New tests of lepton universality using rare B decays with K_S mesons in the final state at LHCb

Paper: LHCb-PAPER-2021-038

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On behalf of the LHCb collaboration

LHC Seminar, CERN
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UNIVERSITY OF CAMBRIDGE

Sheldon Stone 1946-2021

Sheldon was a true all round physicist, having made major contributions to data analysis, detector construction and phenomenology. He was co-spokesperson of both the CLEO and BTeV Collaborations. He was LHCb Upgrade Coordinator 2008-2011, and a driving force behind the Upstream Tracker.

He had a profound impact on the LHCb physics programme and was a lead proponent of a large number of LHCb Physics papers.

He was a constant innovator and inspiration to all those who knew him. We will greatly miss him.

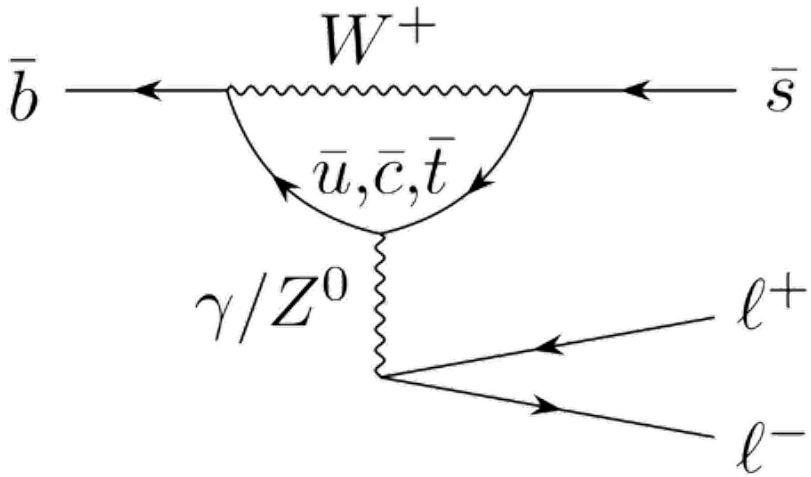
Our deepest condolences to his wife Marina Artuso, & family.

The paper is dedicated to Sheldon.

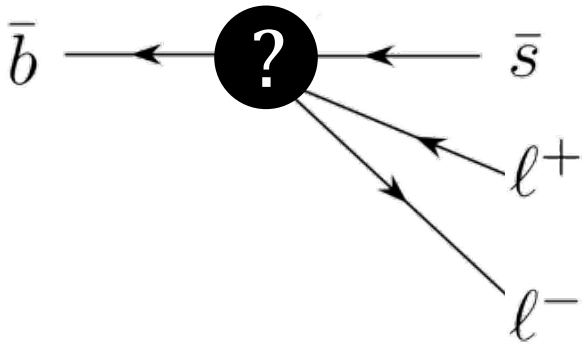
Words prepared by Chris Parkes, LHCb Spokesperson.

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

Standard Model



New Physics

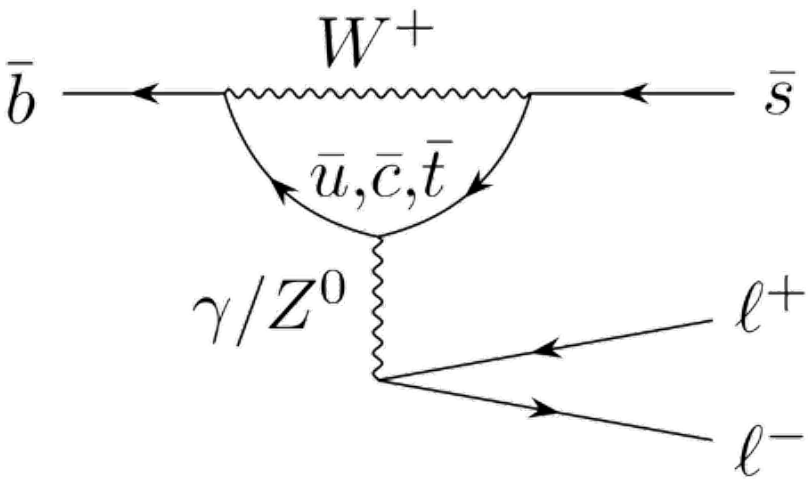


- $b \to s\ell^+\ell^-$ transitions are **flavour-changing neutral current** (FCNC) processes → forbidden at tree level in the Standard Model (SM)
- supressed in SM (branching fractions $\mathcal{O}(10^{-7})$–$\mathcal{O}(10^{-6})$) and hence sensitive to **New Physics** (NP)
- particles associated with NP quantum fields can have masses above reach of direct searches at LHC

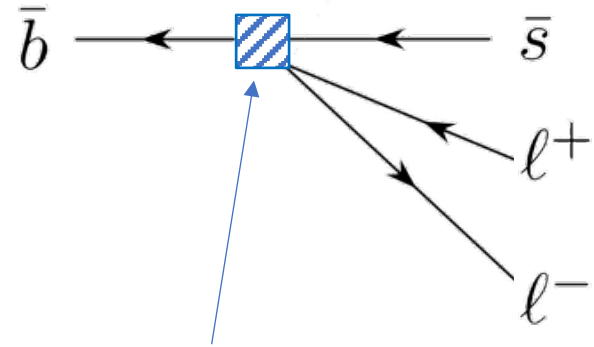
Effective Field Theory of $b \to s\ell^+\ell^-$

$b \to s\ell^+\ell^-$ transitions can be described using an **Effective Field Theory**

- zoom out to b quark scale $\sim$ 4.8 GeV
- integrate out short distance (high energy) interactions
- short distance interactions parametrised using **Wilson Coefficients**



Longer distances



C_9 electroweak vector
C_{10} electroweak axial vector
C_7 electromagnetic

Effective Field Theory of $b \to s\ell^+\ell^-$

Hamiltonian defined in terms of **Wilson Coefficients** $[C_i^{(\prime)}]$ and **Operators** $[\mathcal{O}_i^{(\prime)}]$

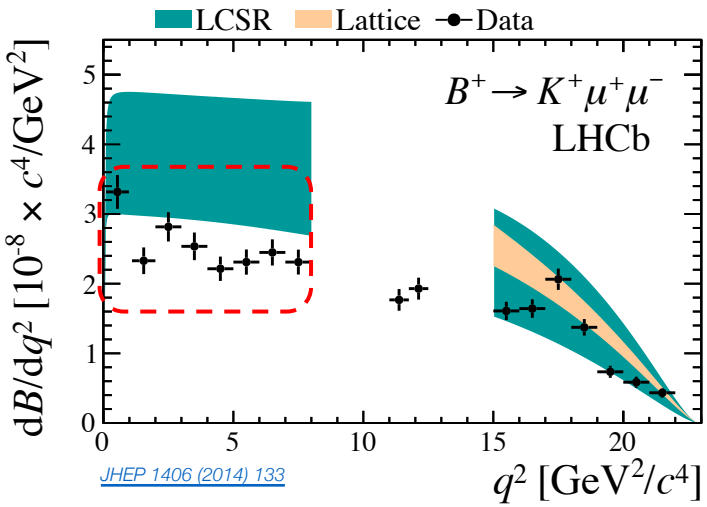
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

- **Wilson Coefficients** encode short-distance physics (the bit we're interested in)
- **Operators** describe low-energy QCD (described using **form factors**), which have large theory uncertainties

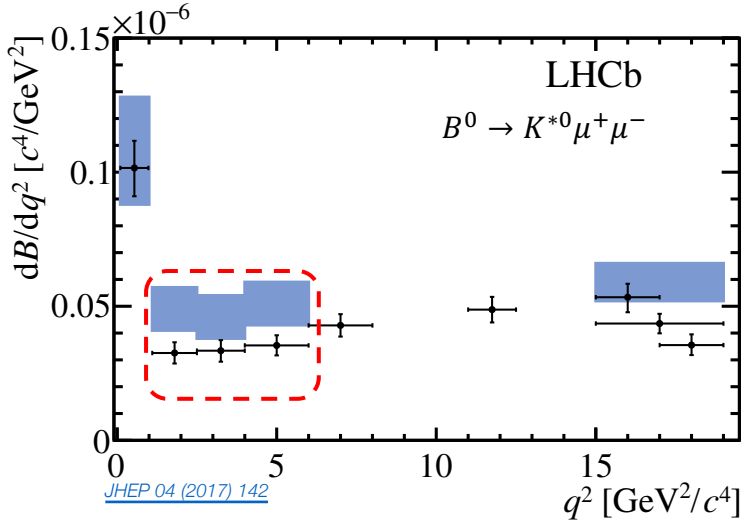
Flavour Anomalies

Several **anomalies** in $b \to s\ell^+\ell^-$ decays emerged over the past decade:

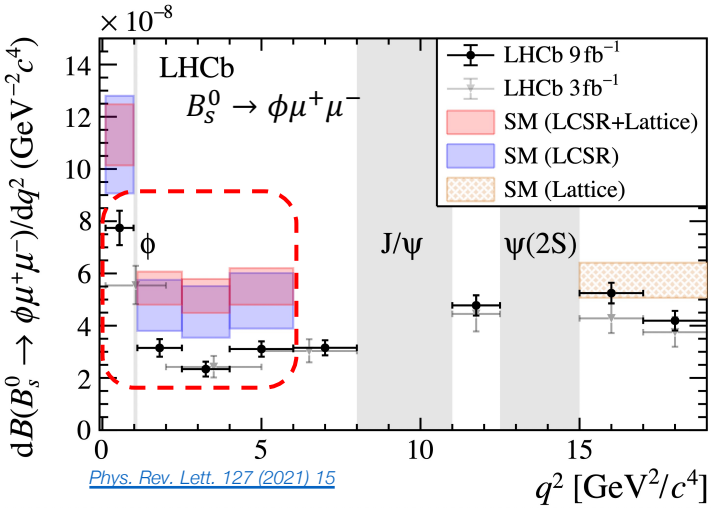
➢ **Branching fractions of $b \to s\mu^+\mu^-$ decays**



JHEP 1406 (2014) 133



JHEP 04 (2017) 142



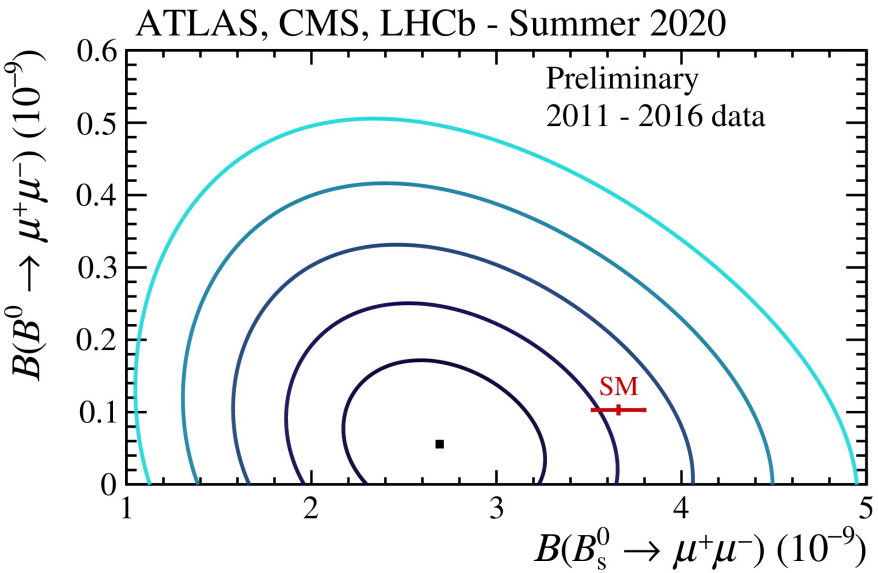
Phys. Rev. Lett. 127 (2021) 15

- Multiple measurements are below SM predictions at low dilepton mass squared (q^2)
- SM predictions suffer from large hadronic uncertainties

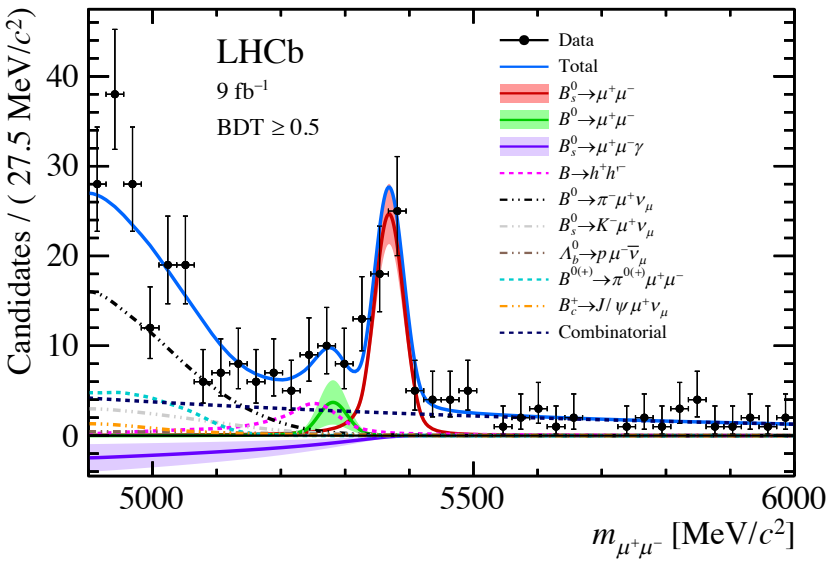
Flavour Anomalies

Several **anomalies** in $b \to s\ell^+\ell^-$ decays emerged over the past decade:

- **Branching fraction of $B^0_{(s)} \to \mu^+\mu^-$ decays**



ATLAS-CONF-2020-049

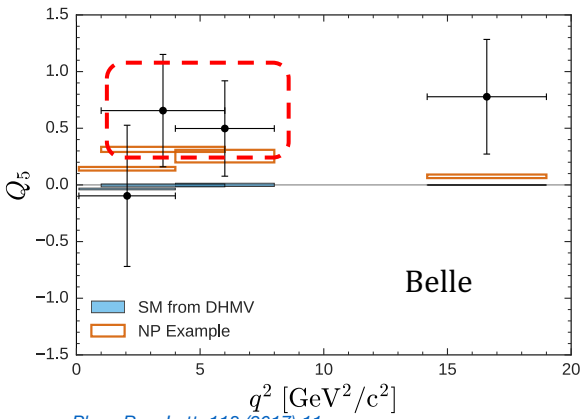


arXiv:2108.09284

Flavour Anomalies

Several **anomalies** in $b \to s\ell^+\ell^-$ decays emerged over the past decade:

➢ **Angular analyses:** $B^0 \to K^{*0}\mu^+\mu^-$



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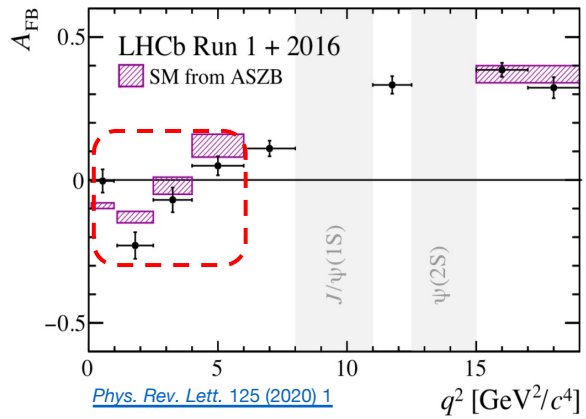
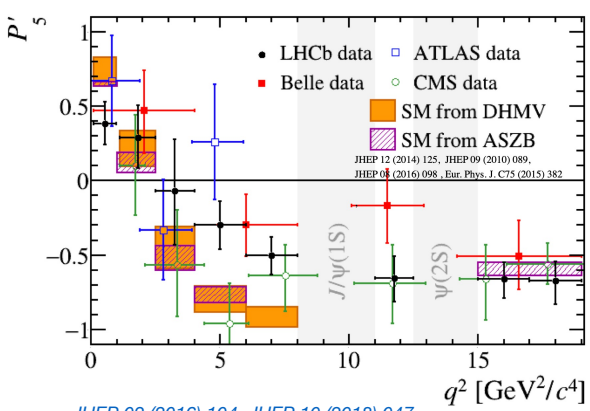
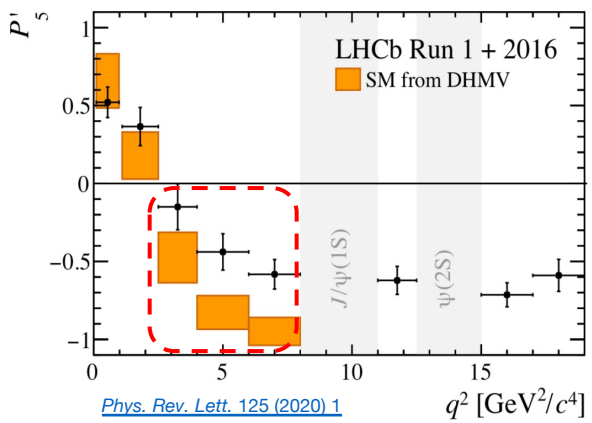


Phys. Rev. Lett. 125 (2020) 1



JHEP 02 (2016) 104, JHEP 10 (2018) 047, Phys. Lett. B 781 (2018) 517, Phys. Rev. Lett. 118 (2017) 11



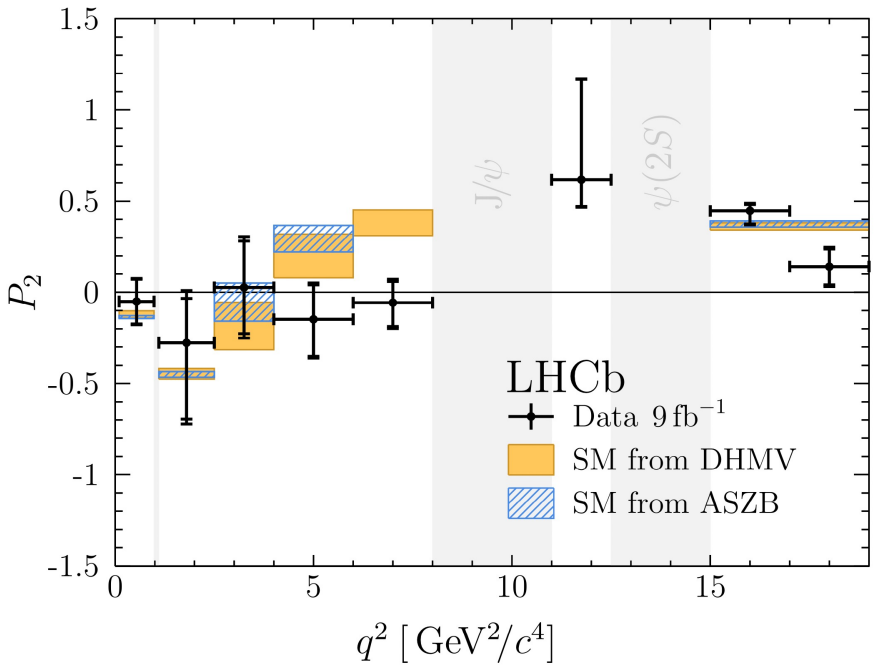
Phys. Rev. Lett. 125 (2020) 1

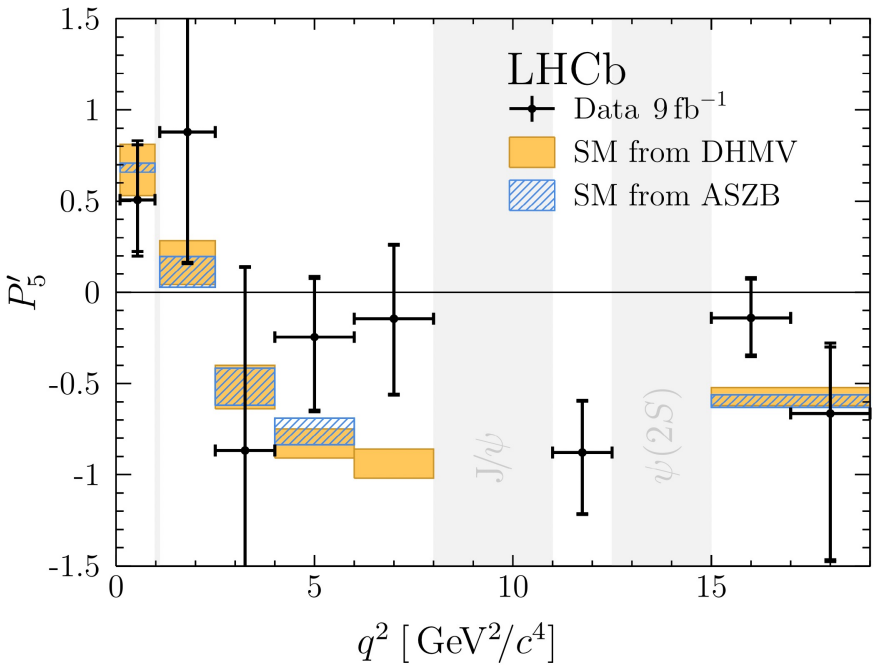
- Large number of observables offering complementary information on NP
- SM uncertainties smaller than for BFs
- Combined tension between latest LHCb analysis and SM at **3.3 sigma** when floating $Re(C_9)$
- Extent of hadronic contributions still matter of debate

Flavour Anomalies

Several **anomalies** in $b \to s\ell^+\ell^-$ decays emerged over the past decade:

➢ **Angular analyses:** $B^+ \to K^{*+}\mu^+\mu^-$





- Combined tension with SM at **3.1 sigma** when floating $Re(C_9)$

Phys. Rev. Lett. 126 (2021) 161802

Flavour Anomalies

Several **anomalies** in $b \to s\ell^+\ell^-$ decays emerged over the past decade:

- **Tests of lepton universality**

  In the SM couplings of gauge fields to the three charged leptons (e, μ, τ) are identical → known as **Lepton Universality**

  Ratios of the form:

$$R_H = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{\mathrm{d}\mathcal{B}(B \to H\mu^+\mu^-)}{\mathrm{d}q^2} \mathrm{d}q^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{\mathrm{d}\mathcal{B}(B \to He^+e^-)}{\mathrm{d}q^2} \mathrm{d}q^2} \cong 1$$

  in the SM, except for small corrections due to different lepton masses.

  - Hadronic uncertainties (which affect BFs and angular observables) cancel in ratio down to $\mathcal{O}(10^{-4})$ [JHEP 07 (2007) 040]
  - QED corrections up to $\mathcal{O}(10^{-2})$ [EPJ C76 (2016) 8, 440], [JHEP 12 (2020) 104]

Significant deviation from unity unambiguous evidence of New Physics

Flavour Anomalies

Several **anomalies** in $b \to s\ell^+\ell^-$ decays emerged over the past decade:

- **Tests of lepton universality**

$B^0 \to K^{*0}\ell^+\ell^-$ (3 fb^{-1})

$R_{K^{*0}} = 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst})$ $[0.045 < q^2/\text{GeV}^2 < 1.1]$

$R_{K^{*0}} = 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst})$ $[1.1 < q^2/\text{GeV}^2 < 6.0]$

2.2–2.5σ deviation from SM in each bin. *[JHEP 08 (2017) 55]*

$\Lambda_b \to pK^-\ell^+\ell^-$ (5 fb^{-1})

$R_{pK^-} = 0.86^{+0.14}_{-0.11}(\text{stat}) \pm 0.05(\text{syst})$

Agrees with SM at 1σ. *[JHEP 05 (2020) 40]*

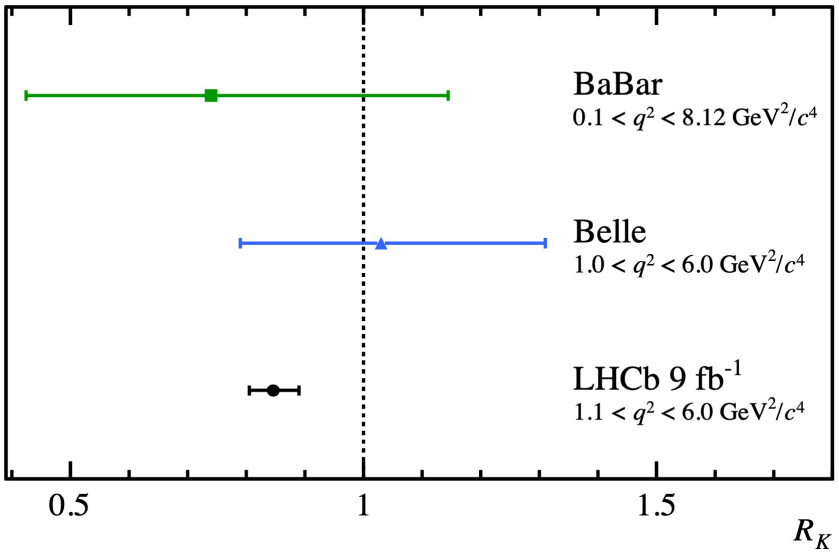
$B^+ \to K^+\ell^+\ell^-$ (9 fb^{-1})

$R_{K^+} = 0.846^{+0.042}_{-0.039}(\text{stat})\,^{+0.013}_{-0.012}(\text{syst})$

3.1σ deviation from SM.

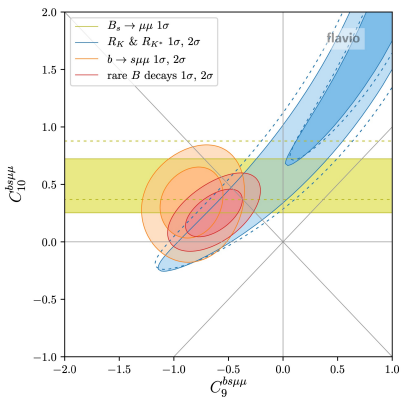
[arxiv: 2103.11769 (submitted to Nature Physics)]

BaBar: Phys. Rev. D86 (2012) 032012
Belle: JHEP 03 (2021) 105

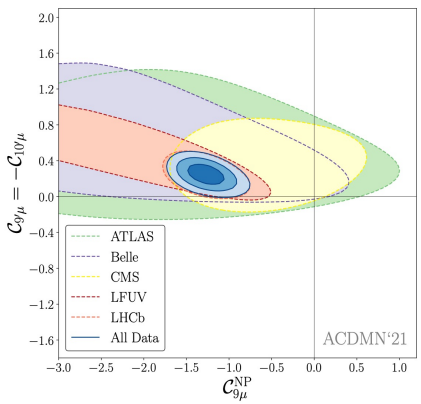


Global Fits

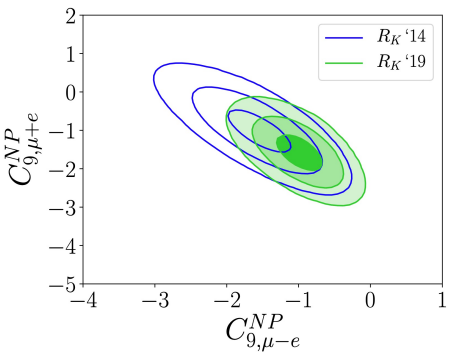
- Combination of of all $b \to s\ell^+\ell^-$ measurements (and $B_s^0 \to \mu^+\mu^-$) through fit for Wilson Coefficients
- Anomalies can be explained **coherently** by:
  - new vector coupling $C_9^{bs\mu\mu}$
  - new vector-axial vector coupling with $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$



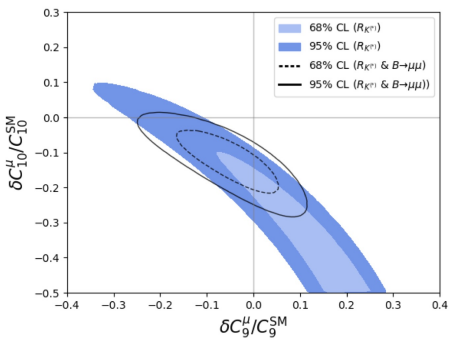
Altmannshofer & Stangl. arxiv:2103.13370



Algueró et al. arXiv:2104.08921



Cuichini et al. EPJ C79 (2019) 719

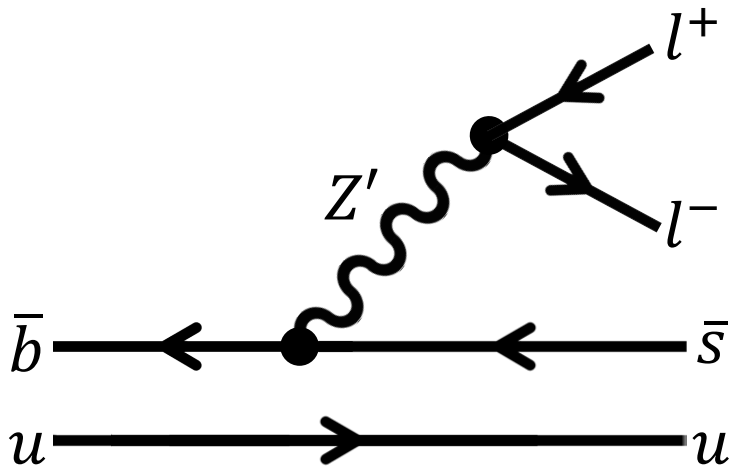


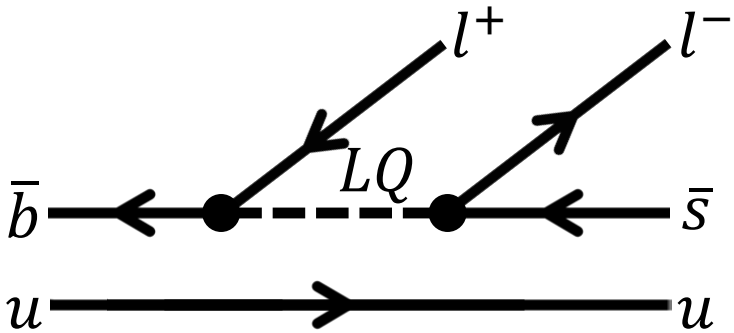
Hurth et al. arXiv:2104.10058

Note: other global fits are available

New Physics?

Possible coherent explanation involving tree-level new physics competing with SM loop and box diagrams.





May be probing Z' or leptoquarks at high mass scales, potentially within reach of direct production at LHC.

➢ **Further measurements are required to clarify situation**

New Tests of Lepton Universality

Today: **tests of lepton universality** using 2011-2012 and 2016-2018 dataset

$B^0 \to K_S^0 \ell^+ \ell^-$ (9 fb^{-1})

$$R_{K_S^0} = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}\left(B^0 \to K_S^0 \mu^+ \mu^-\right)}{\mathrm{d}q^2} \mathrm{d}q^2}{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}\left(B^0 \to K_S^0 e^+ e^-\right)}{\mathrm{d}q^2} \mathrm{d}q^2}$$

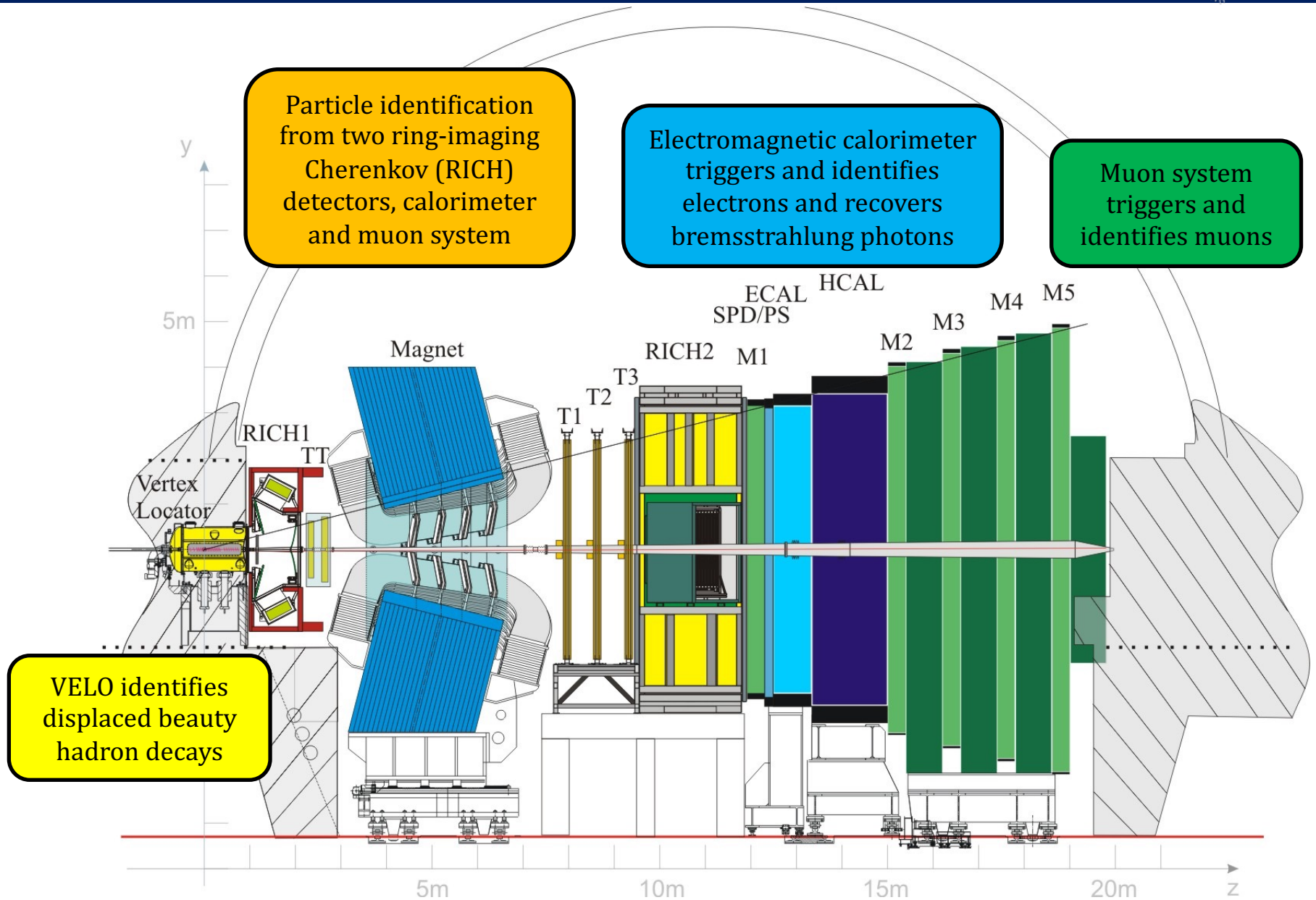
$B^+ \to K^{*+} \ell^+ \ell^-$ (9 fb^{-1})

$$R_{K^{*+}} = \frac{\int_{0.045\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+ \to K^{*+} \mu^+ \mu^-)}{\mathrm{d}q^2} \mathrm{d}q^2}{\int_{0.045\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^0 \to K^{*+} e^+ e^-)}{\mathrm{d}q^2} \mathrm{d}q^2}$$

Final states
$K_S^0 \to \pi^+ \pi^-$
$K^{*+} \to K_S^0 \pi^+$

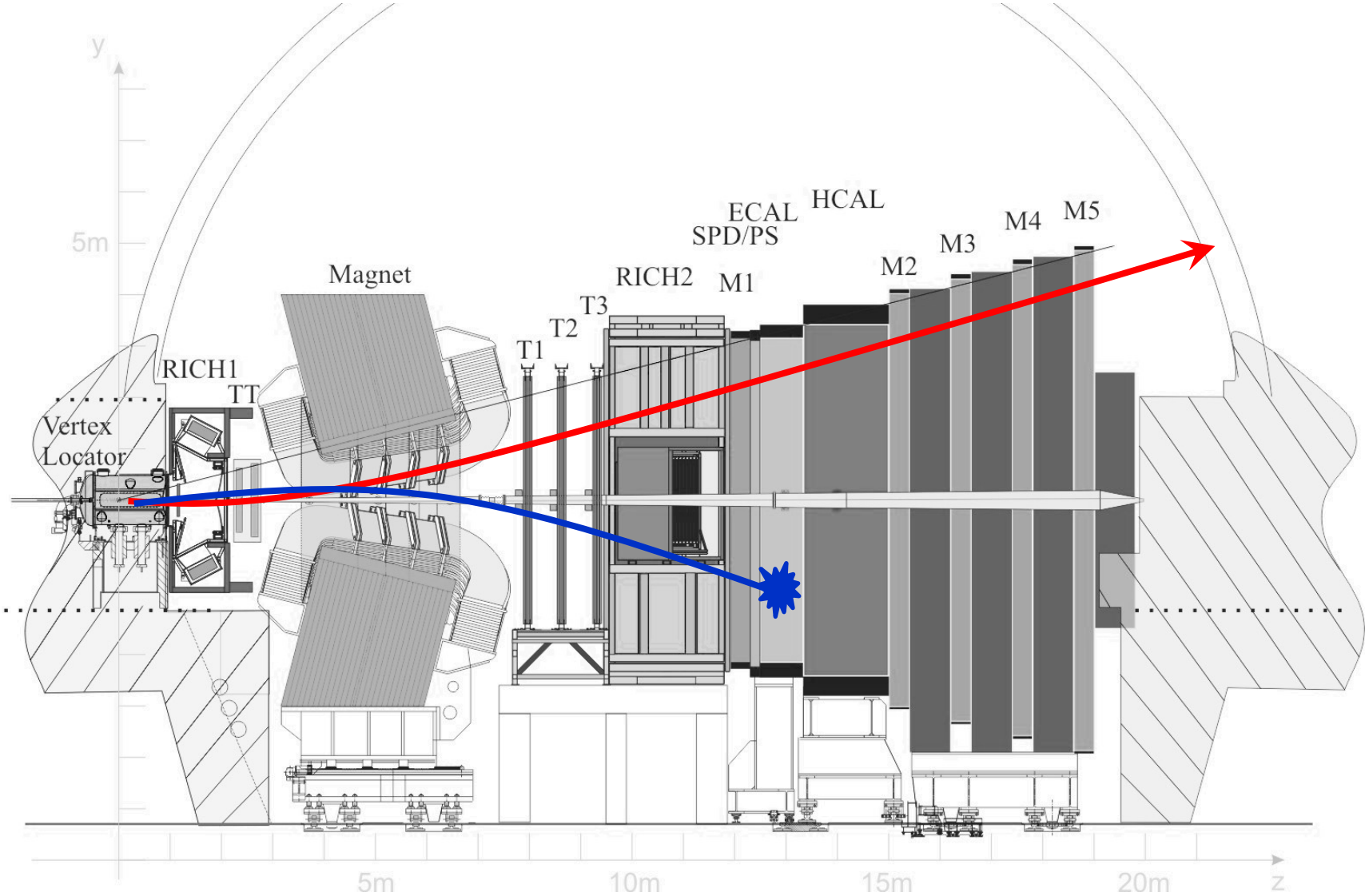
- **Isospin partners** of $B^+ \to K^+ \ell^+ \ell^-$ and $B^0 \to K^{*0} \ell^+ \ell^-$: expect same NP contributions
- **More difficult to reconstruct** due to long-lived K_S^0 in final state
- **First measurements at LHC** – previously measured by Belle with statistical uncertainties ~50%

The LHCb Experiment



Electrons vs Muons

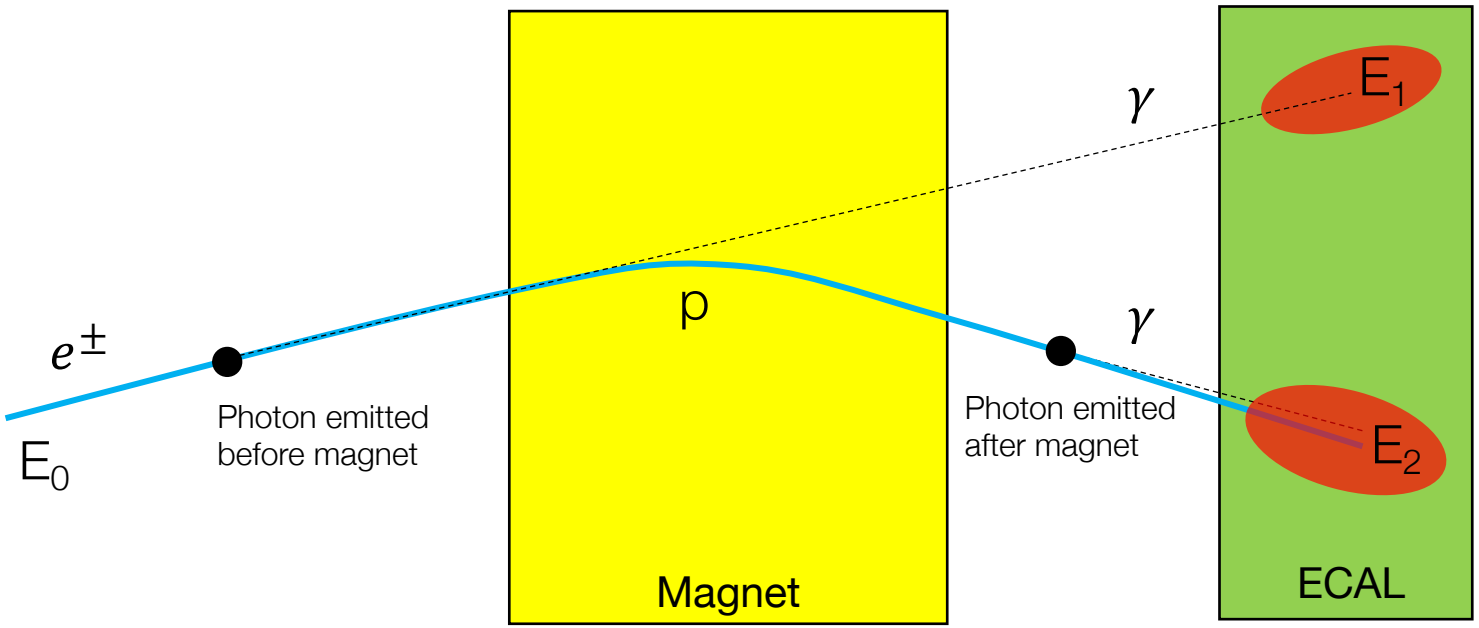
Electrons and muons have very different signatures in the experiment.



Electrons vs Muons

Electrons radiate bremsstrahlung photons when interacting with detector.

Photons radiated before the magnet lead to underestimation of momentum and energy.

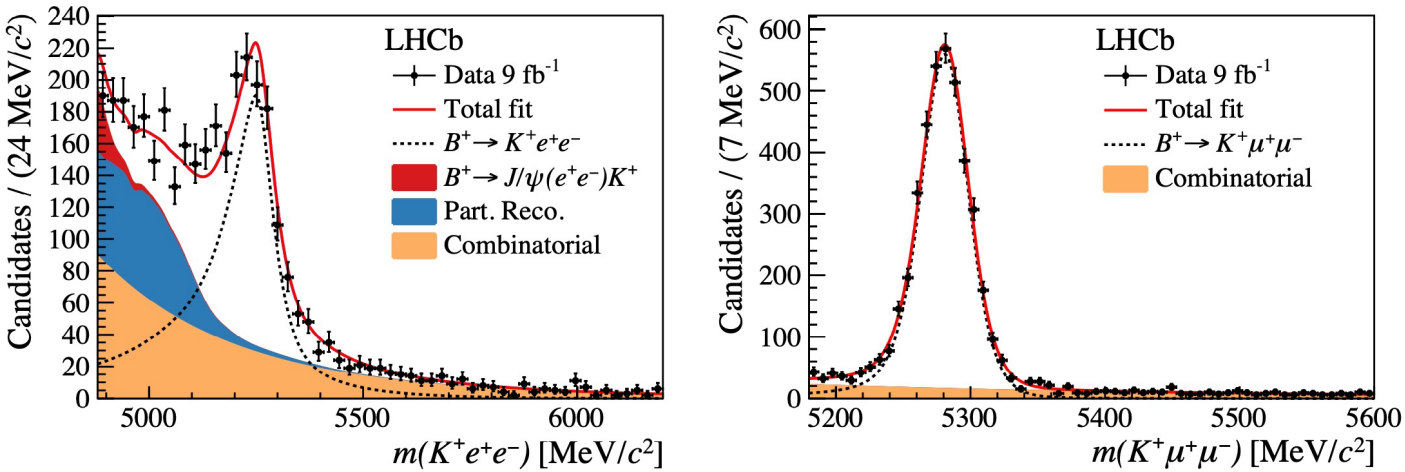


Bremsstrahlung recovery searches for energy deposits in the calorimeter and adds back to electron energy.

Electrons vs Muons

Even after brem. recovery mass resolution for electron modes is poorer than for muon modes.

From 2021 R_K *analysis* [arxiv: 2103.11769 (submitted to Nature Physics)]



Efficiency to reconstruct and select electron modes is ~20% that of muon modes.

Controlling different efficiencies for electrons and muons is key challenge of analysis.

Analysis Strategy

Measure $R_{K^{(*)}}$ as **double ratio** compared to **control decays**:

$$B \to J/\psi(\ell^+\ell^-)K^{(*)}$$

where the J/ψ decays to either e^+e^- or $\mu^+\mu^-$ at an equal rate. Branching fraction ~1/1000.

$$R_{K^{(*)}} = \frac{N(B\to K^{(*)}\mu^+\mu^-)}{N(B\to K^{(*)}e^+e^-)} \frac{N(B\to J/\psi(e^+e^-)K^{(*)})}{N(B\to J/\psi(\mu^+\mu^-)K^{(*)})} \cdot \frac{\epsilon(B\to K^{(*)}e^+e^-)}{\epsilon(B\to K^{(*)}\mu^+\mu^-)} \frac{\epsilon(B\to J/\psi(\mu^+\mu^-)K^{(*)})}{\epsilon(B\to J/\psi(e^+e^-)K^{(*)})}$$

Number (N) of each decay mode extracted from data using a fit to the B mass spectrum

Efficiency (ϵ) to reconstruct and select each decay measured using simulation

Many systematic effects **cancel precisely** in double ratio – highly robust against biases.

Same strategy as previous R measurements **except** we fit $R^{-1}_{K^{(*)}}$ to keep low yield electron modes in the numerator → uncertainties more Gaussian.

Analysis Strategy

Additionally:

- aim for **first observations** of $\boldsymbol{B^0 \to K_S^0 e^+ e^-}$ and $\boldsymbol{B^+ \to K^{*+} e^+ e^-}$ decays
- measurements of their **differential branching fractions**

$$\frac{\mathrm{d}\mathcal{B}\left(B\to K^{(*)}e^+e^-\right)}{\mathrm{d}q^2} = \frac{N\left(B\to K^{(*)}e^+e^-\right)}{\epsilon\left(B\to K^{(*)}e^+e^-\right)} \cdot \frac{\epsilon\left(B\to J/\psi\left(e^+e^-\right)K^{(*)}\right)}{N\left(B\to J/\psi(e^+e^-)K^{(*)}\right)} \cdot \frac{\mathcal{B}\left(B\to J/\psi\left(e^+e^-\right)K^{(*)}\right)}{q^2_{\mathrm{max}}-q^2_{\mathrm{min}}}$$

q^2 and $m(K^{*+})$ regions

Signal modes:

$B^+ \to K^{*+}\ell^+\ell^-$: $[0.045 < q^2/\mathrm{GeV}^2 < 6.0]$

$B^0 \to K_S^0\ell^+\ell^-$: $[1.1 < q^2/\mathrm{GeV}^2 < 6.0]$

Single q^2 bin used due to low statistics despite photon pole

Wider range used in electron mode due to poorer q^2 resolution

Control modes:

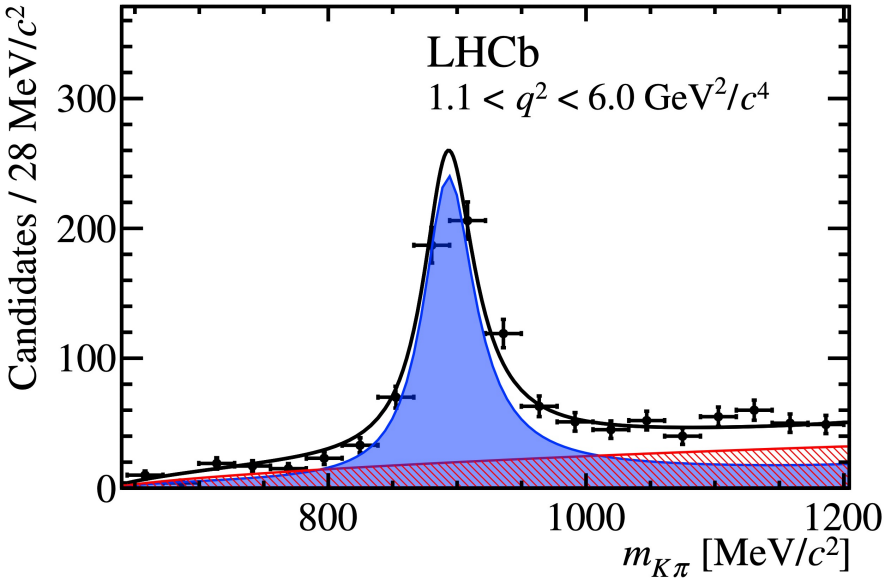
$B^0 \to J/\psi(e^+e^-)K_S^0$ and $B^+ \to J/\psi(e^+e^-)K^{*+}$: $[6.0 < q^2/\mathrm{GeV}^2 < 11.0]$

$B^0 \to J/\psi(\mu^+\mu^-)K_S^0$ and $B^+ \to J/\psi(\mu^+\mu^-)K^{*+}$: $[8.98 < q^2/\mathrm{GeV}^2 < 10.02]$

K^{*+} mass:

$$\left|m\left(K_S^0\pi^+\right) - m(K^{*+})_{\mathrm{PDG}}\right| < 300\ \mathrm{MeV}$$

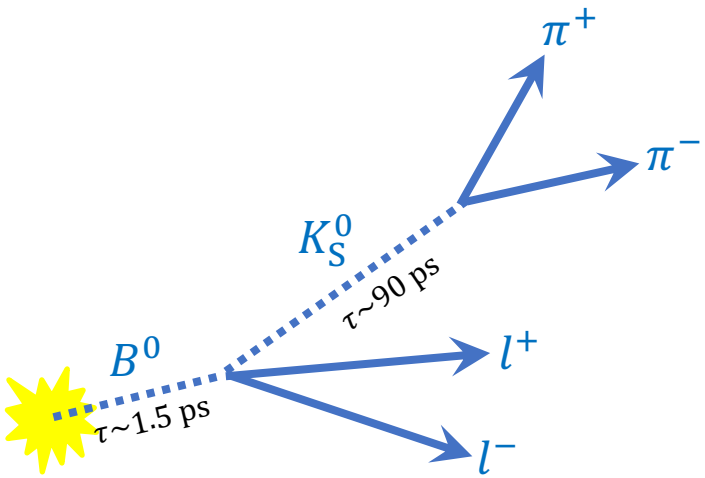
Expect roughly 22% S-wave component based on LHCb $B^0 \to K^+\pi^-\mu^+\mu^-$ analysis. [JHEP 11 (2016) 47]



Selection

Level 0 Trigger

- Muon decays selected by L0 muon trigger
- Electron decays selected by L0 electron or hadron trigger or be triggered on 'independent' part of underlying event

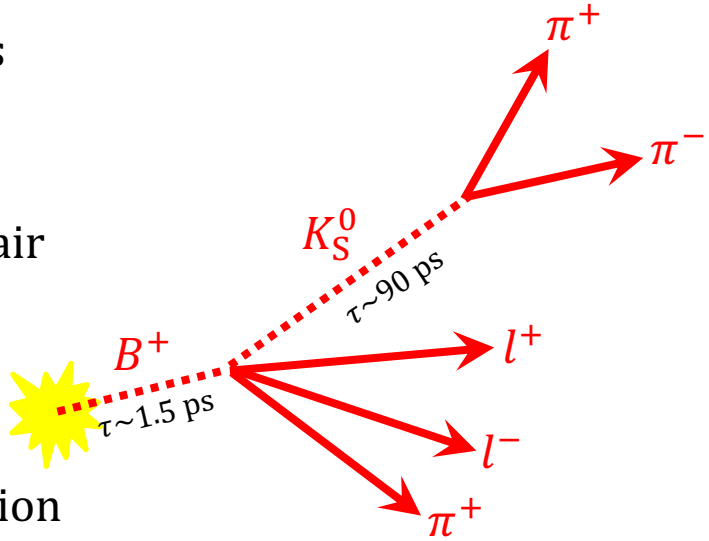


High-Level Trigger (HLT)

- HLT1: candidates selected using **single track** trigger requiring high p_T and impact parameter
- HLT2: candidates selected using **topological** triggers

Selection

- Candidates made by combining displaced dilepton pair with K_S^0 candidate (and π^+ for B^+ modes)
- Requirements on vertex quality, momentum and separation from primary interaction
- **Boosted decision trees** trained on data and simulation used to reject combinatorial background



Backgrounds

Backgrounds from mis-reconstructed b-hadron decays

Reduced to negligible levels by kinematic, mass and PID requirements:

B^0 backgrounds	B^+ backgrounds	
$H_b \to hh'\ell^+\ell^-$	$H_b \to hh'\pi^+\ell^+\ell^-$	$B^0 \to K_S^0\ell^+\ell^-$ + random π^+
$\Lambda_b \to \Lambda\ell^+\ell^-$	$\Lambda_b \to \Lambda hh\ell^+\ell^-$	$B^+ \to J/\psi(\ell^+\ell^-)K^{*+}(K_S^0\pi^+)$ with $\ell^+ \leftrightarrow \pi^+$ swap
$B^0 \to D^-(K_S^0X)Y$	$B^+ \to \bar{D}^0(K_S^0\pi^+X)Y$	$B^+ \to \psi_{2S}(\ell^+\ell^-)K^{*+}(K_S^0\pi^+)$ with $\ell^+ \leftrightarrow \pi^+$ swap

$X,Y = \pi^\pm$ or $\ell^\pm\nu_l$

Modelled in the fits

- B^0: part. reco. $B^+ \to K^{*+}(K_S^0\pi^+)\ell^+\ell^-$ and mis-ID $B^0 \to K_S^0\pi^+\pi^-$
- B^+: part. reco. $B \to K^*(K_S^0\pi^+\pi^-)\ell^+\ell^-$ and mis-ID $B^+ \to K^{*+}\pi^+\pi^-$

Efficiency Calibration

Accurate calculation of efficiencies is essential to making an unbiased measurement.

Simulation is corrected using data-driven weights to improve agreement with data:

1. **PID efficiencies**
2. **Electron tracking efficiency**
3. **Generated B kinematics**
4. **Event multiplicity**
5. **Fraction of K_S^0 mesons from long and downstream tracks**
6. **Trigger response**
7. **BDT response**
8. **q^2 resolution**

Maximum likelihood fits

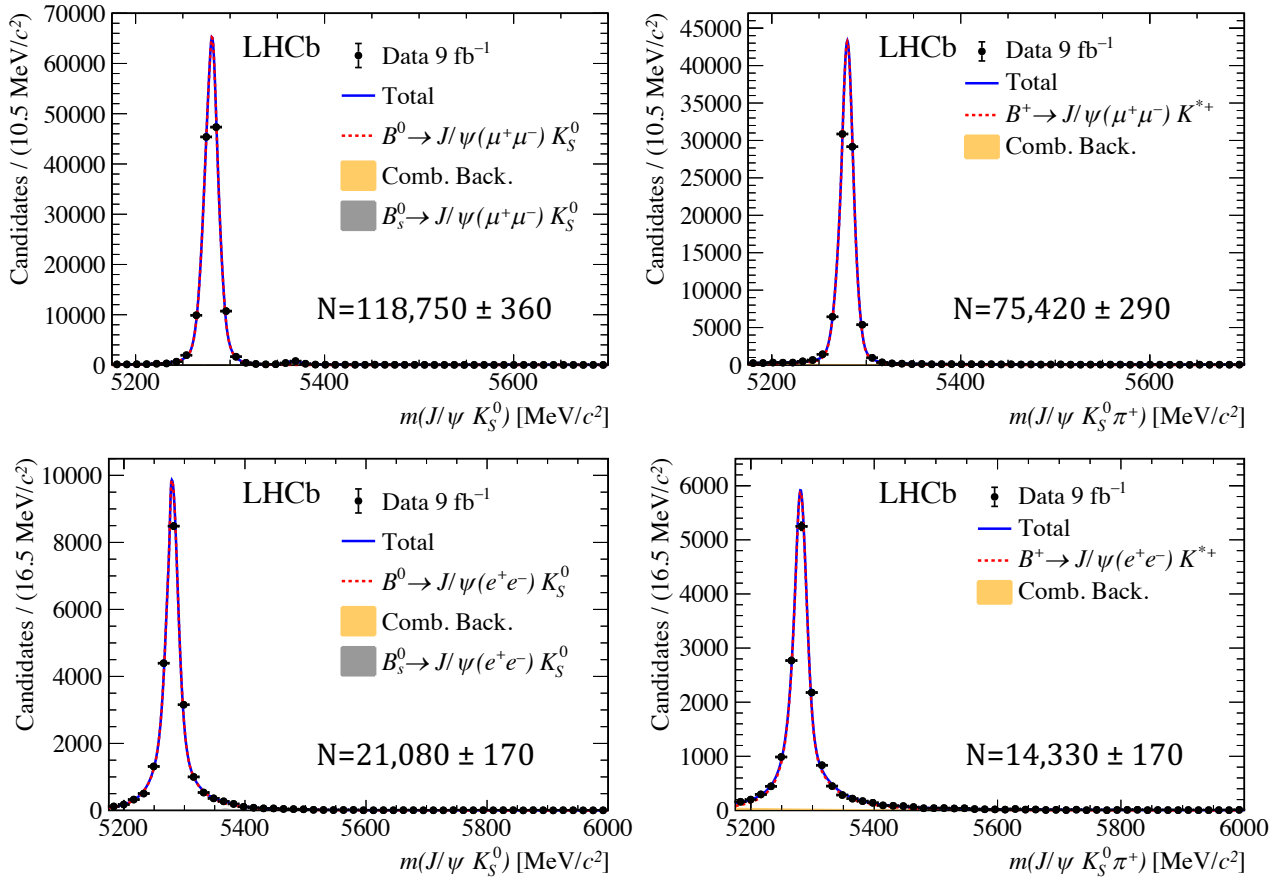
Yields of **control modes** extracted using maximum likelihood fits:

- Resolution improved by constraining J/ψ and K_S^0 mass
- Parameters of control mode PDFs from simulation except mean and width

B^0 B^+

muons

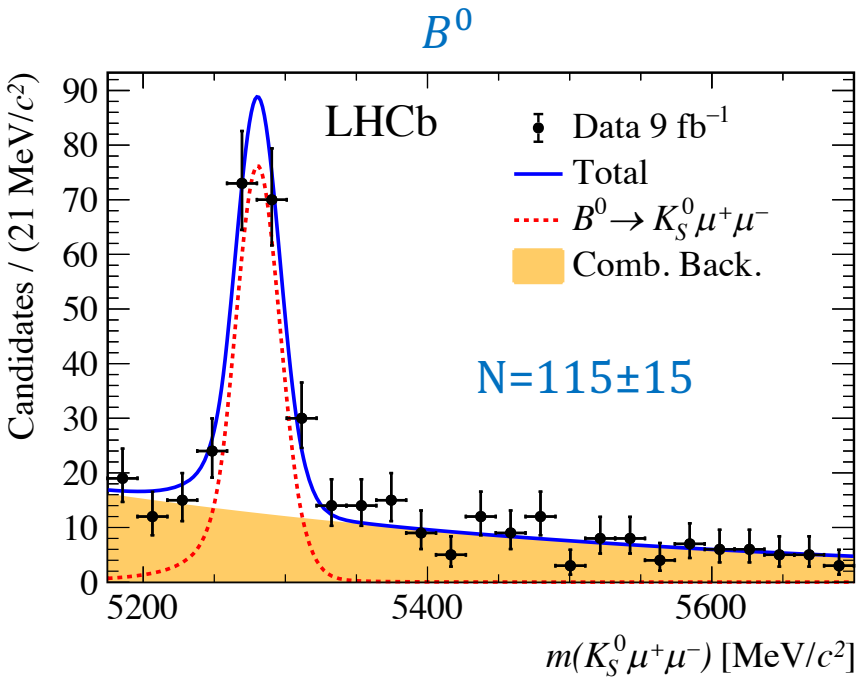
electrons

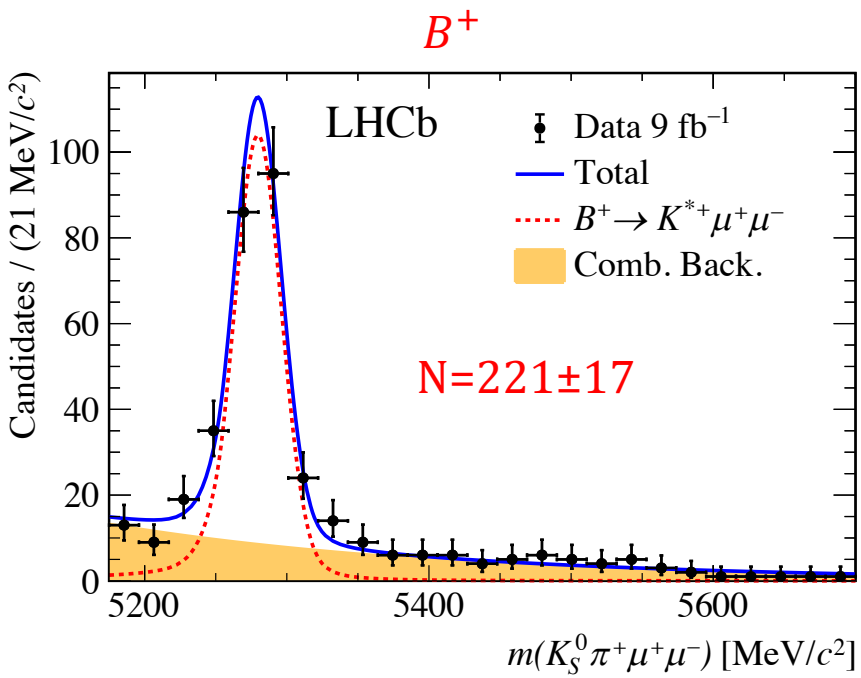


Maximum likelihood fits

Yields of **signal muon modes** and $R_{K^{(*)}}$ extracted using simultaneous maximum likelihood fits to signal mass spectra:

- Resolution improved by constraining K_S^0 mass
- Parameters of signal PDFs from simulation
- Shifts in mean and width from control mode data fits





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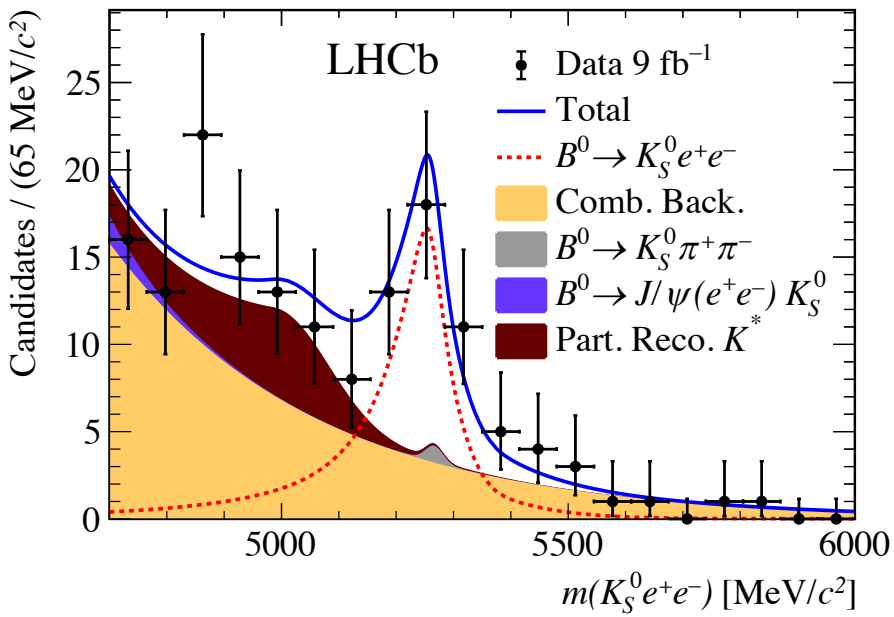
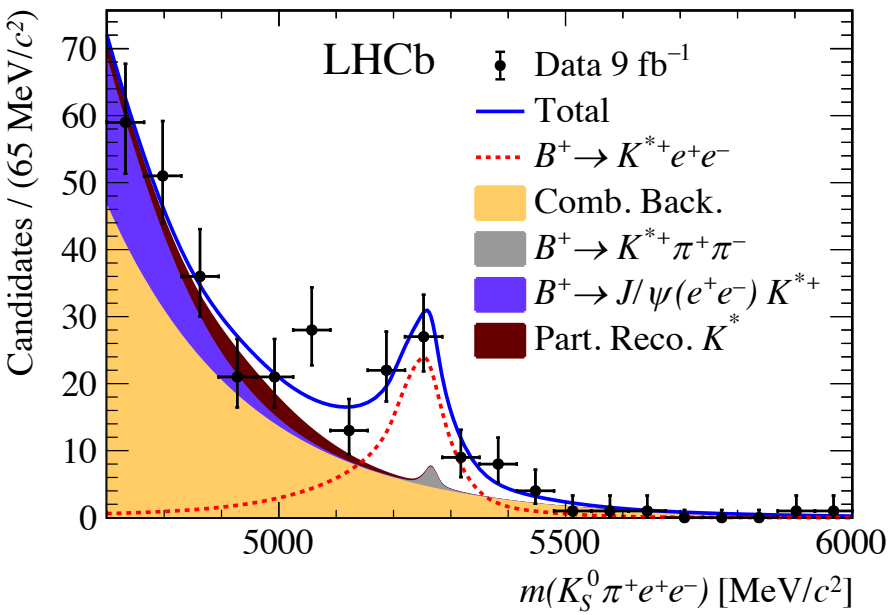
B^0



$B^0 \to K_S^0 \ell^+\ell^-$ significance: 5.3σ

B^+



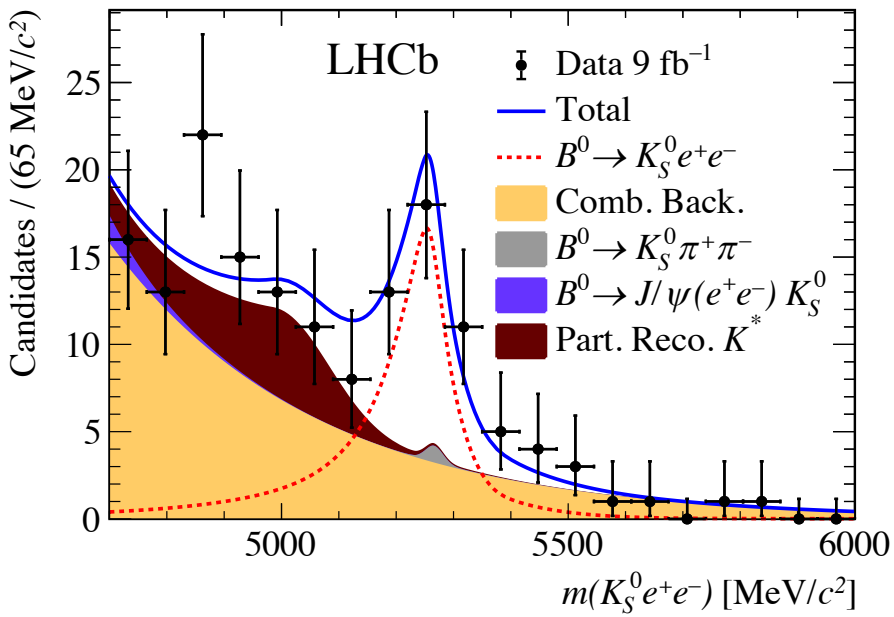
$B^+ \to K^{*+} \ell^+\ell^-$ significance: 6.0σ

Maximum likelihood fits

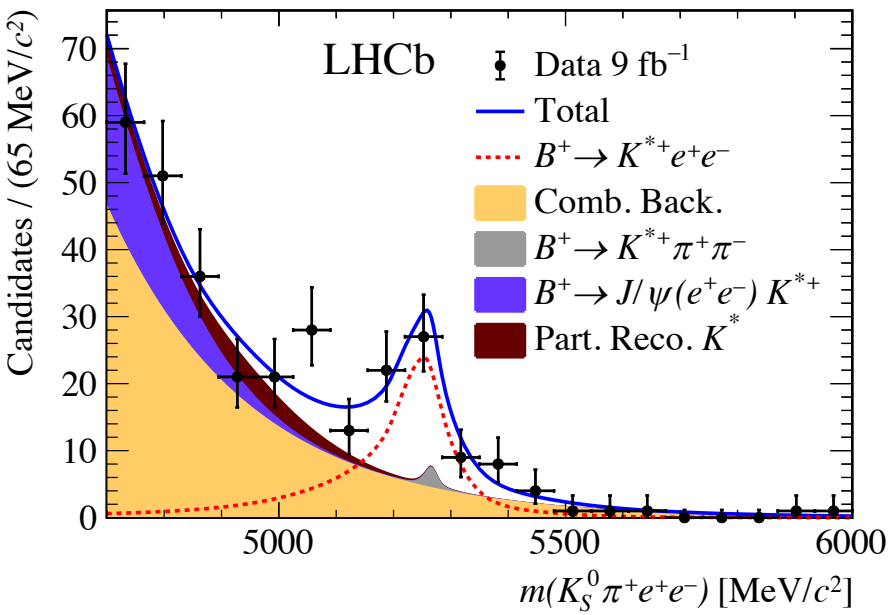
Yields of **signal muon modes** and $R_{K^{(*)}}$ extracted using simultaneous maximum likelihood fits to signal mass spectra:

- Resolution improved by constraining K_S^0 mass
- Parameters of signal PDFs from simulation
- Shifts in mean and width from control mode data fits

First Observation!



$B^0 \to K_S^0 \ell^+\ell^-$ significance: 5.3σ



$B^+ \to K^{*+} \ell^+\ell^-$ significance: 6.0σ

Systematic Uncertainties

Dominant systematics (~2-3%):

- statistical uncertainty on efficiencies

Next-to-dominant (1-2%):

- size of sample of simulated candidates used to determine PDF shapes
- models used for partially reconstructed and J/ψ leakage backgrounds

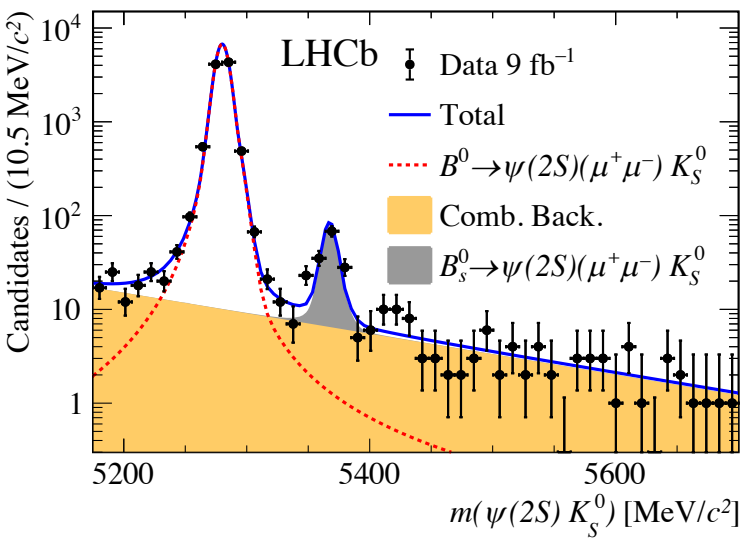
Sub-dominant (≤1%):

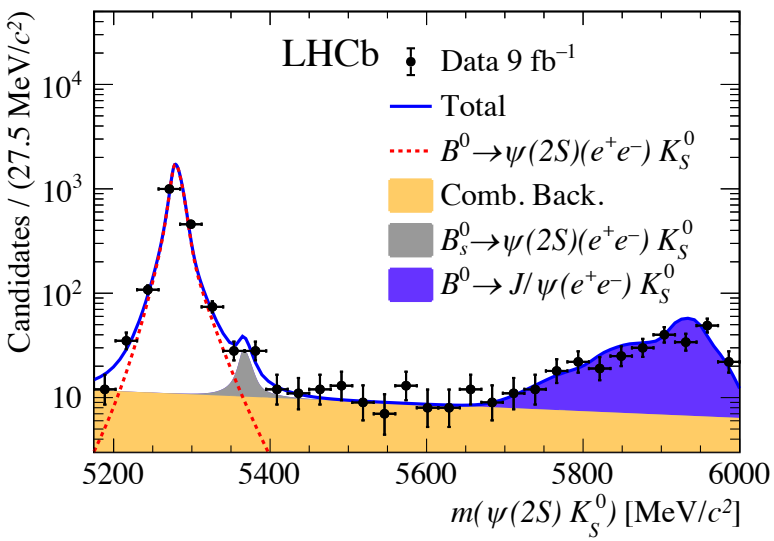
- size of simulated samples used to determine correction weights
- PID efficiency correction: choice of binning and correlation in efficiency between the two electrons
- Choice of method used to calculate trigger correction
- imperfect modelling of muon track reconstruction efficiency
- residual mismodelling of the BDT classifier response in simulation
- residual contamination from cascade D decays
- residual bias in the fitting procedure evaluated using pseudoexperiments

Validation

Method validated by measuring double ratio:

$$R^{-1}_{\psi(2S)K^{(*)}} = \frac{N\left(B\to\psi_{2S}(e^+e^-)K^{(*)}\right)}{N\left(B\to\psi_{2S}(\mu^+\mu^-)K^{(*)}\right)}\frac{N\left(B\to J/\psi(\mu^+\mu^-)K^{(*)}\right)}{N\left(B\to J/\psi(e^+e^-)K^{(*)}\right)}\cdot\frac{\epsilon\left(B\to\psi_{2S}(\mu^+\mu^-)K^{(*)}\right)}{\epsilon\left(B\to\psi_{2S}(e^+e^-)K^{(*)}\right)}\frac{\epsilon\left(B\to J/\psi(e^+e^-)K^{(*)}\right)}{\epsilon\left(B\to J/\psi(\mu^+\mu^-)K^{(*)}\right)}$$





Finding:

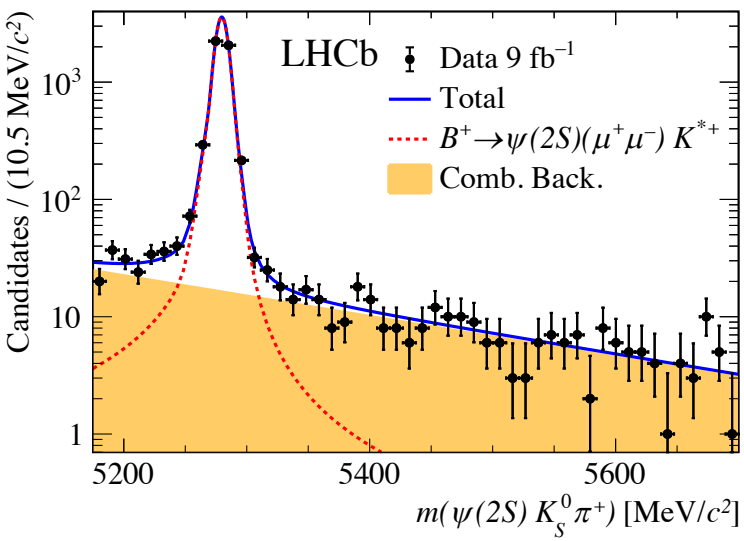
$$R^{-1}_{\psi(2S)K^0_S} = 1.014 \pm 0.030\ (\text{stat.}) \pm 0.020\ (\text{syst.})$$

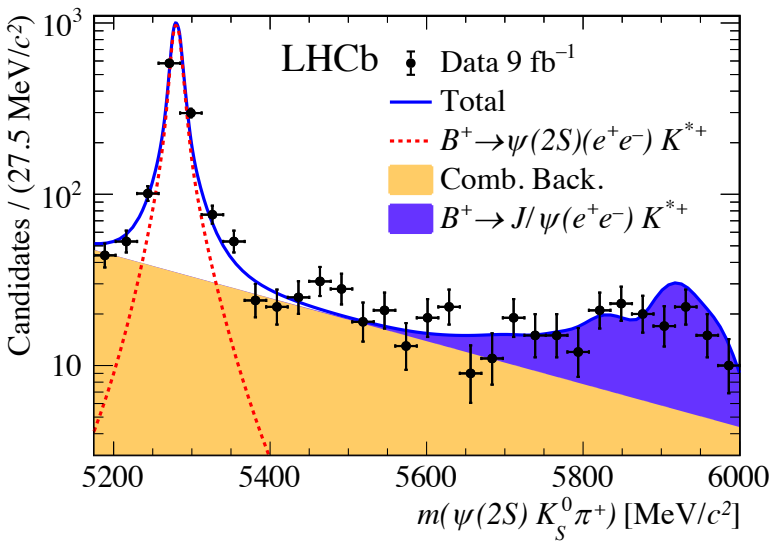
Consistent with unity.

Validation

Method validated by measuring double ratio:

$$R^{-1}_{\psi(2S)K^{(*)}} = \frac{N\left(B\to\psi_{2S}(e^+e^-)K^{(*)}\right)}{N\left(B\to\psi_{2S}(\mu^+\mu^-)K^{(*)}\right)}\frac{N\left(B\to J/\psi(\mu^+\mu^-)K^{(*)}\right)}{N\left(B\to J/\psi(e^+e^-)K^{(*)}\right)}\cdot\frac{\epsilon\left(B\to\psi_{2S}(\mu^+\mu^-)K^{(*)}\right)}{\epsilon\left(B\to\psi_{2S}(e^+e^-)K^{(*)}\right)}\frac{\epsilon\left(B\to J/\psi(e^+e^-)K^{(*)}\right)}{\epsilon\left(B\to J/\psi(\mu^+\mu^-)K^{(*)}\right)}$$





Finding:

$$R^{-1}_{\psi(2S)K^{*+}} = 1.017 \pm 0.045\ (\text{stat.}) \pm 0.023\ (\text{syst.})$$

Consistent with unity.

Validation

Validation of the method by measuring single ratio:

$$r^{-1}_{J/\psi K^{(*)}} = \frac{N\left(B \to J/\psi(e^+e^-)K^{(*)}\right)}{N\left(B \to J/\psi(\mu^+\mu^-)K^{(*)}\right)} \cdot \frac{\epsilon\left(B \to J/\psi(\mu^+\mu^-)K^{(*)}\right)}{\epsilon\left(B \to J/\psi(e^+e^-)K^{(*)}\right)}$$

Stringent test of analysis due to lack of cancellation of electron vs muon systematics.

Finding:

$$r^{-1}_{J/\psi K^0_S} = 0.977 \pm 0.008\ (\text{stat.}) \pm 0.027\ (\text{syst.})$$

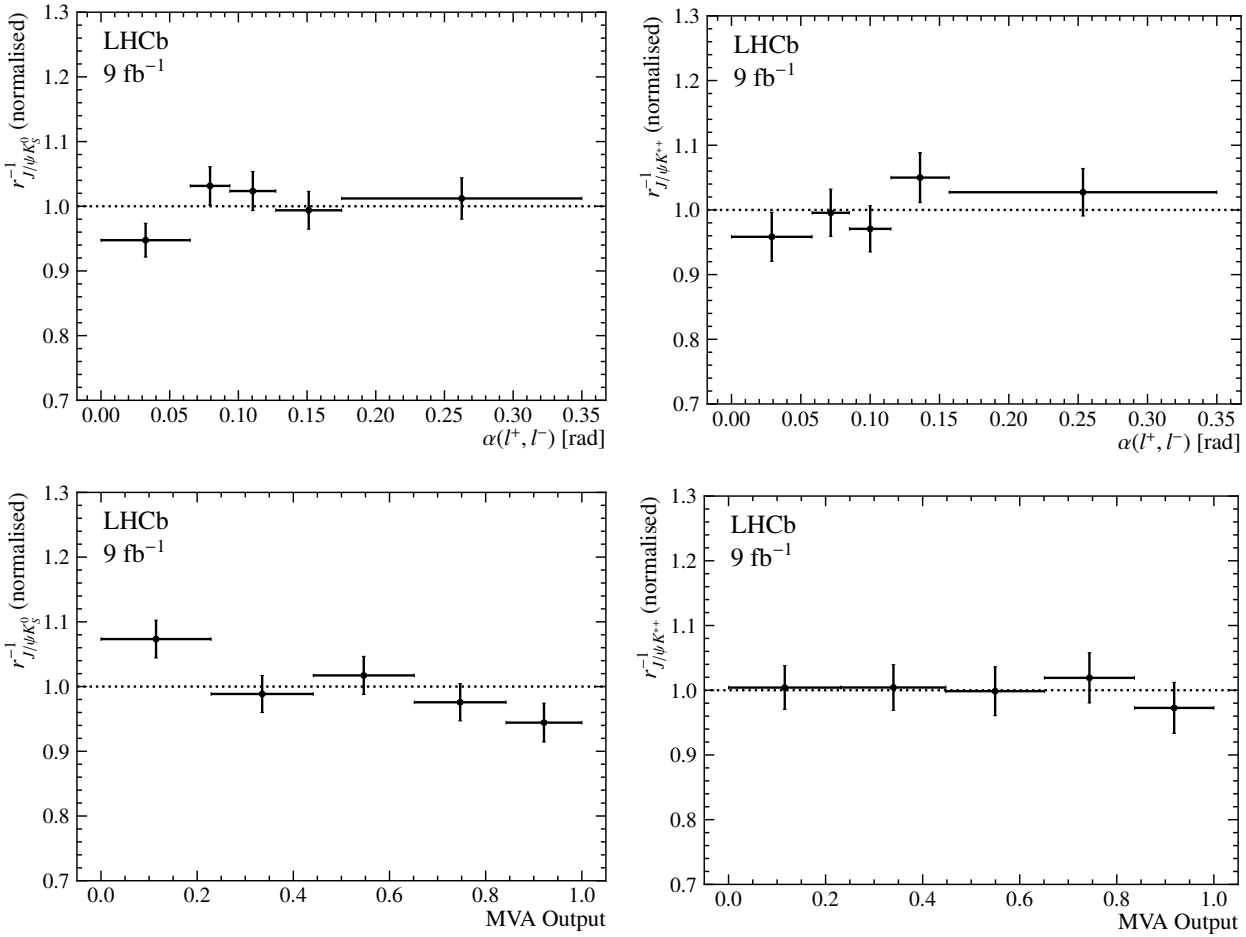
and

$$r^{-1}_{J/\psi K^{*+}} = 0.965 \pm 0.011\ (\text{stat.}) \pm 0.045\ (\text{syst.})$$

Both consistent with unity.

Validation

We also study $r^{-1}_{J/\psi K^{(*)}}$ differentially as a function of several variables that are differently distributed beween signal and control modes

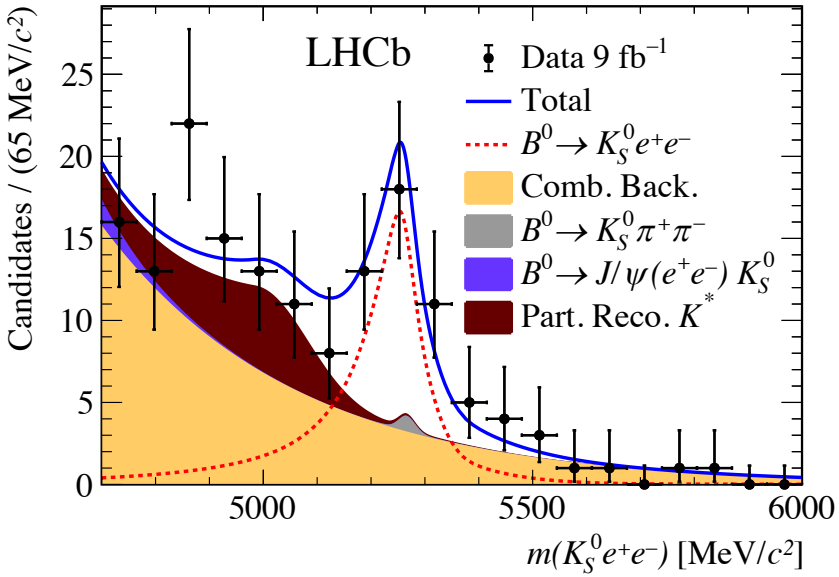


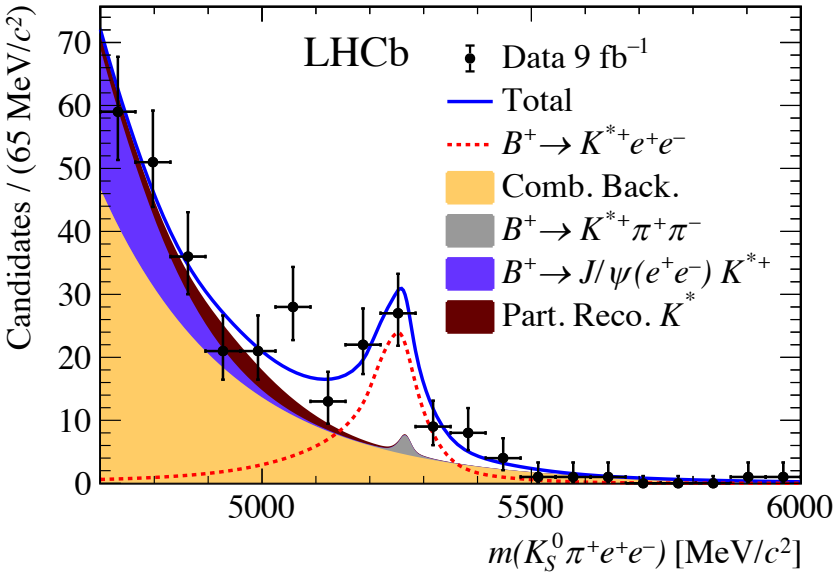
Di-lepton opening angle

MVA trained to distinguish signal from control decays

Results: Electron Decays

Electron modes are **observed for the first time**





$B^0 \to K_S^0 \ell^+\ell^-$ significance: 5.3σ

$B^+ \to K^{*+} \ell^+\ell^-$ significance: 6.0σ

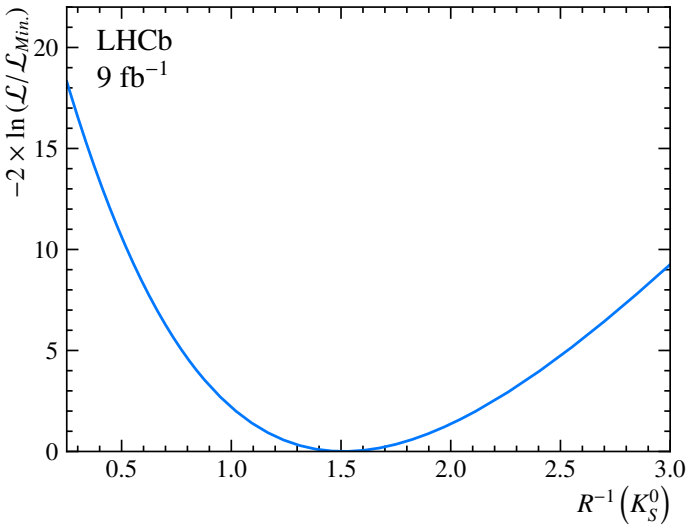
$$\frac{d\mathcal{B}(B^0 \to K_S^0 e^+e^-)}{dq^2} = 2.6 \pm 0.6 \pm 0.1 \times 10^{-8} \mathrm{GeV}^{-2} c^4$$

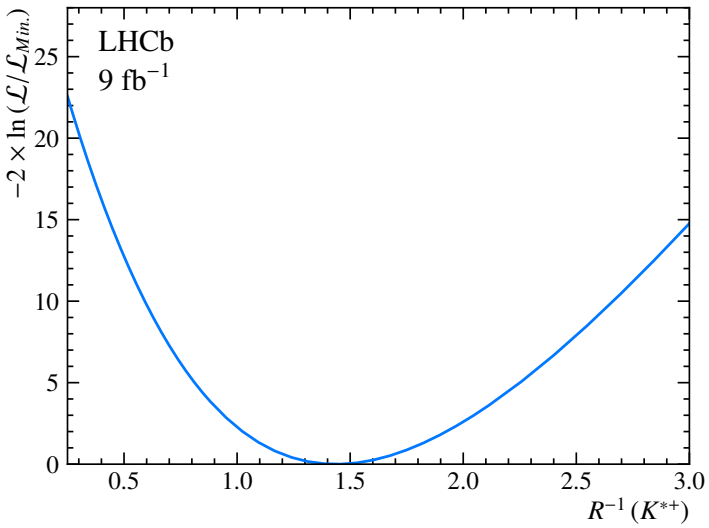
$[1.1 < q^2/\mathrm{GeV}^2 < 6.0]$

$$\frac{d\mathcal{B}(B^+ \to K^{*+} e^+e^-)}{dq^2} = 9.2^{+1.9+0.8}_{-1.8-0.6} \times 10^{-8} \mathrm{GeV}^{-2} c^4$$

$[0.045 < q^2/\mathrm{GeV}^2 < 6.0]$

Results: LFU Ratios





$$R^{-1}_{K^0_S} = 1.51^{+0.40}_{-0.35}(\text{stat})^{+0.09}_{-0.04}(\text{syst})$$

$$R^{-1}_{K^{*+}} = 1.44^{+0.32}_{-0.29}(\text{stat})^{+0.09}_{-0.06}(\text{syst})$$

Inverting values and 1σ intervals

$$R_{K^0_S} = 0.66^{+0.20}_{-0.15}(\text{stat})^{+0.02}_{-0.04}(\text{syst})$$

$$R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(\text{stat})^{+0.03}_{-0.04}(\text{syst})$$

$[1.1 < q^2/\text{GeV}^2 < 6.0]$

$[0.045 < q^2/\text{GeV}^2 < 6.0]$

Significance w.r.t SM: 1.5σ

Significance w.r.t SM: 1.4σ

Results: Combination

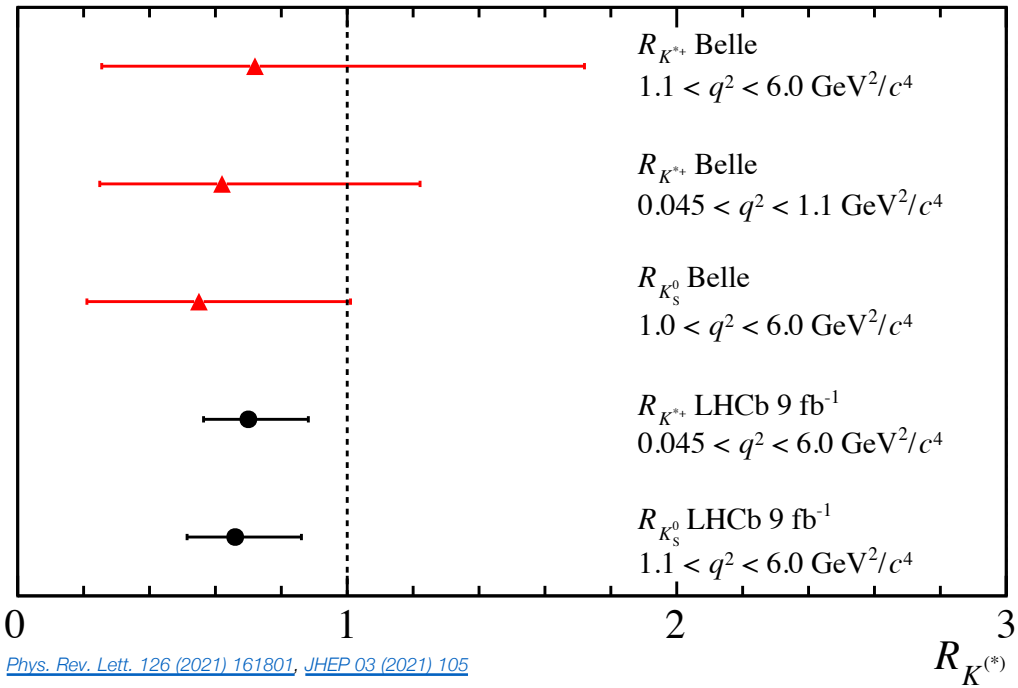
Two results combined to evaluate total significance with respect to the SM:

- Fit for Wilson Coefficients using Flavio [arxiv:1810.08132]
- Float $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ (LFU ratios cannot disentangle C_9 and C_{10})

Combined significance = 2σ

Best fit value:

$$C_9^{bs\mu\mu} = -0.8^{+0.4}_{-0.3}$$



Phys. Rev. Lett. 126 (2021) 161801, JHEP 03 (2021) 105

Conclusions

Today:

- **First observation** of $B^0 \to K_S^0 e^+ e^-$ and $B^+ \to K^{*+} e^+ e^-$ decays at 5.3σ and 6.0σ
- World's most precise measurements of $B^0 \to K_S^0 e^+ e^-$ and $B^+ \to K^{*+} e^+ e^-$ **differential branching** fractions at low q^2
- World's most precise **tests of lepton universality** in $B^0 \to K_S^0 \ell^+ \ell^-$ and $B^+ \to K^{*+} \ell^+ \ell^-$ decays

$$R_{K_S^0} = 0.66^{+0.20}_{-0.15}(\text{stat})^{+0.02}_{-0.04}(\text{syst})$$

$$R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(\text{stat})^{+0.03}_{-0.04}(\text{syst})$$

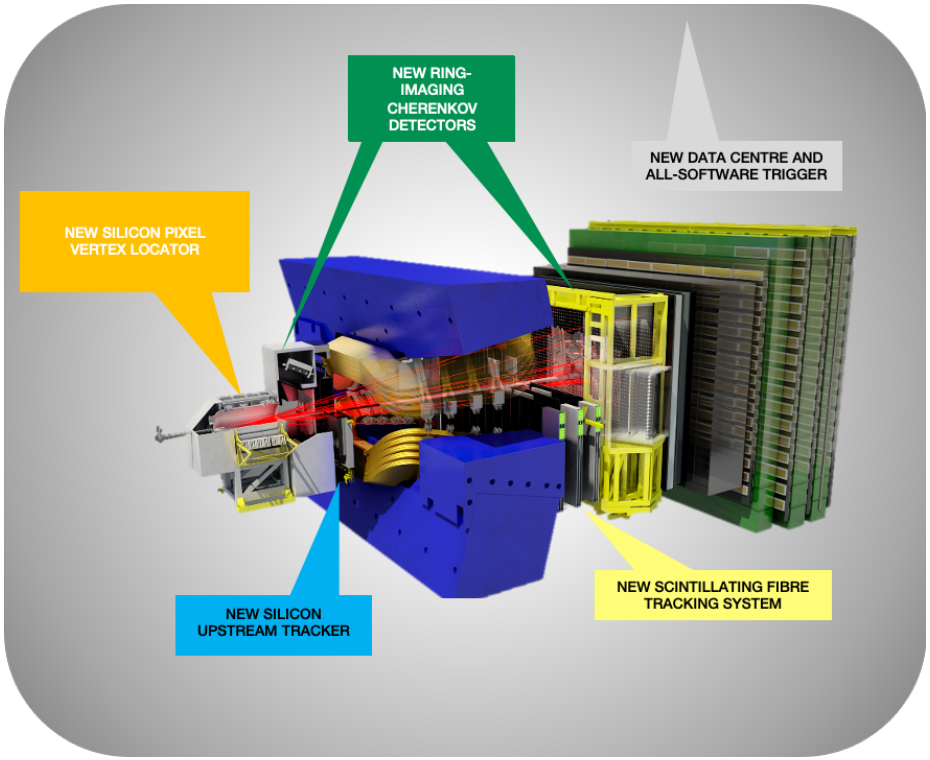
- Values consistent with SM at 1.5σ and 1.4σ
- Combined significance of WC fit compared to SM at 2σ
- Same pattern as deviations seen in other LFU tests

Many other LFU tests in progress at LHCb with full Run 1 and Run 2 data…

LHCb Upgrade

The **LHCb Upgrade** is coming soon!

- (Almost) all-new detector to allow readout at 30 MHz
- Full software trigger
- Data taking with five times previous rate

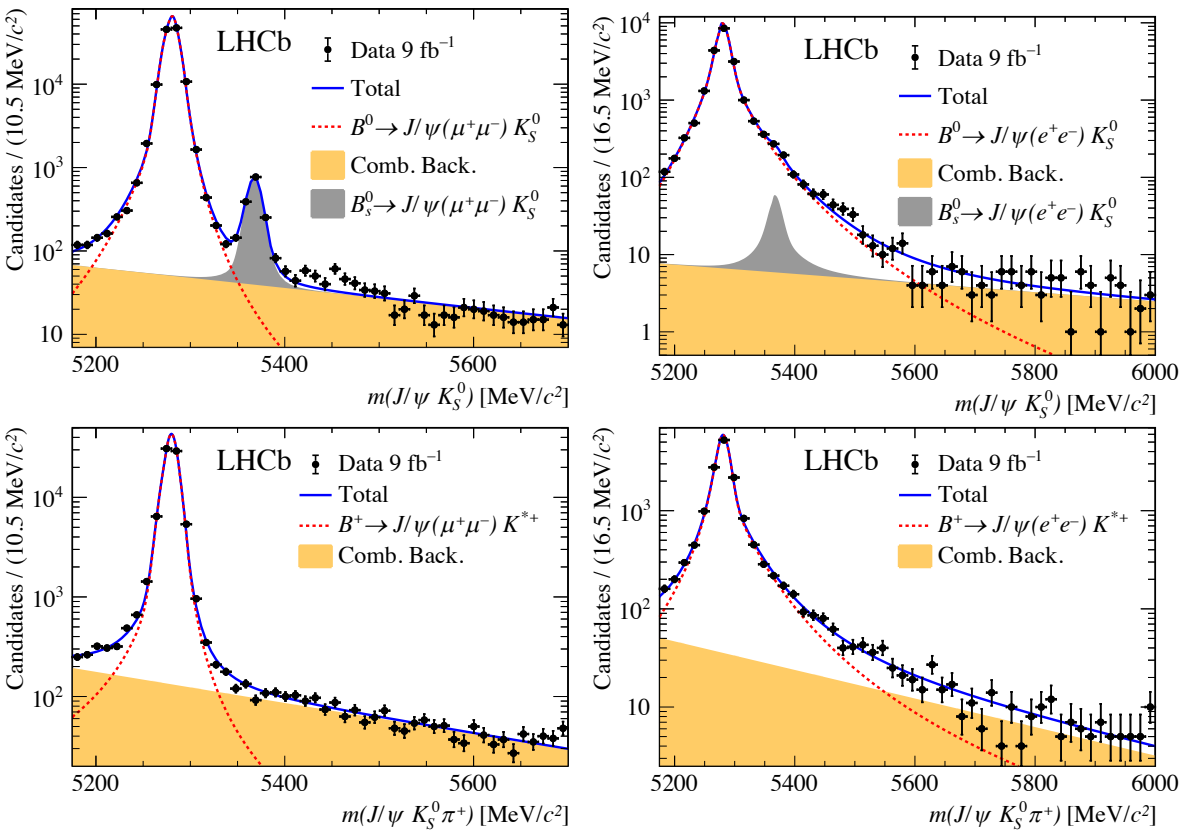


Backup

Maximum likelihood fits

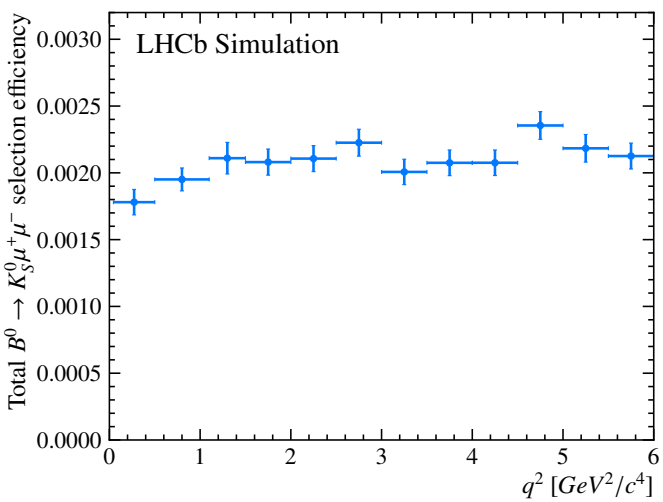
Yields of **control modes** extracted using maximum likelihood fits:

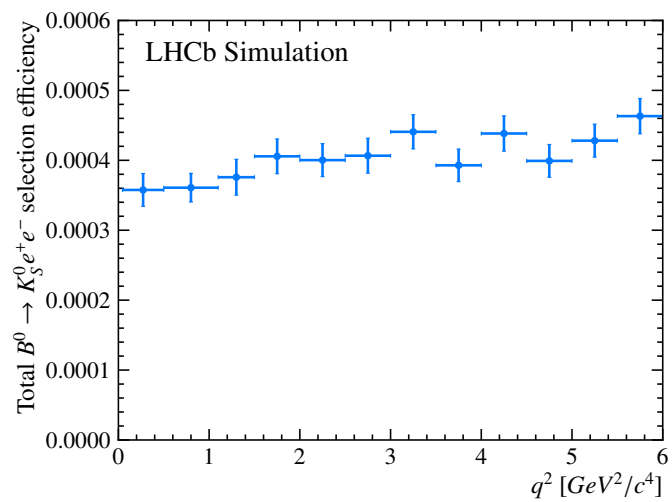
- Resolution improved by constraining J/ψ and K_S^0 mass
- Parameters of control mode PDFs determined from simulation with mean mass and mass resolution allowed to float in fit to data

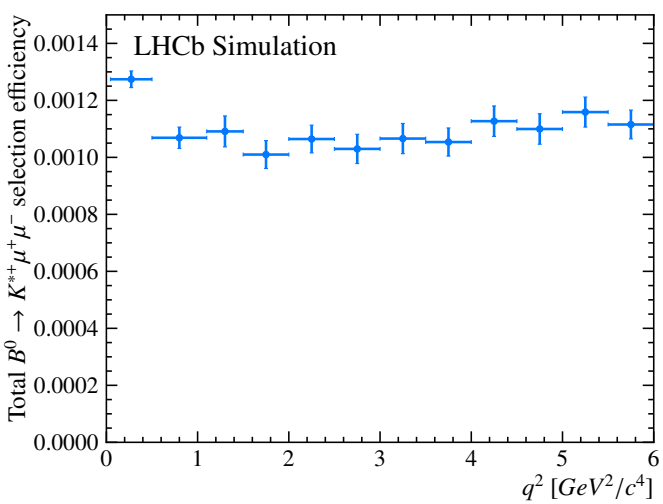


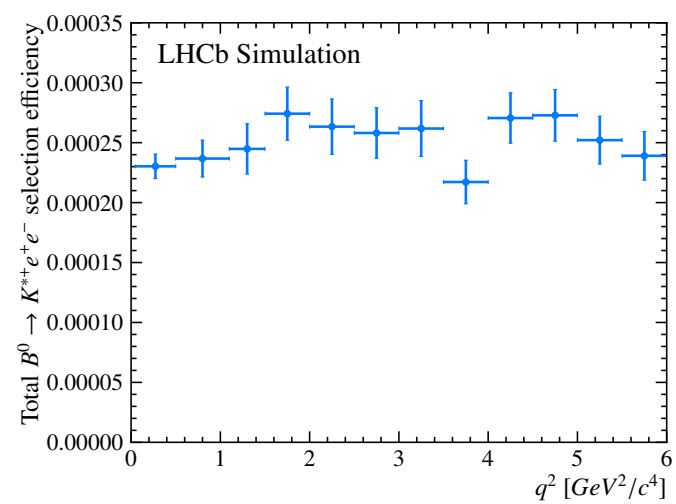
Decay	Yield
$B^0 \to J/\psi(\mu^+\mu^-)K_S^0$	118,750 ± 360
$B^0 \to J/\psi(e^+e^-)K_S^0$	21,080 ± 170
$B^+ \to J/\psi(\mu^+\mu^-)K^{*+}$	75,420 ± 290,
$B^+ \to J/\psi(e^+e^-)K^{*+}$	14,330 ± 170

Efficiencies

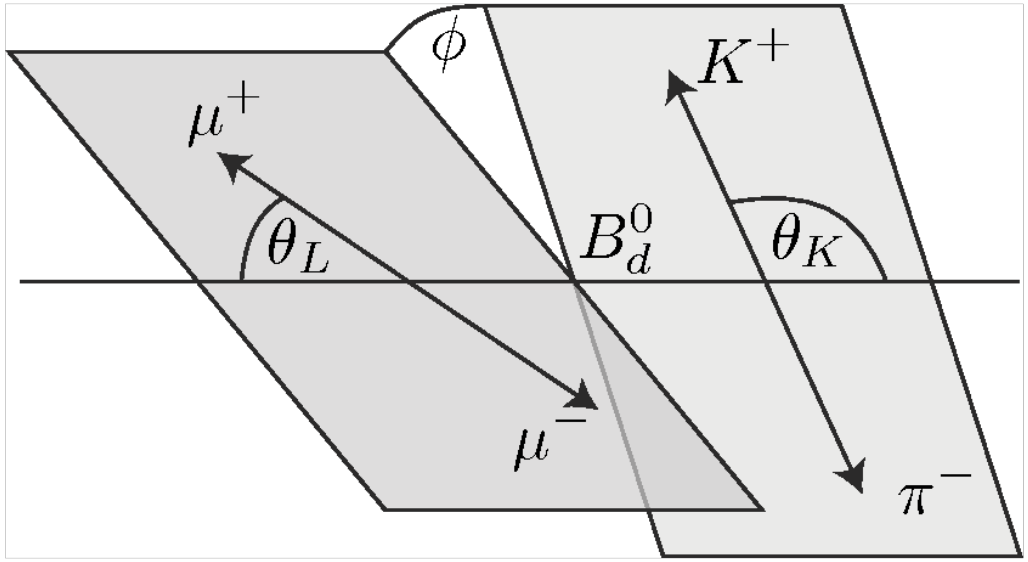








Angular Distributions



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