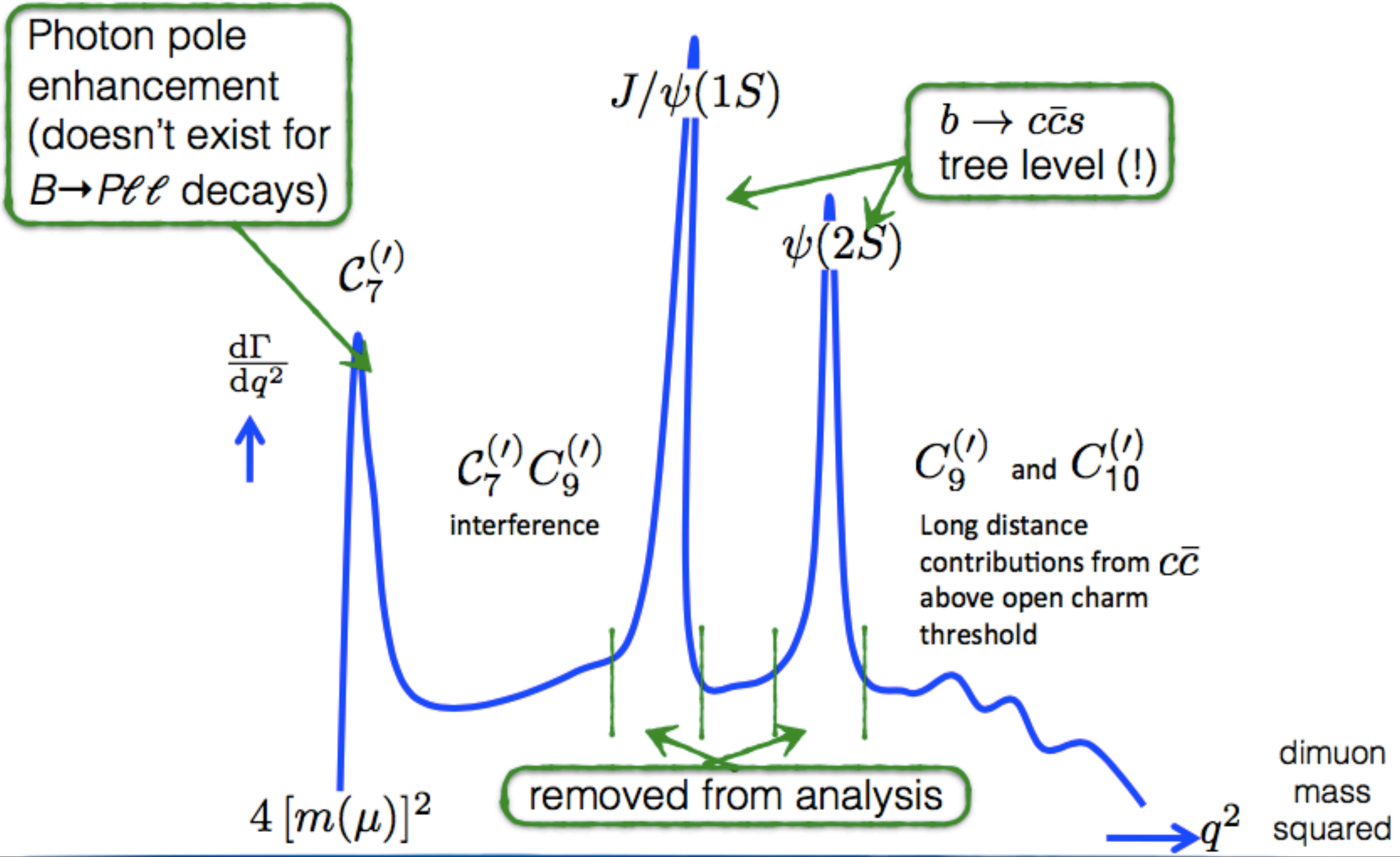
- **Differential branching fractions** of $B^0 \to K^{(*)0}\mu\mu$, $B^+ \to K^{(*)+}\mu\mu$, $B_s \to \phi\mu\mu$, $B^+ \to \pi^+\mu\mu$ and $\Lambda_b \to \Lambda\mu\mu$
  - Presence of hadronic uncertainties in theory predictions
- **Angular analyses** of $B \to K^{(*)}\mu\mu$, $B_s \to \phi\mu\mu$,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



Different q² regions probe different processes
In the OPE framework the short-distance contribution is described by Wilson coefficients

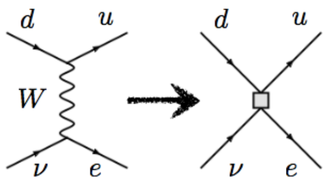
$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum \left[C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right]$$

Di-Lepton Mass



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.



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

- Can write a Hamiltonian for the effective theory as

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

Wilson coefficient (integrating out scales above μ)

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

Operators

SM operators

photon penguin

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

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

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

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

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:

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Big|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K + \boxed{F_{\mathrm{L}}}\cos^2\theta_K +$$

$$+\tfrac{1}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K\cos 2\theta_l$$

$$-\boxed{F_{\mathrm{L}}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$

$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + \boxed{S_5}\sin 2\theta_K\sin\theta_l\cos\phi$$

$$+\tfrac{4}{3}\boxed{A_{\mathrm{FB}}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$

$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

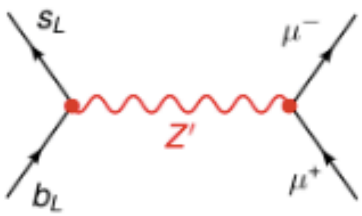
fraction of longitudinal polarisation of the K*

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).

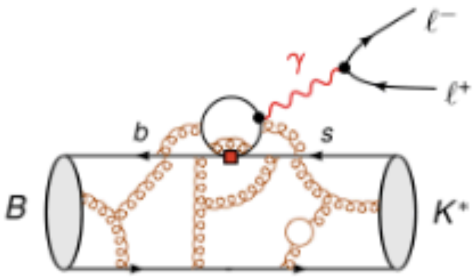
Interpretation of Global Fits

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

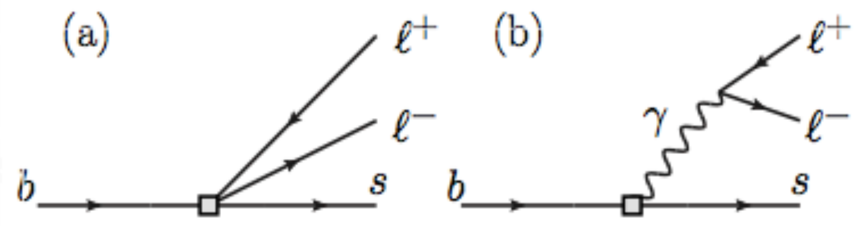


Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon.

More work needed from experiment/theory to disentangle the two

Interpretation of Global Fits

- This is the physics we are interested in.



Short distance part integrates out (as a Wilson coefficient)

- We also get long-distance hadronic contributions. Included in the SM but are the predictions correct?