Seeking new fundamental phenomena in rare beauty decays

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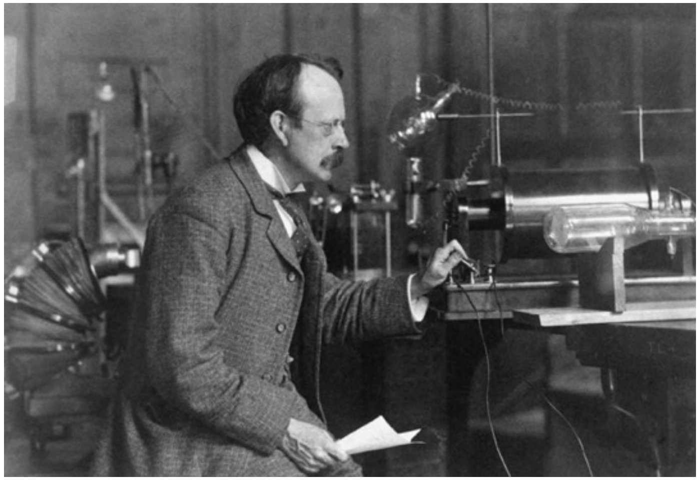
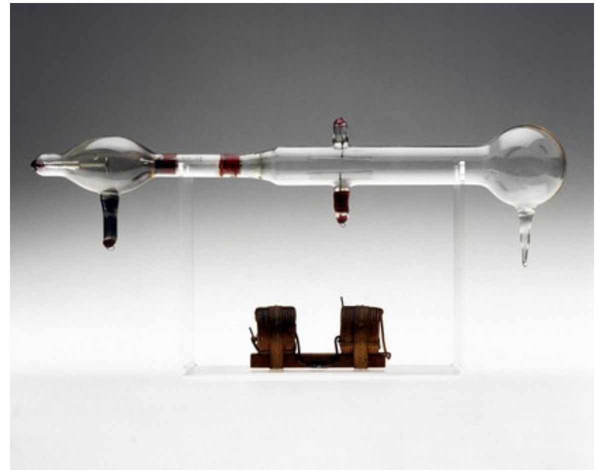
Teilchenphysik Seminar, TU Dortmund
Thursday 9th June 2022

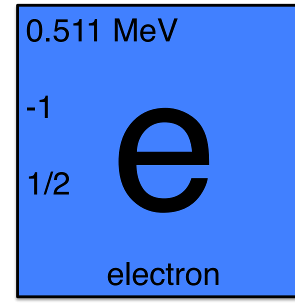
The Standard Model



J.J. Thomson, 7th August 1897



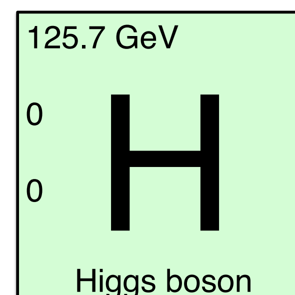
Cathode ray tube ~30cm long



Mass = 0.5 MeV

ATLAS and CMS, 4th July 2012

LHC ~ 3 million cm long



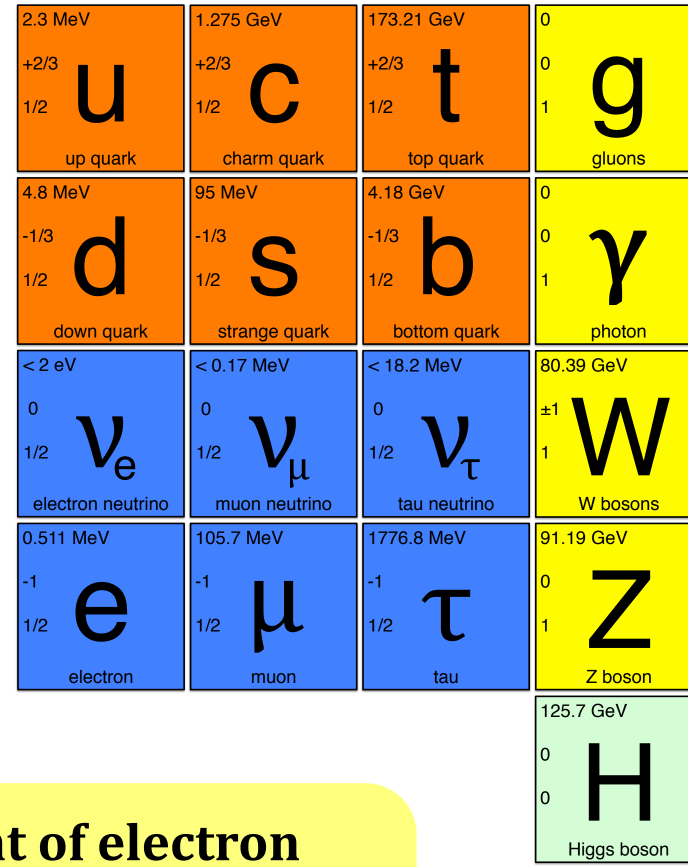
Mass = 125 GeV

The Standard Model

Quantum Field Theory with U(1) x SU(2) x SU(3) gauge symmetry:

- Three vector forces (EM, Weak, Strong)
- Six quarks
- Six leptons
- Mass generated by spontaneous symmetry breaking leaving one scalar Higgs boson

Stupendously successful!



Anomalous magnetic dipole moment of electron

Theory: $11596521807.3 \pm 2.8 \times 10^{-13}$

Experiment: $11596521817.8 \pm 7.6 \times 10^{-13}$

Beyond the Standard Model

Observational challenges:

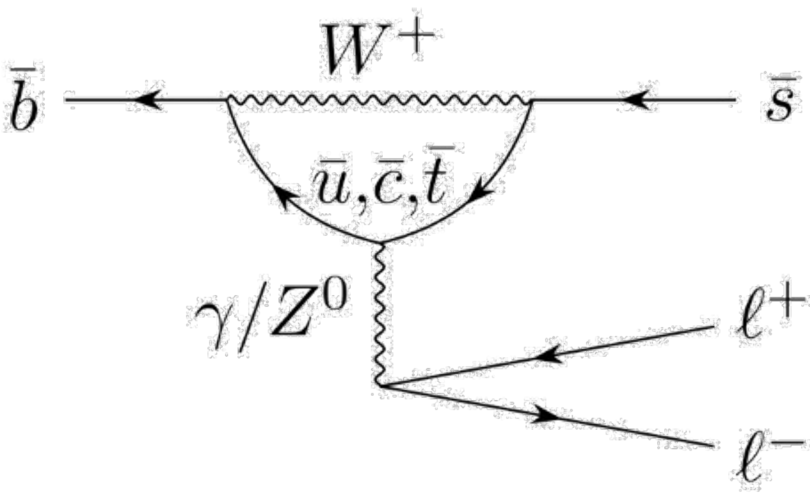
Matter-antimatter asymmetry

Open questions:

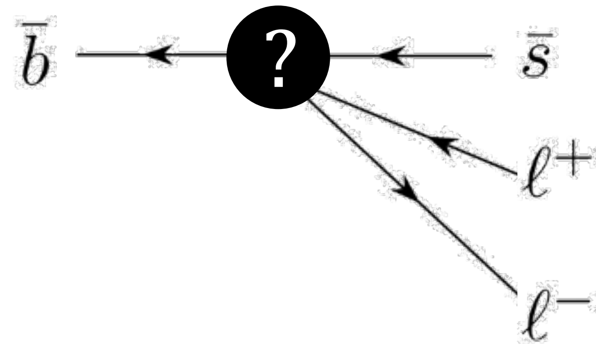
- Fine-tuning of the Higgs field (Hierarchy Problem)
- Origin of neutrino masses
- Flavour structure of the SM (why three generations, six quarks, six leptons?)
- Why U(1) x SU(2) x SU(3)?
- Unification of strong and electroweak forces?
- Gravity???

Why rare beauty decays?

Standard Model



New Physics

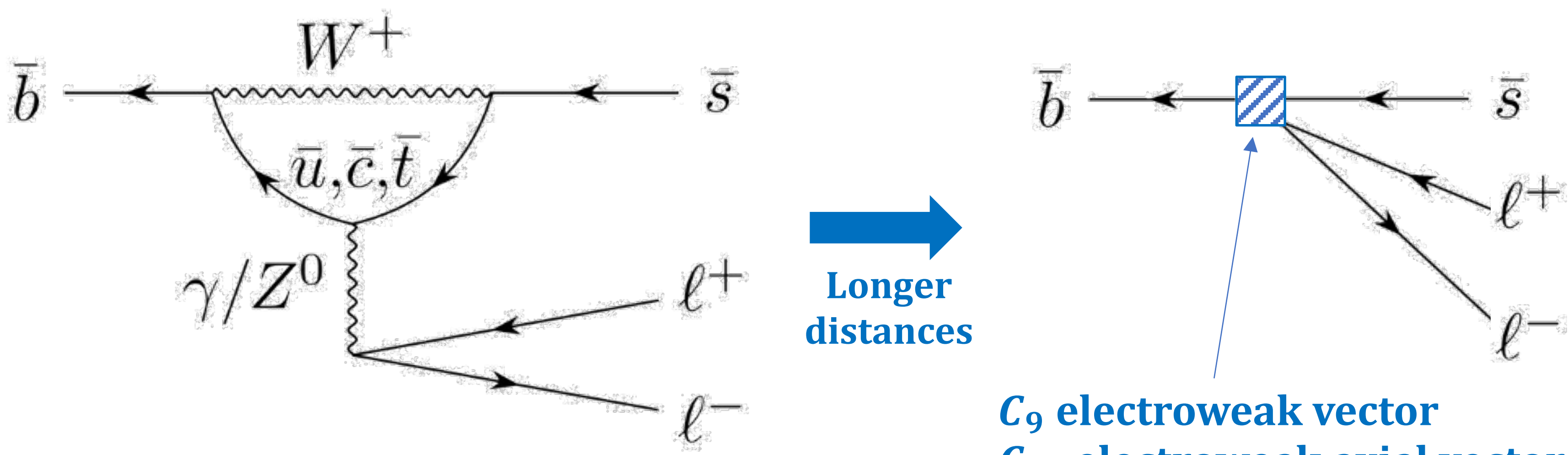


- $b \to s\ell^+\ell^-$ and $b\bar{s} \to \ell^+\ell^-$ transitions, are **flavour-changing neutral current** (FCNC) processes → forbidden at tree level in the Standard Model (SM)
- supressed in SM (branching fractions $\mathcal{O}(10^{-10})$–$\mathcal{O}(10^{-6})$) and hence sensitive to **New Physics**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

Effective Field Theory

Such 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**

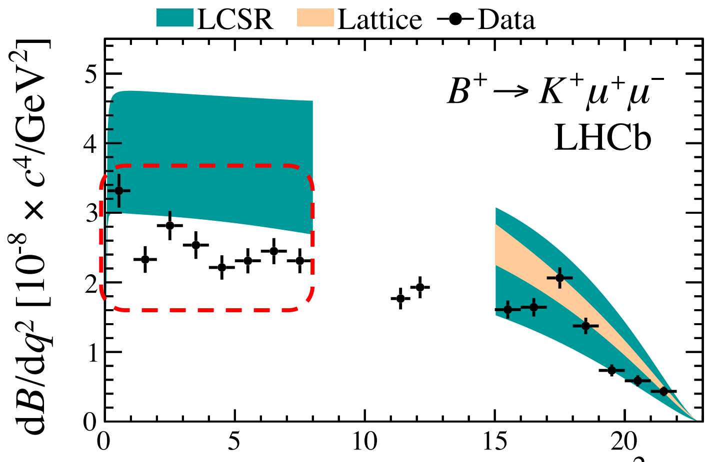


C_9 electroweak vector
C_{10} electroweak axial vector
C_7 electromagnetic

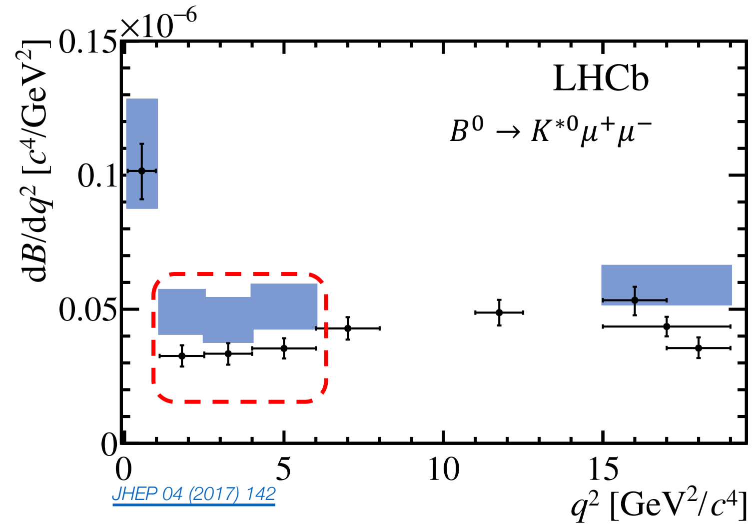
Flavour Anomalies

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

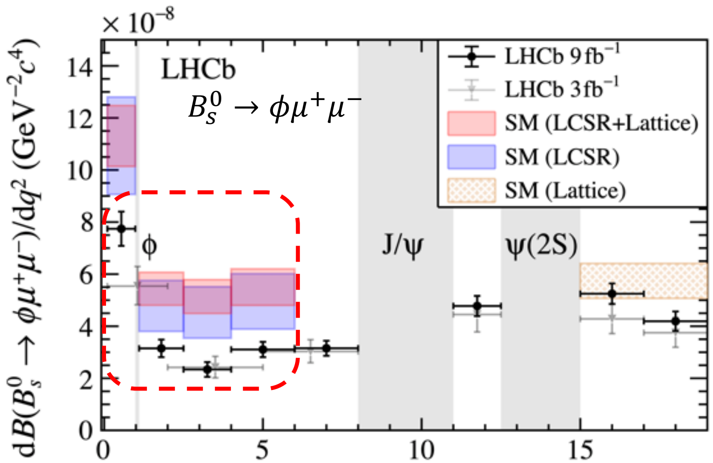
➢ **Branching fractions of $b \to s\mu^+\mu^-$ decays**



JHEP 1406 (2014) 133



JHEP 04 (2017) 142



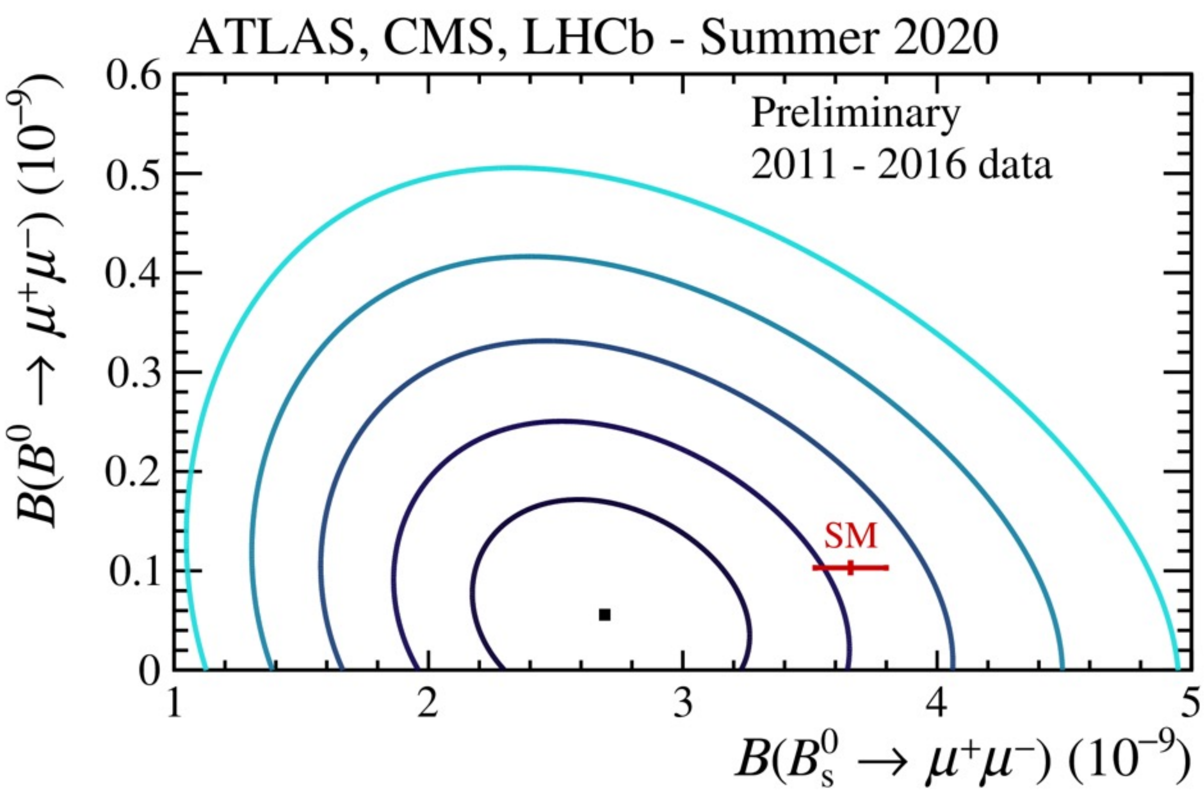
Phys. Rev. Lett. 127 (2021) 15

- 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:

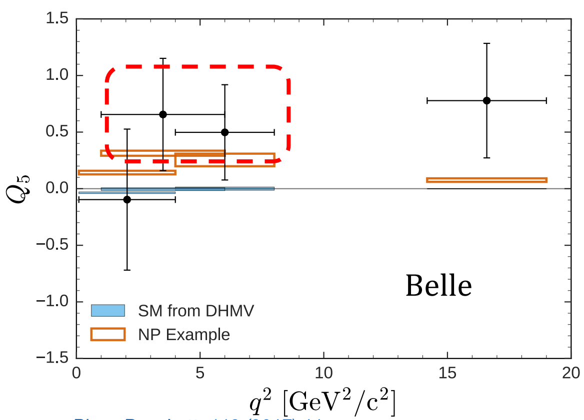
➢ **Branching fraction of $B^0_{(s)} \to \mu^+\mu^-$ decays**



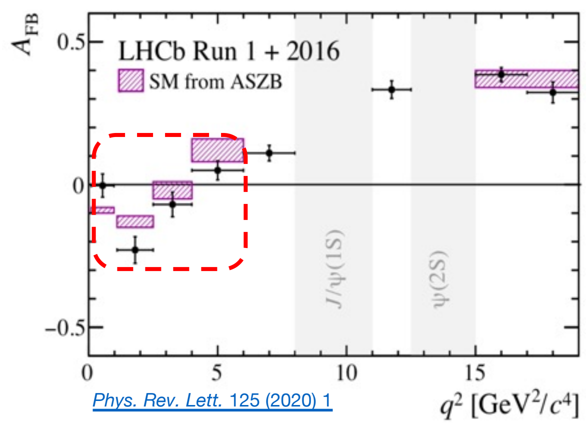
ATLAS-CONF-2020-049

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

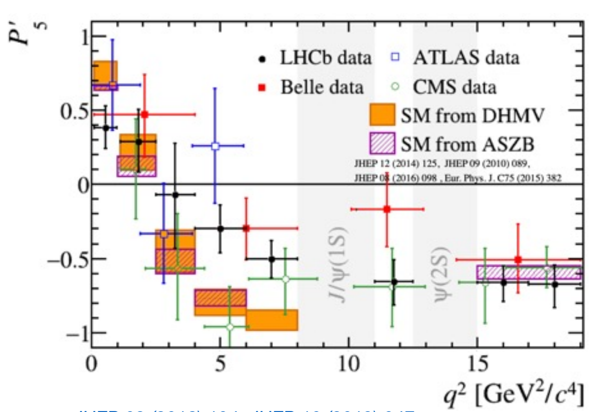
➢ **Angular analyses:** $B^0 \to K^{*0}\mu^+\mu^-$



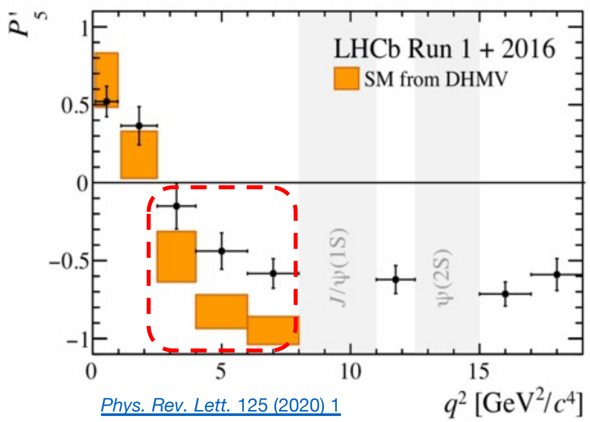
Phys. Rev. Lett. 118 (2017) 11



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

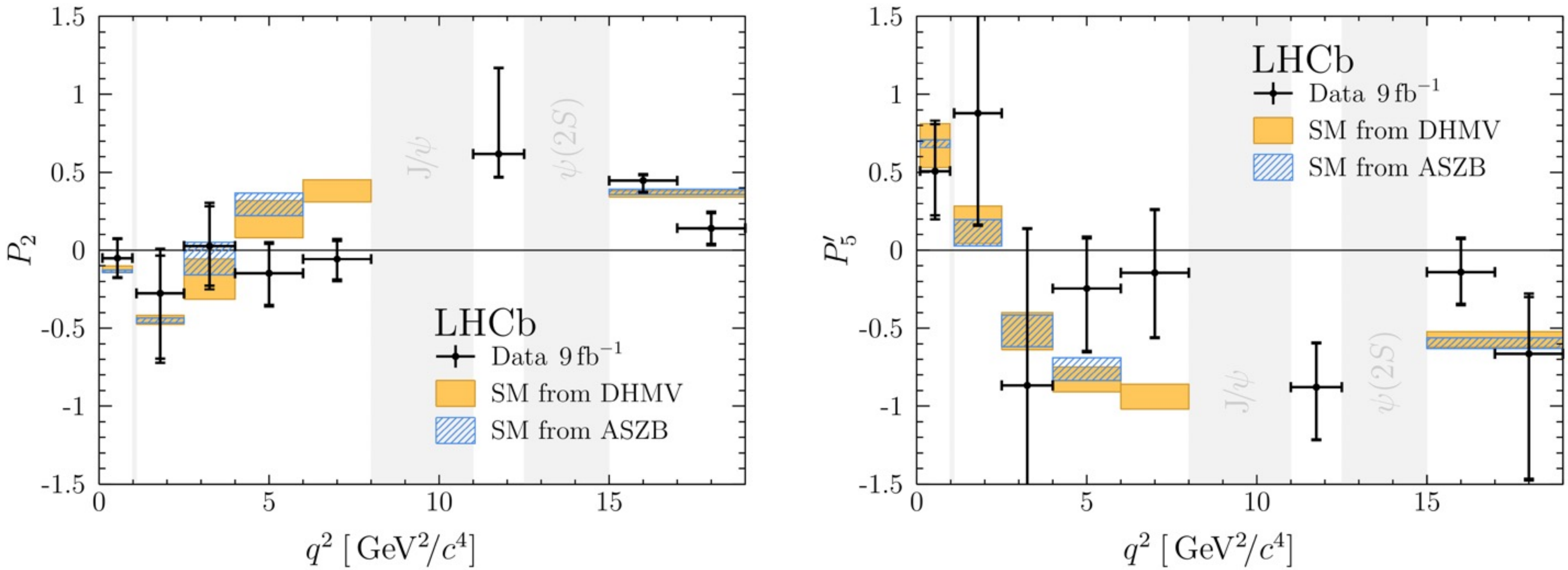


Phys. Rev. Lett. 125 (2020) 1

- 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

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

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]*

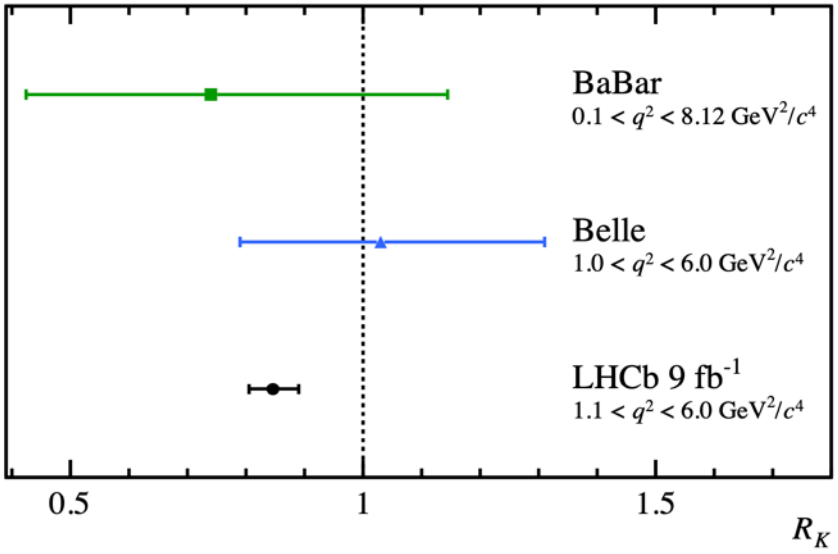
$B^+ \to K^+\ell^+\ell^-$ (9 fb^{-1})

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

3.1σ deviation from SM.

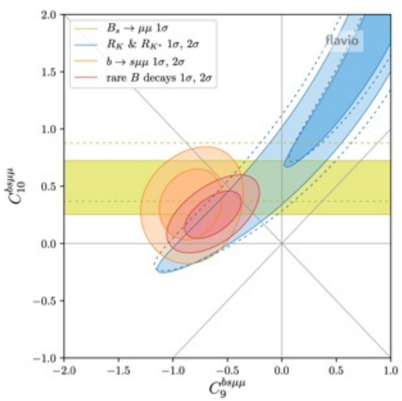
[Nature Physics 18, (2022) 277-282]

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

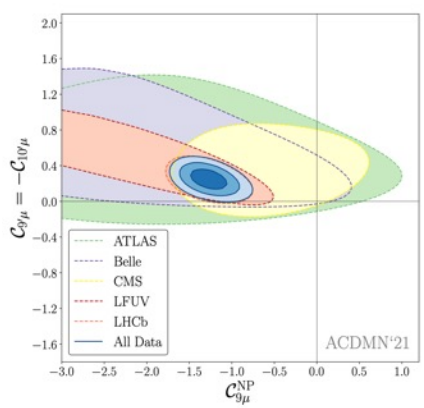


Global Fits

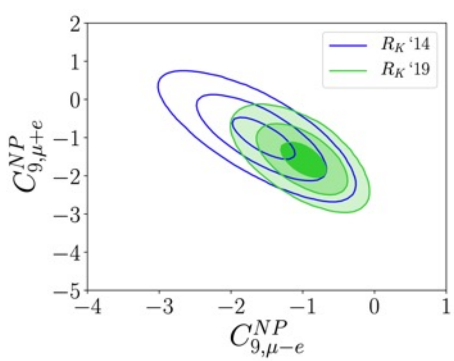
- Combination of of all $b \to s\ell^+\ell^-$ measurements (and $B_s^0 \to \mu^+\mu^-$) through fit for Wilson Coefficients
- Anomalies can be explained **coherently** by:
  - new vector coupling $C_9^{bs\mu\mu}$
  - new vector-axial vector coupling with $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$



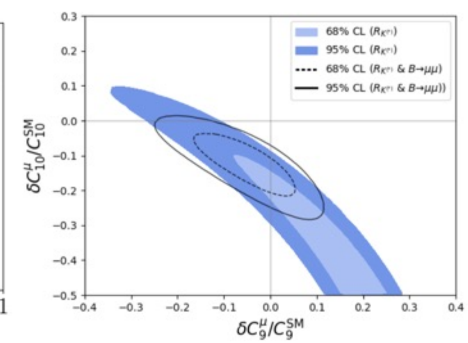
Altmannshofer & Stangl. arxiv:2103.13370



Algueró et al. arXiv:2104.08921



Cuichini et al. EPJ C79 (2019) 719

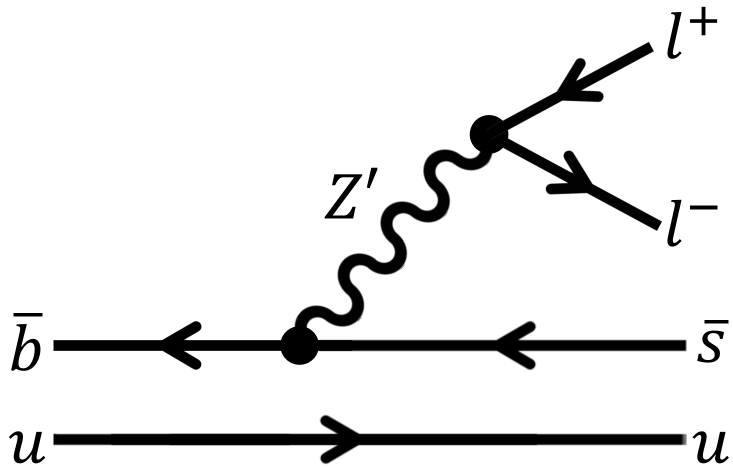


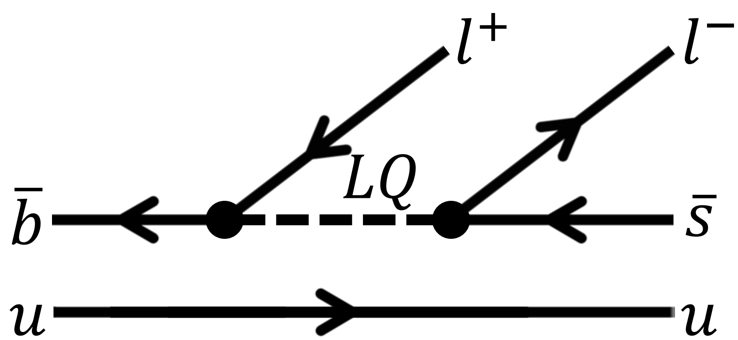
Hurth et al. arXiv:2104.10058

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 Physics?

Today:

1. **Tests of lepton universality** in $B^0 \to K_S^0 \ell^+ \ell^-$ and $B^0 \to K_S^0 \ell^+ \ell^-$ decays

2. **Measurements** of $B_s^0 \to \mu^+ \mu^-$ decays and search for $B^0 \to \mu^+ \mu^-$ and $B_s^0 \to \mu^+ \mu^- \gamma$ decays

New Tests of Lepton Universality

Tests of lepton universality using 2011-2012 and 2016-2018 dataset

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

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

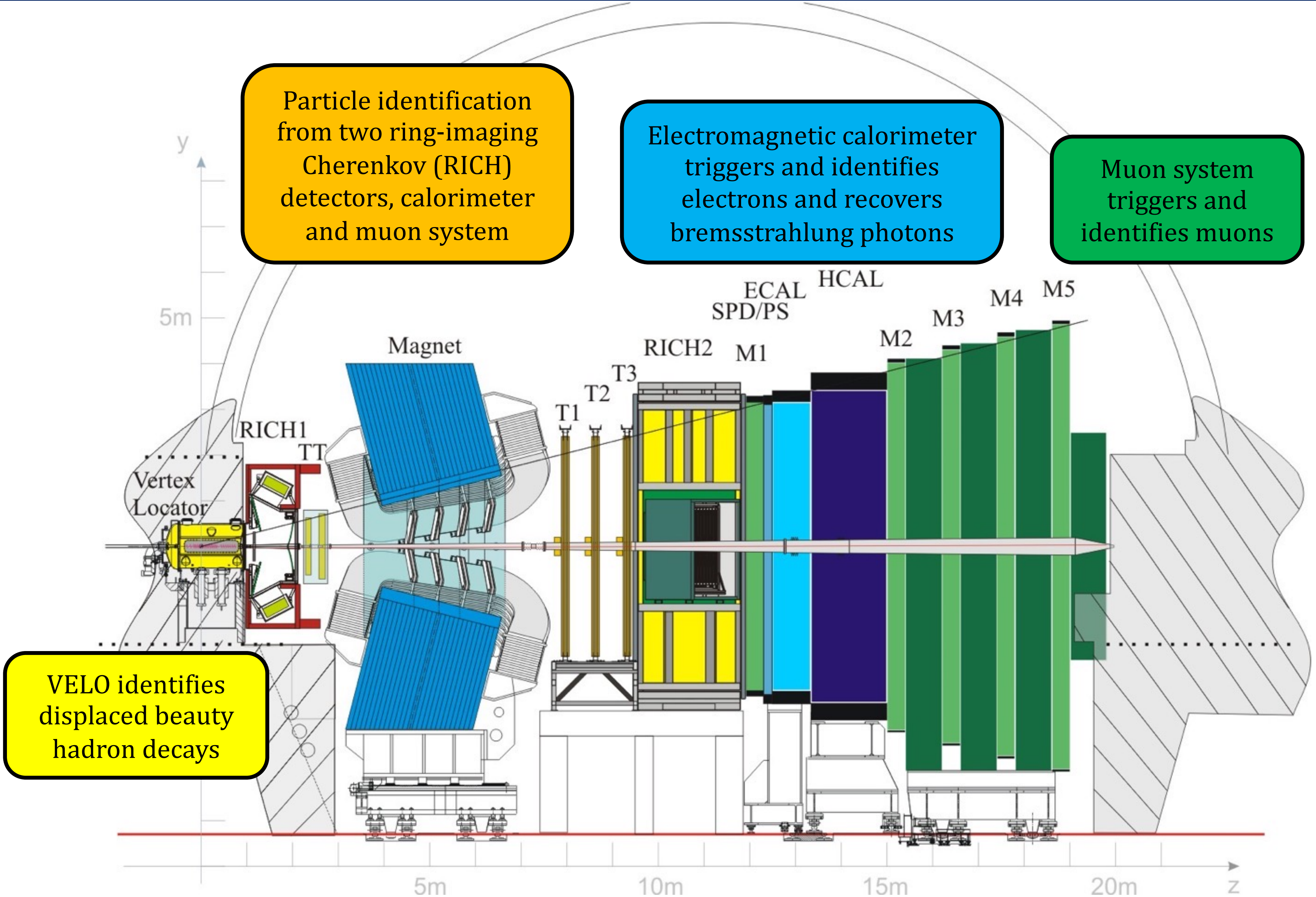
$B^+ \to K^{*+} \ell^+ \ell^-$ (9 fb^{-1})

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

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

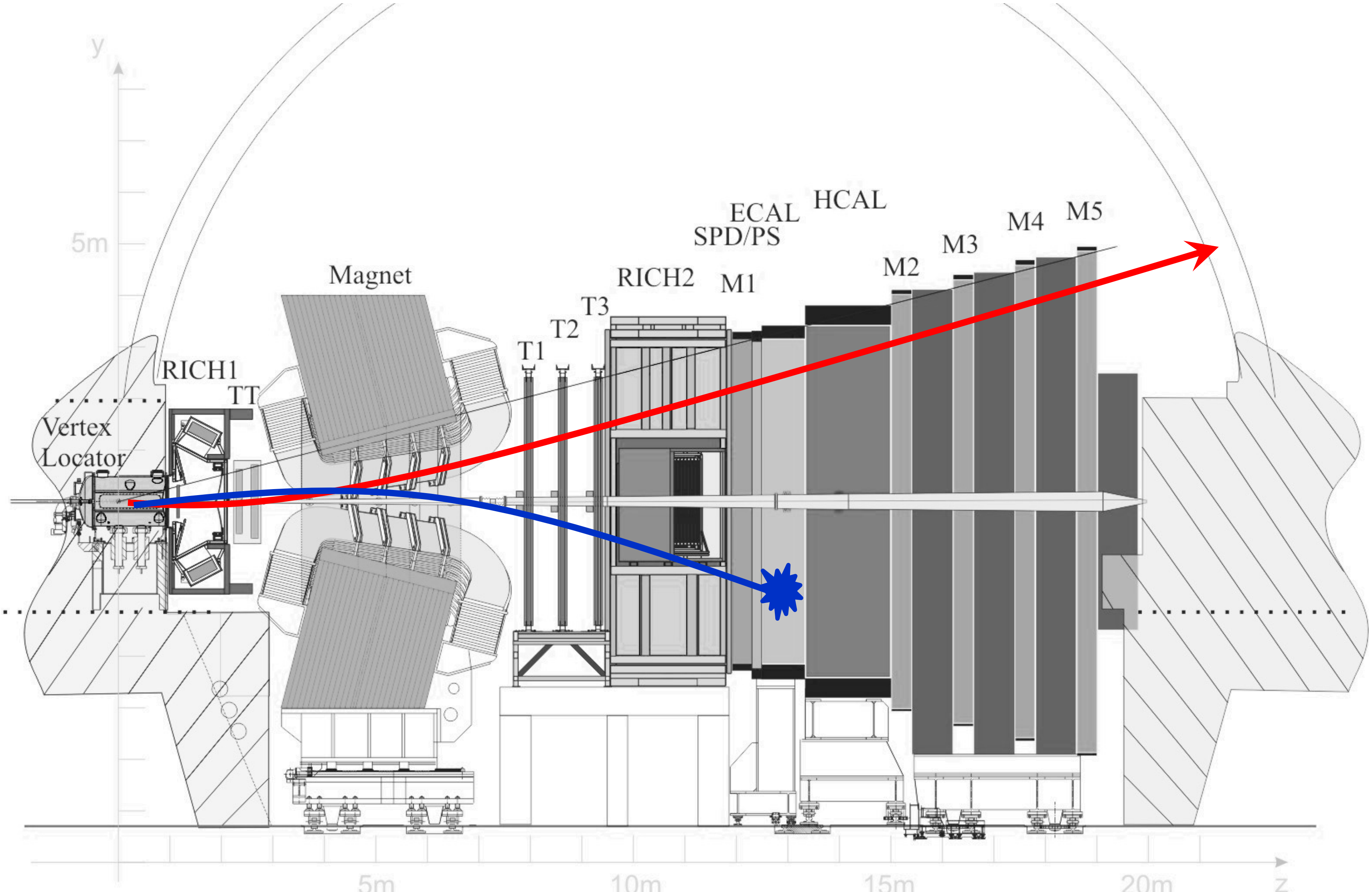
- **Isospin partners** of $B^+ \to K^+ \ell^+ \ell^-$ and $B^0 \to K^{*0} \ell^+ \ell^-$: expect same NP contributions
- **More difficult to reconstruct** due to long-lived K_S^0 in final state
- **First measurements at LHC** – previously measured by Belle with statistical uncertainties ~50%

The LHCb Experiment



Electrons vs Muons

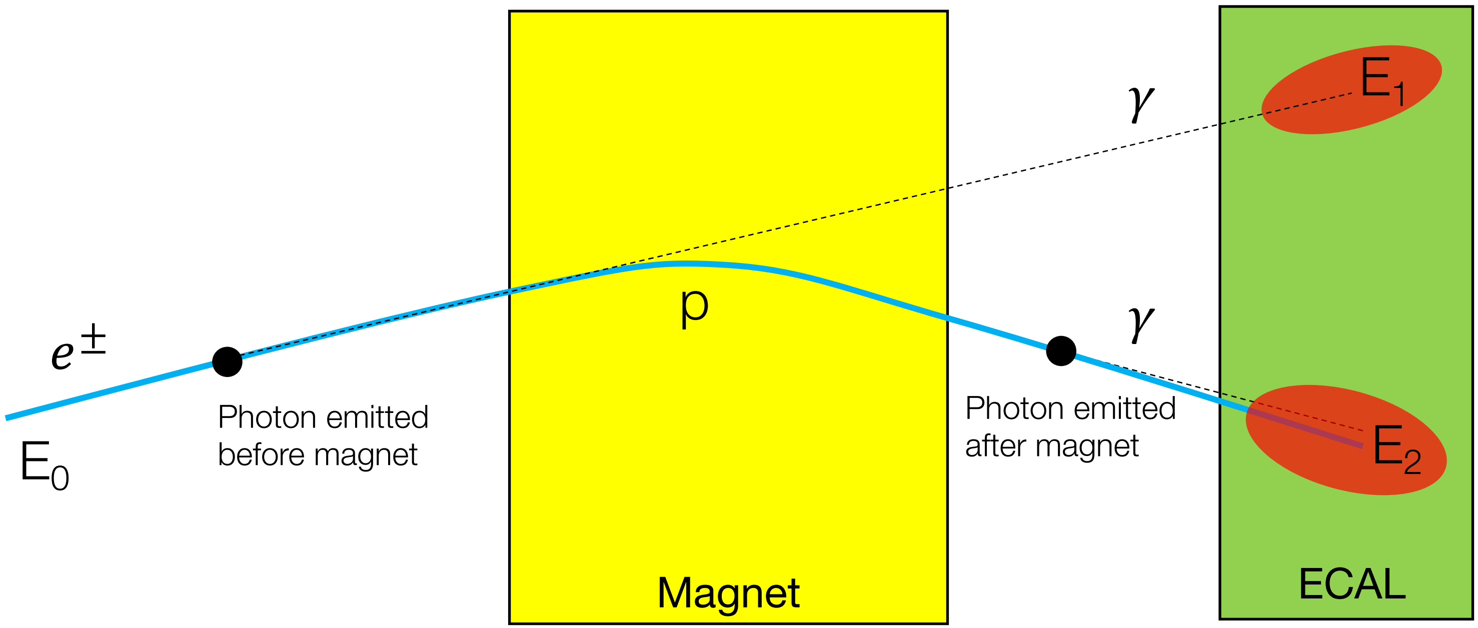
Electrons and muons have very different signatures in the experiment.



Electrons vs Muons

Electrons radiate bremsstrahlung photons when interacting with detector.

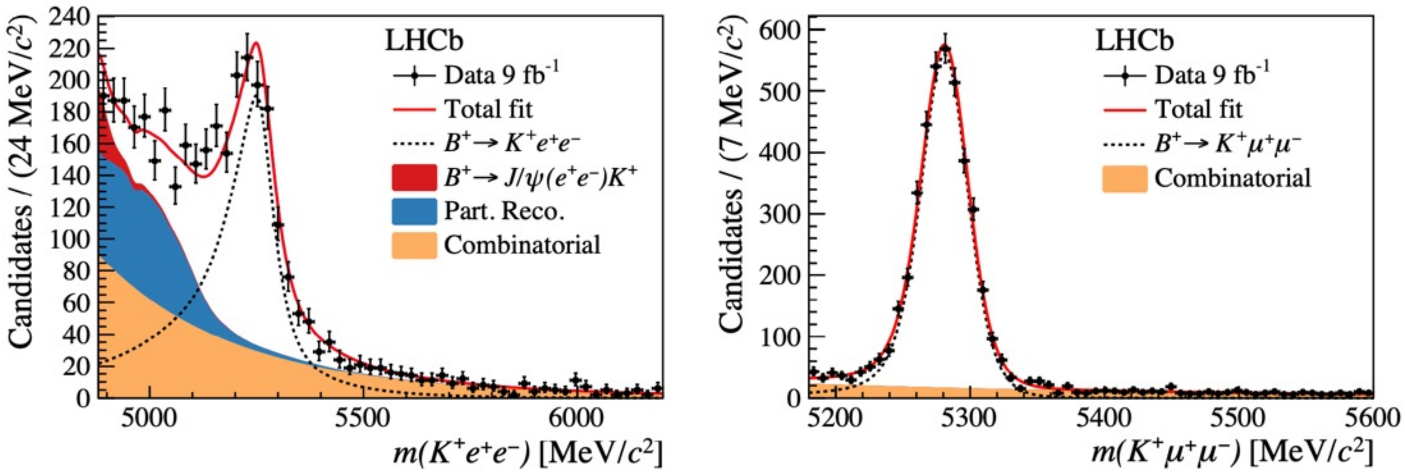
Photons radiated before the magnet lead to underestimation of momentum and energy.



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

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

From 2021 R_K *analysis [Nature Physics 18, (2022) 277-282]*



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**:

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

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

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

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**

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

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

Signal modes:

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

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

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:

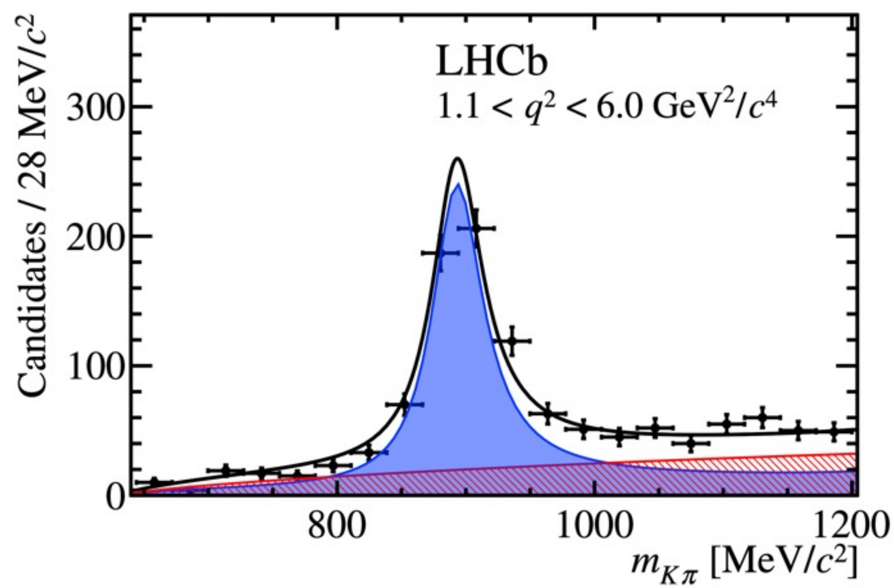
$B^0 \to J/\psi(e^+e^-)K^0_S$ and $B^+ \to J/\psi(e^+e^-)K^{*+}$: $[6.0 < q^2/\text{GeV}^2 < 11.0]$

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

K^{*+} mass:

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

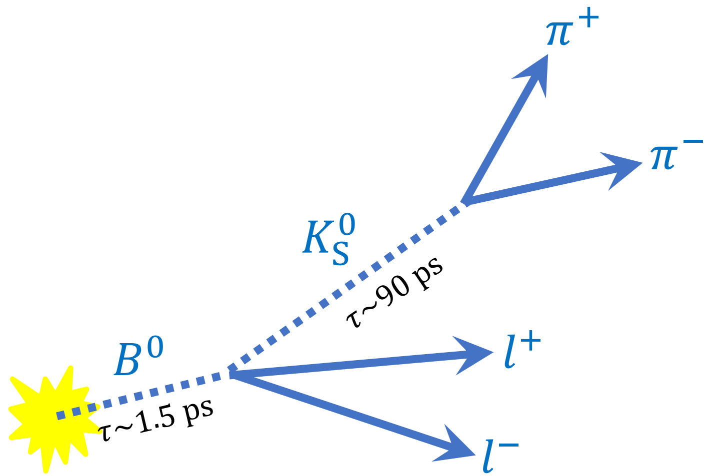
Expect roughly 22% S-wave component based on LHCb $B^0 \to K^+\pi^-\mu^+\mu^-$ analysis. [JHEP 11 (2016) 47]



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

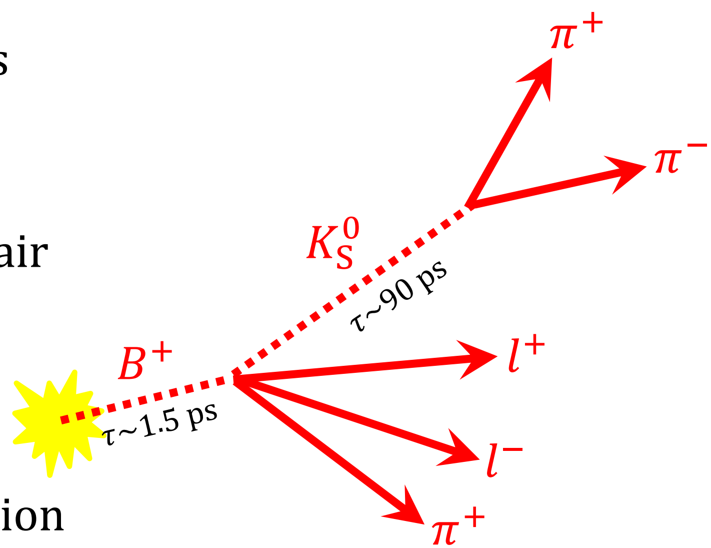


High-Level Trigger (HLT)

- 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
$B^0 \to D^-(K_S^0 X)Y$	$B^+ \to \overline{D}^0(K_S^0\pi^+ X)Y$	$B^+ \to \psi_{2S}(\ell^+\ell^-)K^{*+}(K_S^0\pi^+)$ 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**

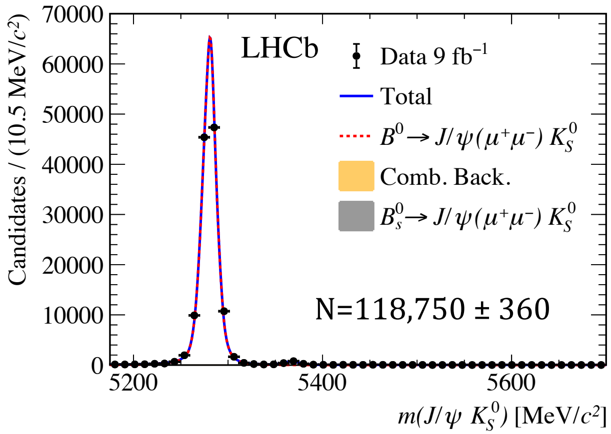
Maximum likelihood fits

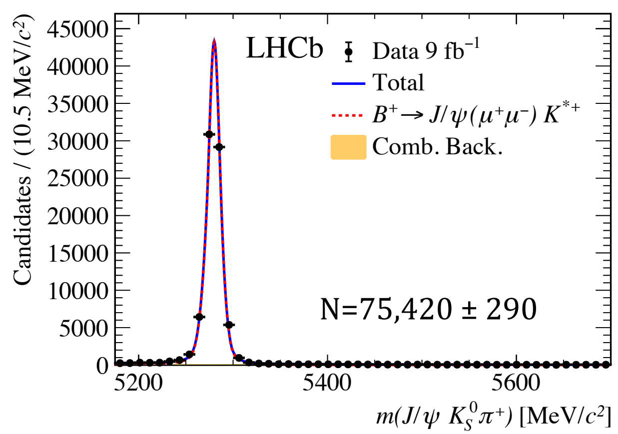
Yields of **control modes** extracted using maximum likelihood fits:

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

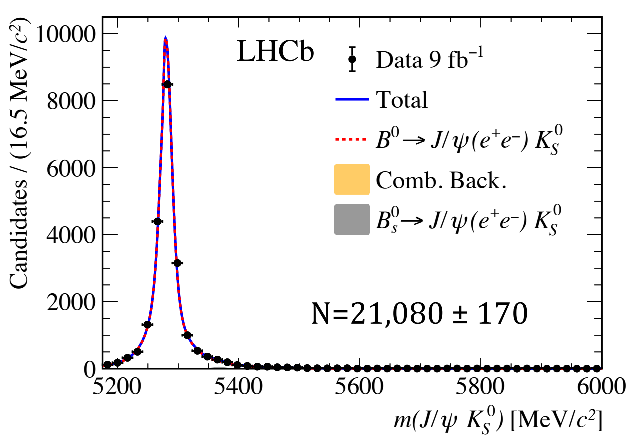
B^0 B^+

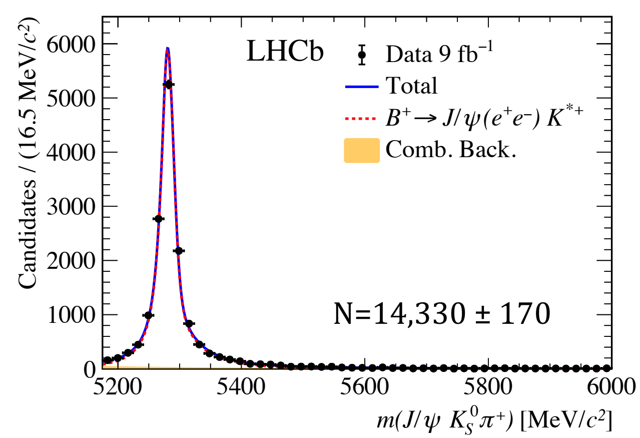
muons





electrons



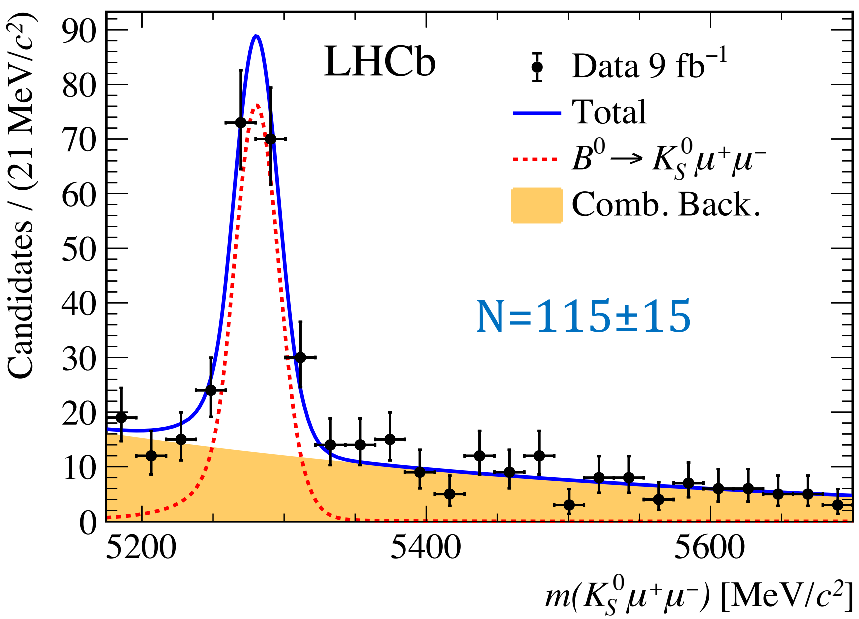


Maximum likelihood fits

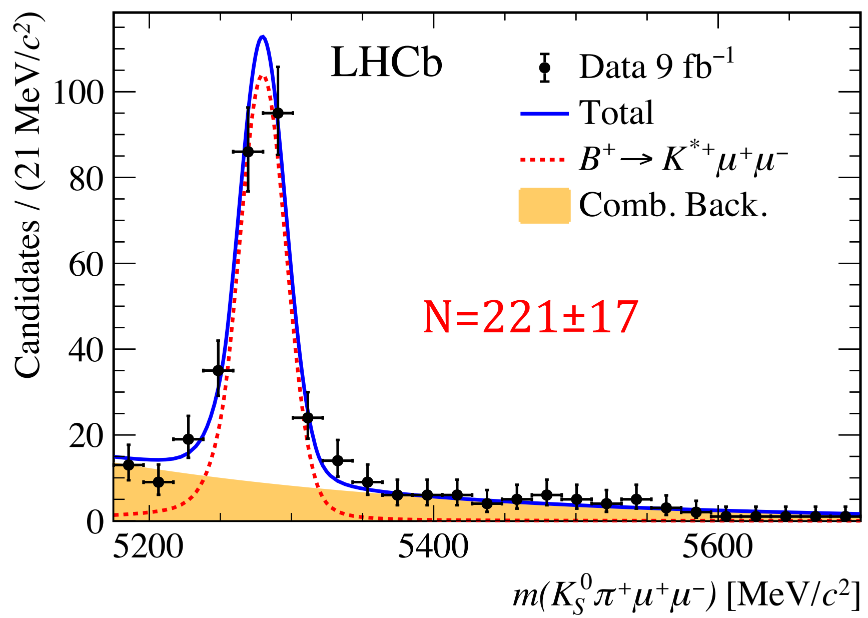
Yields of **signal muon modes** and $\boldsymbol{R_{K^{(*)}}}$ extracted using simultaneous maximum likelihood fits to signal mass spectra:

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

B^0



B^+



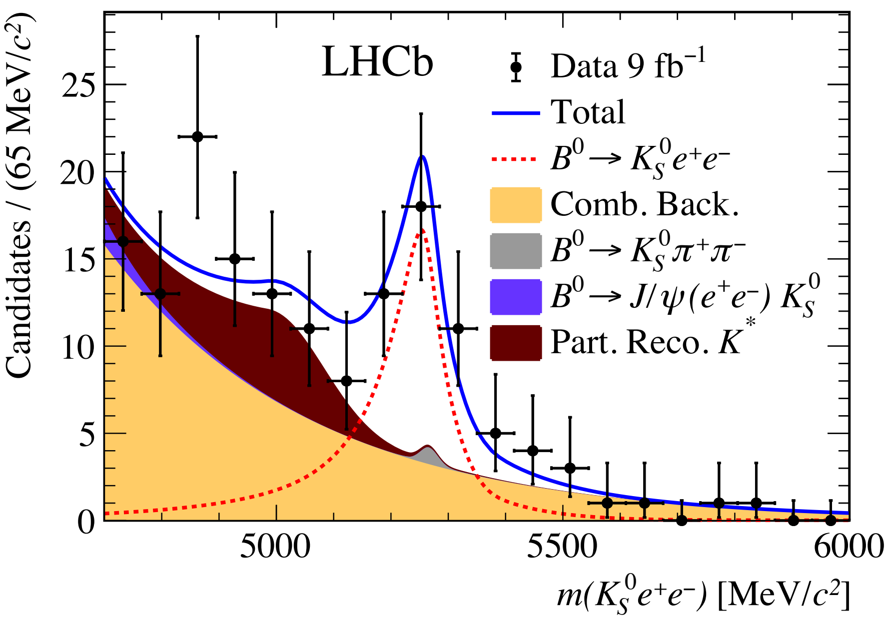
Maximum likelihood fits

Yields of **signal muon modes** and $\boldsymbol{R_{K^{(*)}}}$ 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

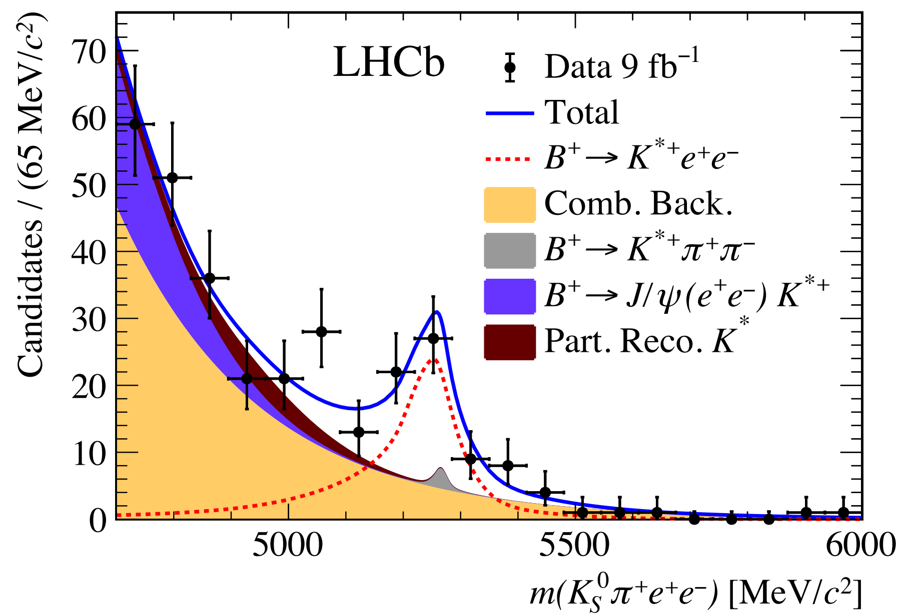
First Observation!

B^0



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

B^+



$B^+ \to K^{*+} \ell^+\ell^-$ 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

Validation of the method by measuring single ratio:

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

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

Finding:

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

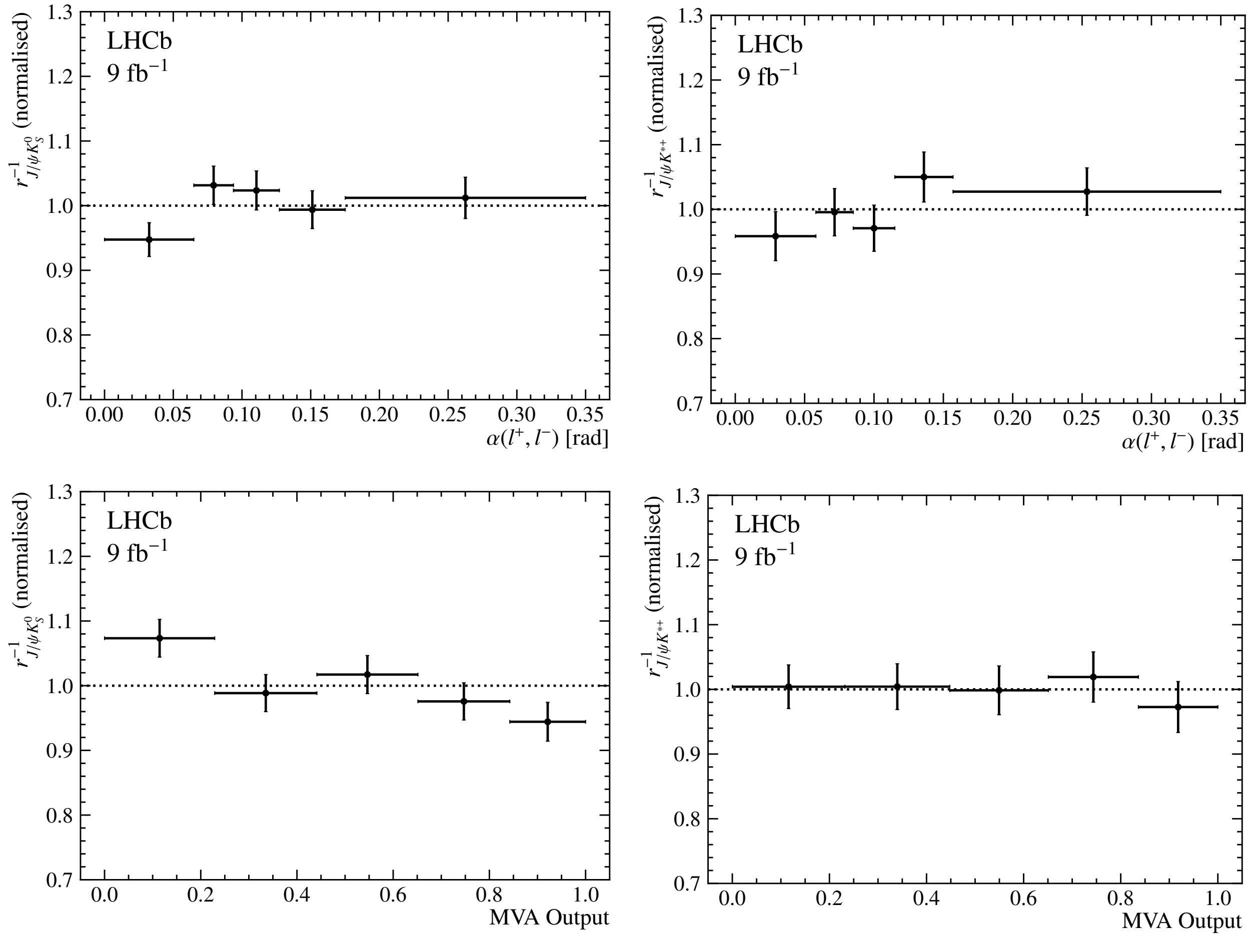
and

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

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

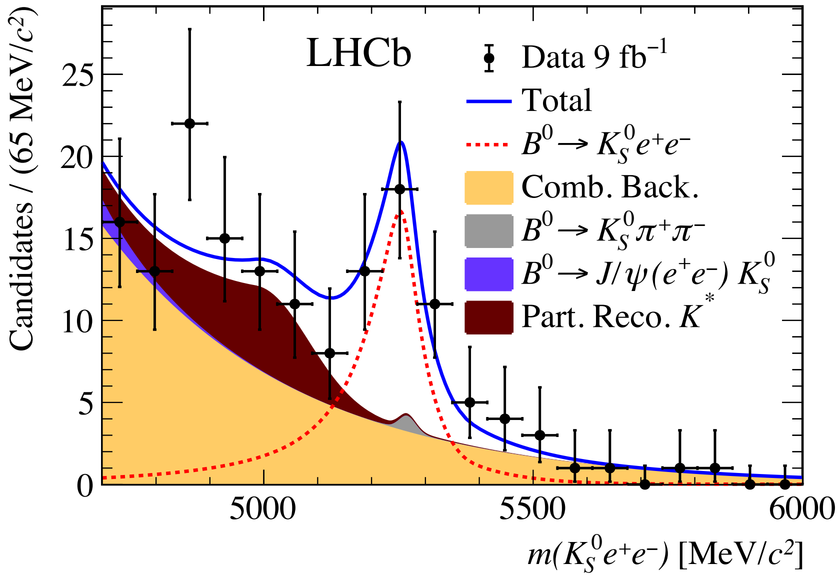


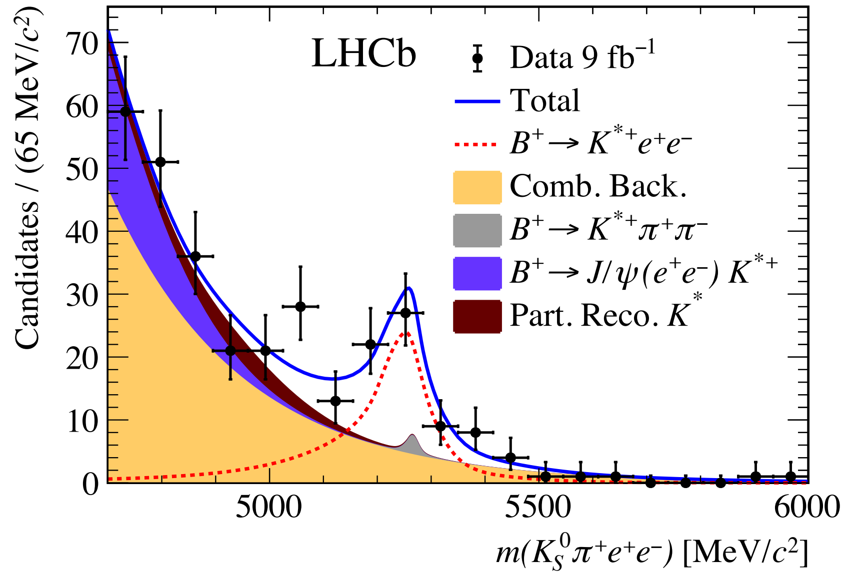
Di-lepton opening angle

MVA trained to distinguish signal from control decays

Results: Electron Decays

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





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

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

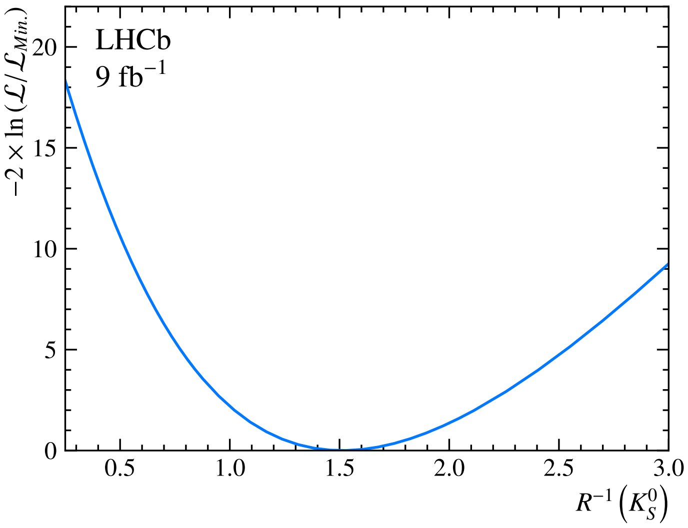
$$\frac{d\mathcal{B}(B^0 \to K^0_S e^+e^-)}{dq^2} = 2.6 \pm 0.6 \pm 0.1 \times 10^{-8}\,\mathrm{GeV}^{-2} c^4$$

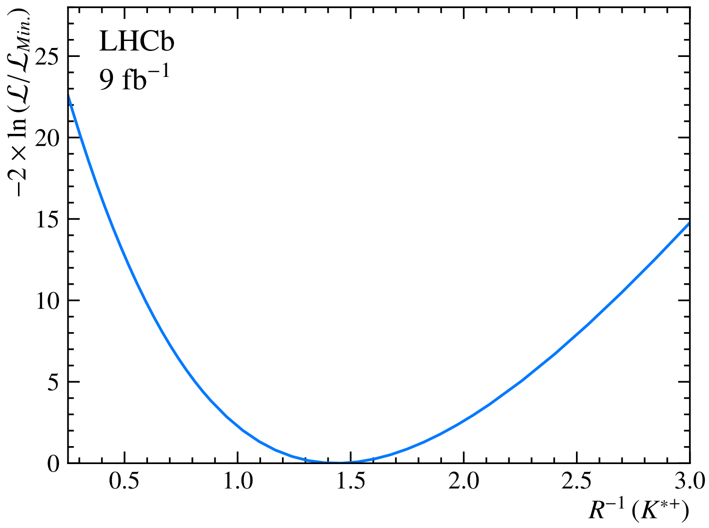
$$\frac{d\mathcal{B}(B^+ \to K^{*+} e^+e^-)}{dq^2} = 9.2^{+1.9+0.8}_{-1.8-0.6} \times 10^{-8}\,\mathrm{GeV}^{-2} c^4$$

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

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

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

$$B^0_{(s)} \to \mu^+\mu^-$$

Theoretical motivation

$B^0_{(s)} \to \mu^+\mu^-$ decays are a **FCNC** decay *and* **helicity suppressed** – very rare.

Matrix element factorises into (trivial) leptonic part and B_q decay constant:

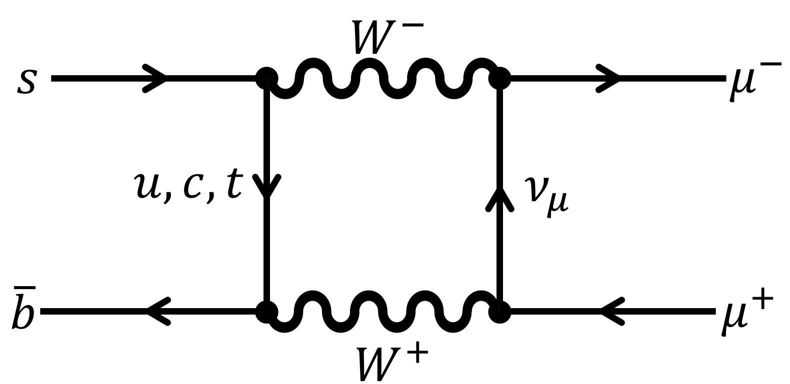
$$\langle \mu\mu | Q | B_q \rangle = \langle \mu\mu | j_\mu \cdot j_q | B_q \rangle = \langle \mu\mu | j_\mu | 0 \rangle \cdot \langle 0 | j_q | B_q \rangle \sim \langle \mu\mu | j_\mu | 0 \rangle \cdot f_{B_q}$$

- Decay constant (f_{B_q}) calculated with lattice QCD to a few percent.
- Decay depends only on Wilson coefficient C_{10} in SM.

Low theoretical uncertainty:

$$\mathrm{BR}(B^0_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.66 \pm 0.14)\times 10^{-9}$$

$$\mathrm{BR}(B^0 \to \mu^+\mu^-)_{\mathrm{SM}} = (1.03 \pm 0.05)\times 10^{-10}$$



C. Bobeth et.al. (2014) + M. Beneke, C. Bobeth, and R. Szafron (2019)

Theoretical motivation

Decay sensitive to **scalar (S)** and **pseudoscalar (P)** operators – not helicity suppressed and can lead to large enhancements (and suppression in case of P):

- Models with extended Higgs sector (e.g. MSSM) and vector leptoquarks

Also NP in C_{10} or C'_{10}:

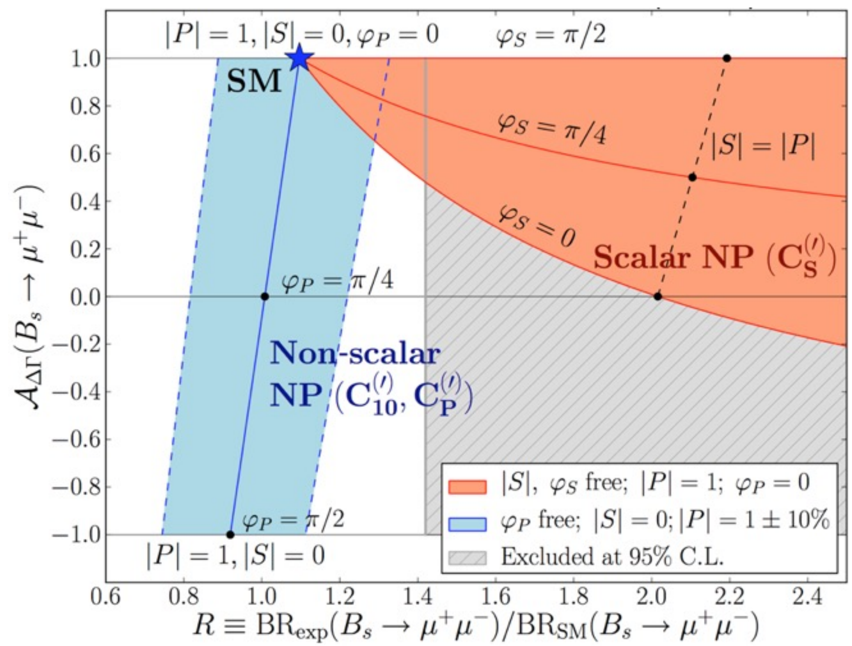
- Effective FCNC Z couplings (MSSM, partial composite, Randall-Sundrum)
- Short distance semi-leptonic operators (Z', scalar or vector leptoquarks)

Key observables:

$$\frac{\mathrm{BR}(B_q \to \mu^+\mu^-)}{\mathrm{BR}(B_q \to \mu^+\mu^-)_{\mathrm{SM}}} = \frac{|S|^2\left(1 - \frac{4m_\mu^2}{m_{B_q}^2}\right) + |P|^2}{\left|C_{10}^{\mathrm{SM}}\right|^2}$$

$$\mathcal{A}_{\Delta\Gamma} = \frac{\mathrm{Re}(P^2 - S^2)}{|P|^2 + |S|^2}$$

can disentangle scalar & pseudoscalar NP.



K. De Bruyn et.al (2012)

Analysis strategy

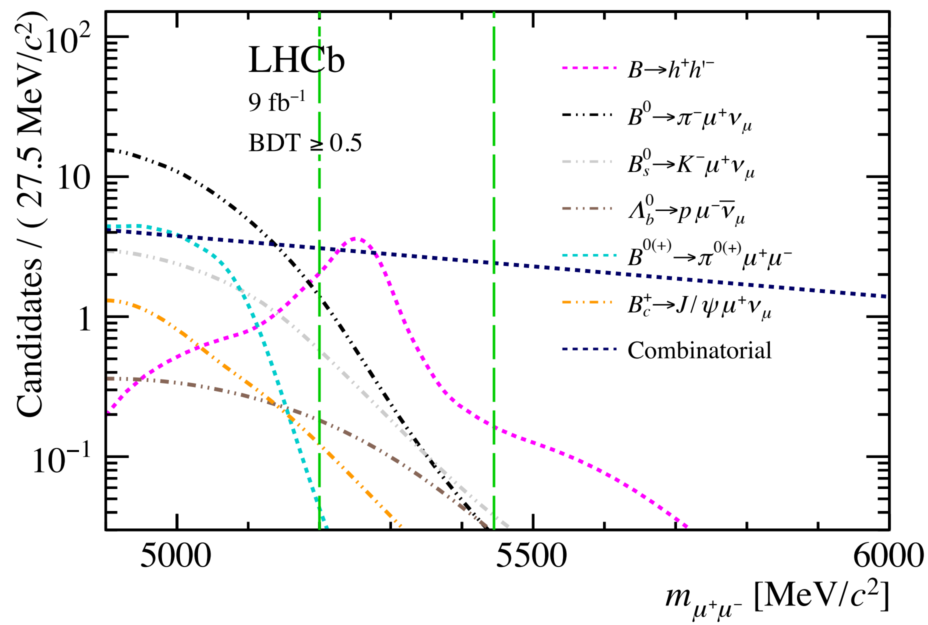
Used full 2011-2018 (9 fb^{-1}) data. Four goals:

1. Measure the $B_s^0 \to \mu^+\mu^-$ branching fraction
2. Search for the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ decays
3. Measure the $B_s^0 \to \mu^+\mu^-$ effective lifetime (sensitive to $\mathcal{A}_{\Delta\Gamma}$):

$$\tau_{\mu\mu} \equiv \frac{\int_0^\infty t\langle\Gamma(B_s(t)\to\mu^+\mu^-)\rangle dt}{\int_0^\infty\langle\Gamma(B_s(t)\to\mu^+\mu^-)\rangle dt} \qquad \mathcal{A}_{\Delta\Gamma} = \frac{(1-y_s^2)\tau_{\mu\mu}-(1+y_s^2)\tau_{B_s}}{y_s(2\tau_{B_s}-(1-y_s^2)\tau_{\mu\mu})} \qquad y_s \equiv \tau_{B_s}\Delta\Gamma/2$$

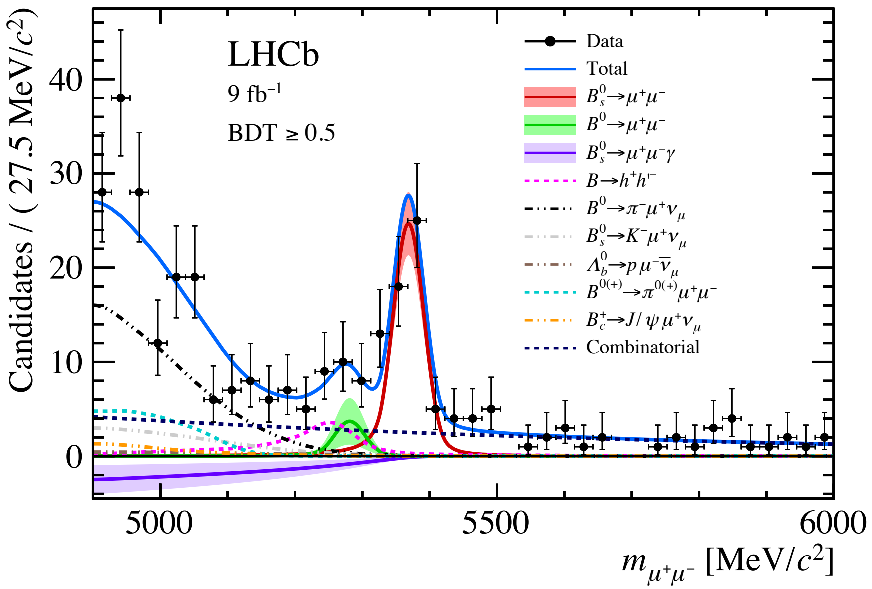
Key features / challenges:

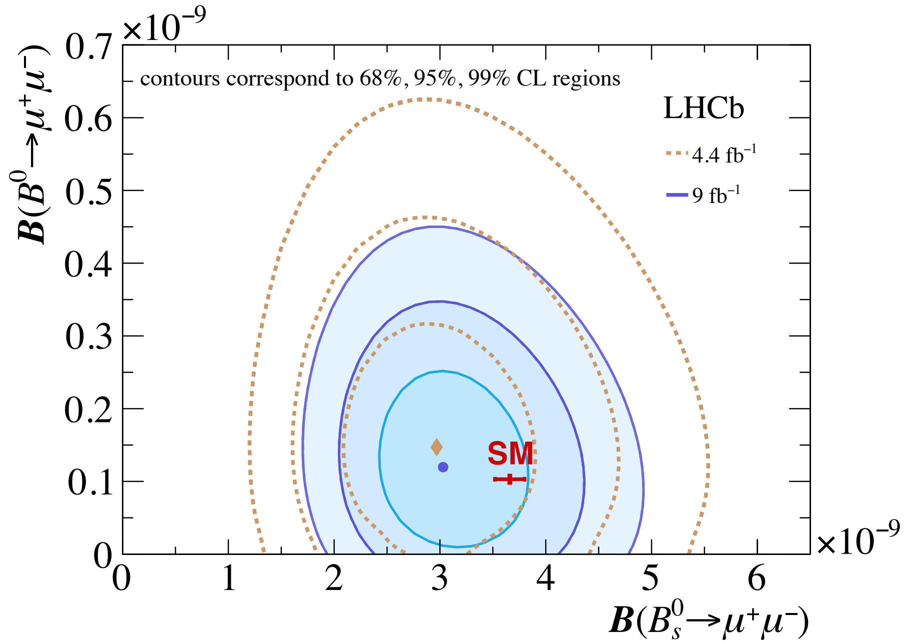
- Normalise $B_s^0 \to \mu^+\mu^-$ branching fraction w.r.t. $B^0 \to K^+\pi^-$ and $B^+ \to J/\psi K^+$
- Reject /control physical backgrounds (esp. $B \to h^+h^-$) using particle ID
- Rejection of combinatorial background (mostly from semi-muonic b-hadron decays) using boosted decision tree (BDT)
- Correct for decay time efficiency using MC



Branching fraction

Improved measurement of $B_s^0 \to \mu^+\mu^-$ decay but no evidence of $B^0 \to \mu^+\mu^-$ or $B_s^0 \to \mu^+\mu^-\gamma$ (yet!)





$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = \left(3.09^{+0.46}_{-0.43}{}^{+0.15}_{-0.11}\right)\times10^{-9}$ vs $\mathrm{BR}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}} = (3.66 \pm 0.14)\times10^{-9}$

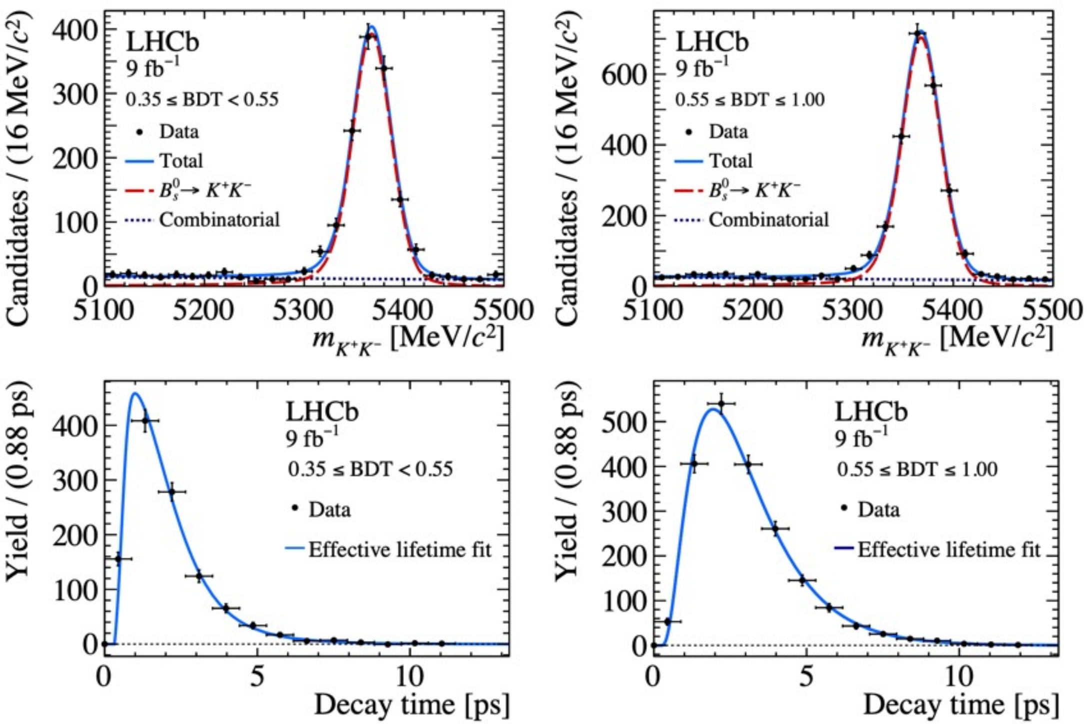
$\mathrm{BR}(B^0 \to \mu^+\mu^-) < 2.6\times10^{-10}$ at 95% conf. vs $\mathrm{BR}(B^0 \to \mu^+\mu^-)_{\mathrm{SM}} = (1.03 \pm 0.05)\times10^{-10}$

$\mathrm{BR}(B_s^0 \to \mu^+\mu^-\gamma) < 2.0\times10^{-9}$ at 95% conf.
$(m_{\mu\mu} > 4.9\ \mathrm{GeV})$

Effective lifetime

Improved measurement of the $B_s^0 \to \mu^+\mu^-$ effective lifetime (with I. Williams):

- Simultaneous fit to two bins of BDT (simple cut in 2017 analysis)
- Softer PID requirements as $B \to h^+h^-$ background less problematic for B_s^0
- Decay time distribution extracted using *sWeights*
- Decay time efficiency calculated from weighted simulation
- Method validated on $B^0 \to K^+\pi^-$ and $B_s^0 \to K^+K^-$



$\tau_{B_s^0 \to K^+K^-} = 1.435 \pm 0.026$ ps

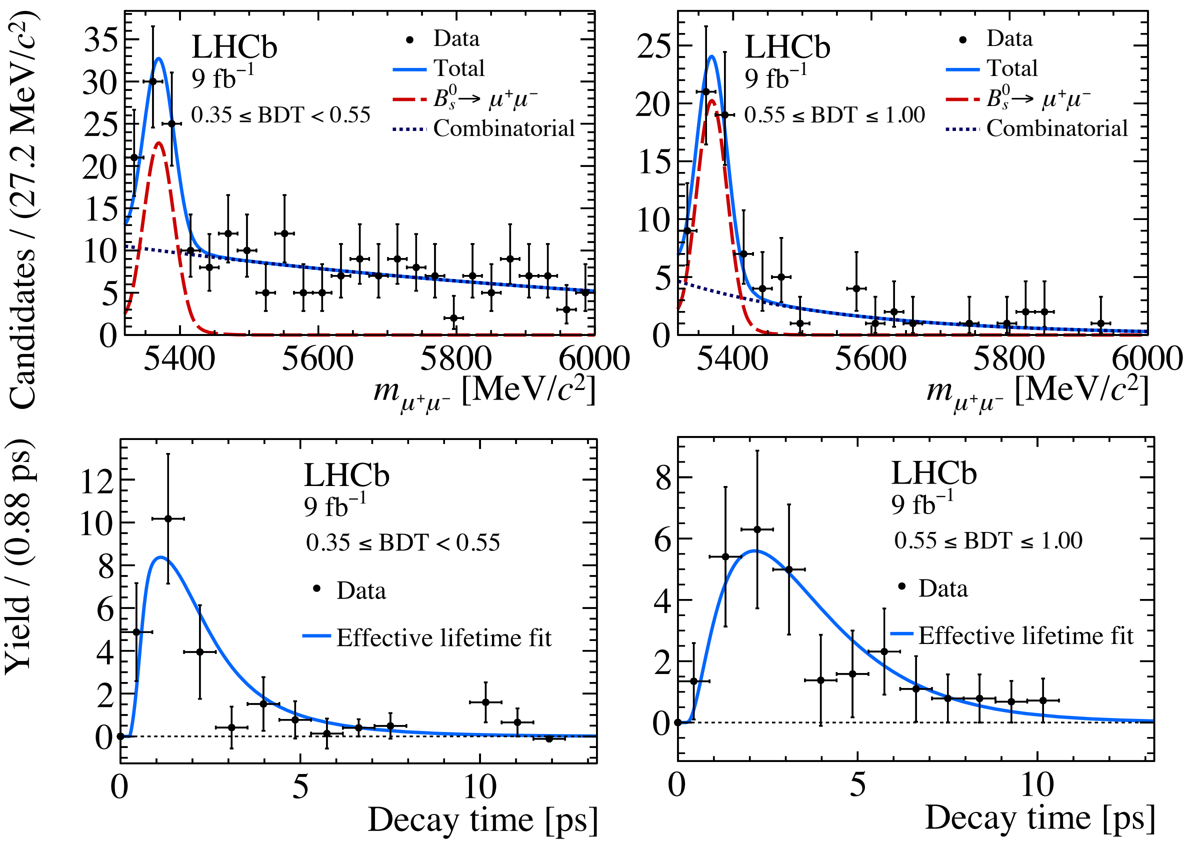
$\tau_{B^0 \to K^+\pi^-} = 1.510 \pm 0.015$ ps

vs PDG:

$\tau_{B_s^0 \to K^+K^-} = 1.407 \pm 0.016$ ps

$\tau_{B^0 \to K^+\pi^-} = 1.524 \pm 0.011$ ps

Effective lifetime



$\tau_{\mu\mu} = 2.07 \pm 0.29 \pm 0.03$ ps

Currently statistically limited but favours SM $\mathcal{A}_{\Delta\Gamma}$ =1 (SM).

Dominant systematic uncertainty from $B^0 \to K^+\pi^-$ validation – will decrease with more data.

Summary

We live in exciting times…

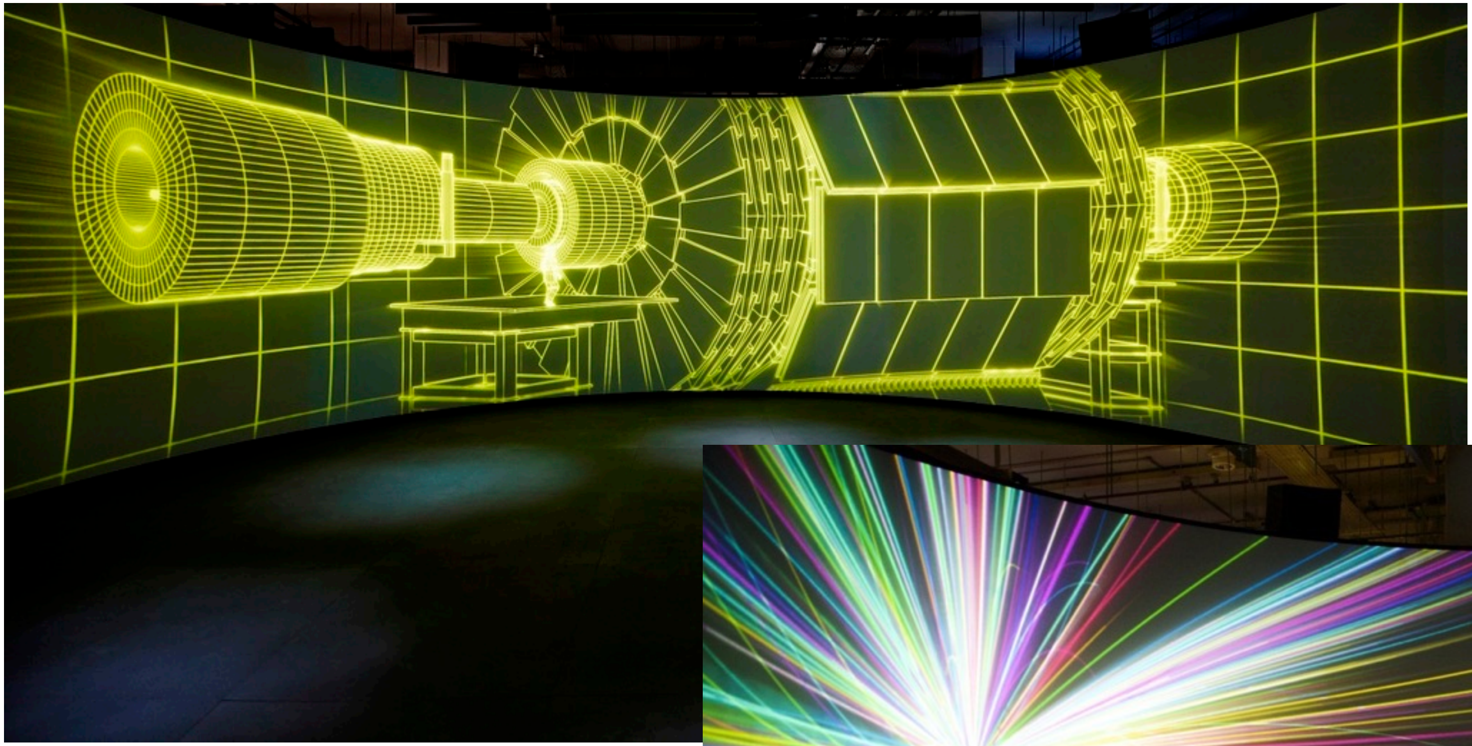
- No new particles at the LHC (yet)
- Rare beauty decays offer one of the best ways to probe for new physics at and above the TeV scale

Intriguing anomalies require urgent further experimental tests:

- Many new measurements possible with just the Run II LHCb data
- The **LHCb Upgrade I** and **II** will bring fantastic opportunities for precise measurements with great potential to discover deviations from the Standard Model


And now for something
completely different...

Exhibitions

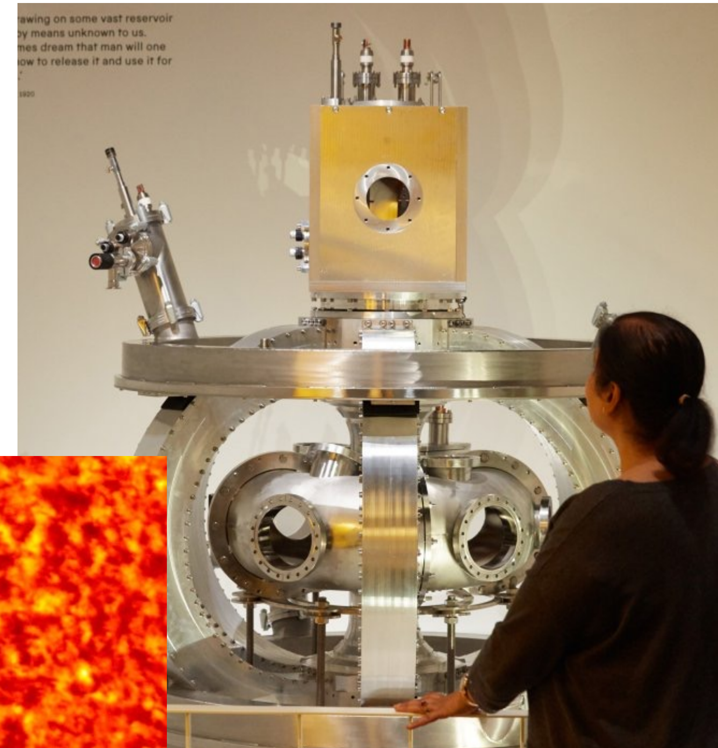


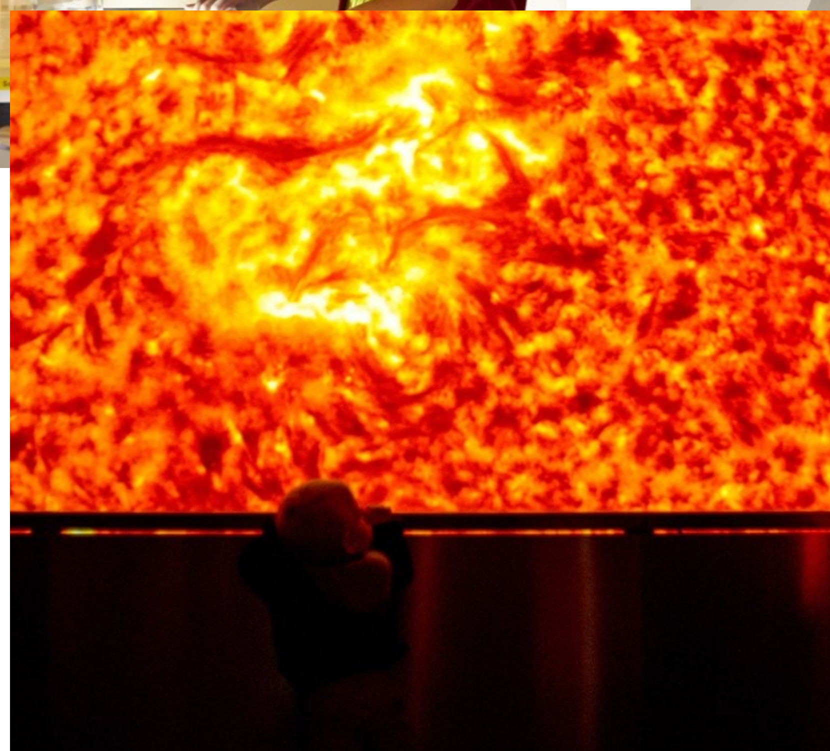
Exhibitions

Exhibitions

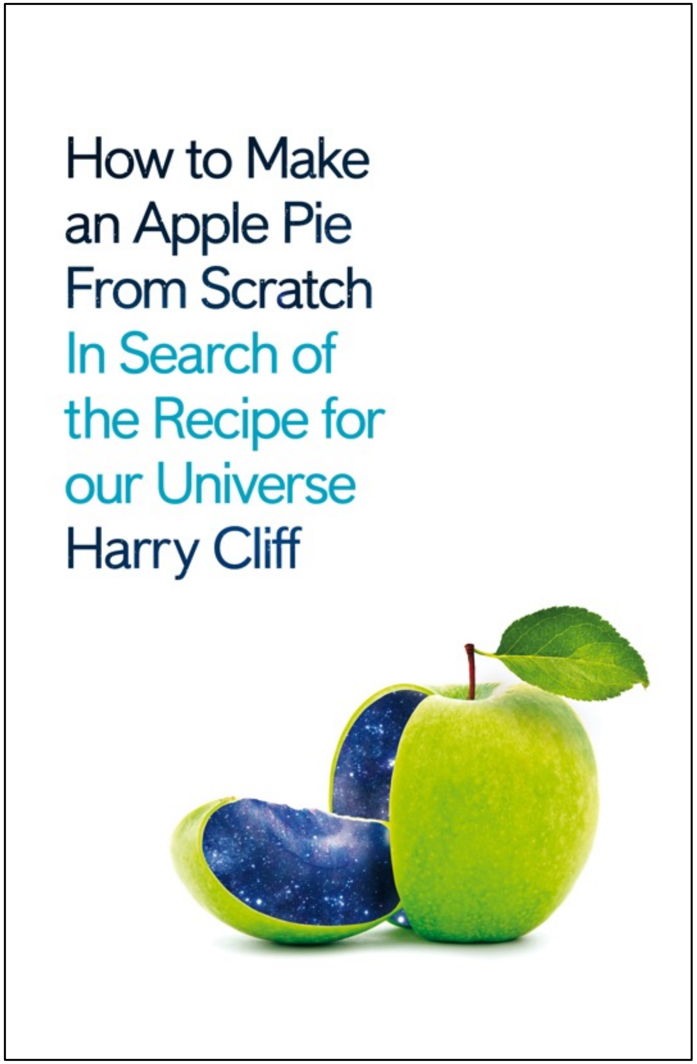
Exhibitions

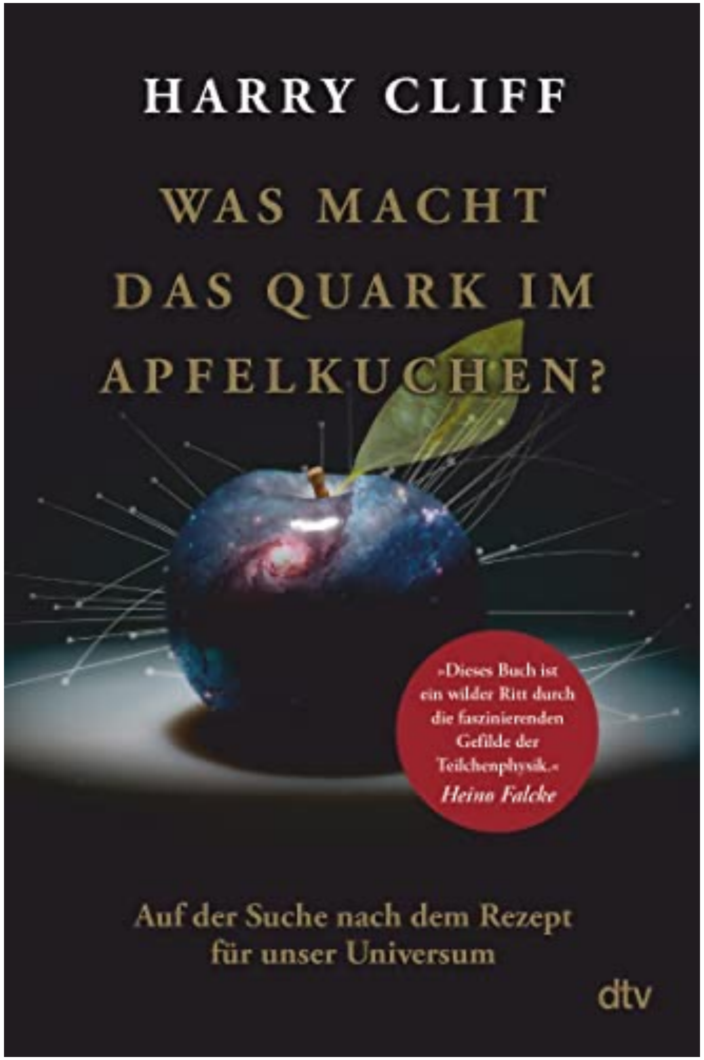
Exhibitions





Books


How to Make
an Apple Pie
From Scratch
In Search of
the Recipe for
our Universe
Harry Cliff

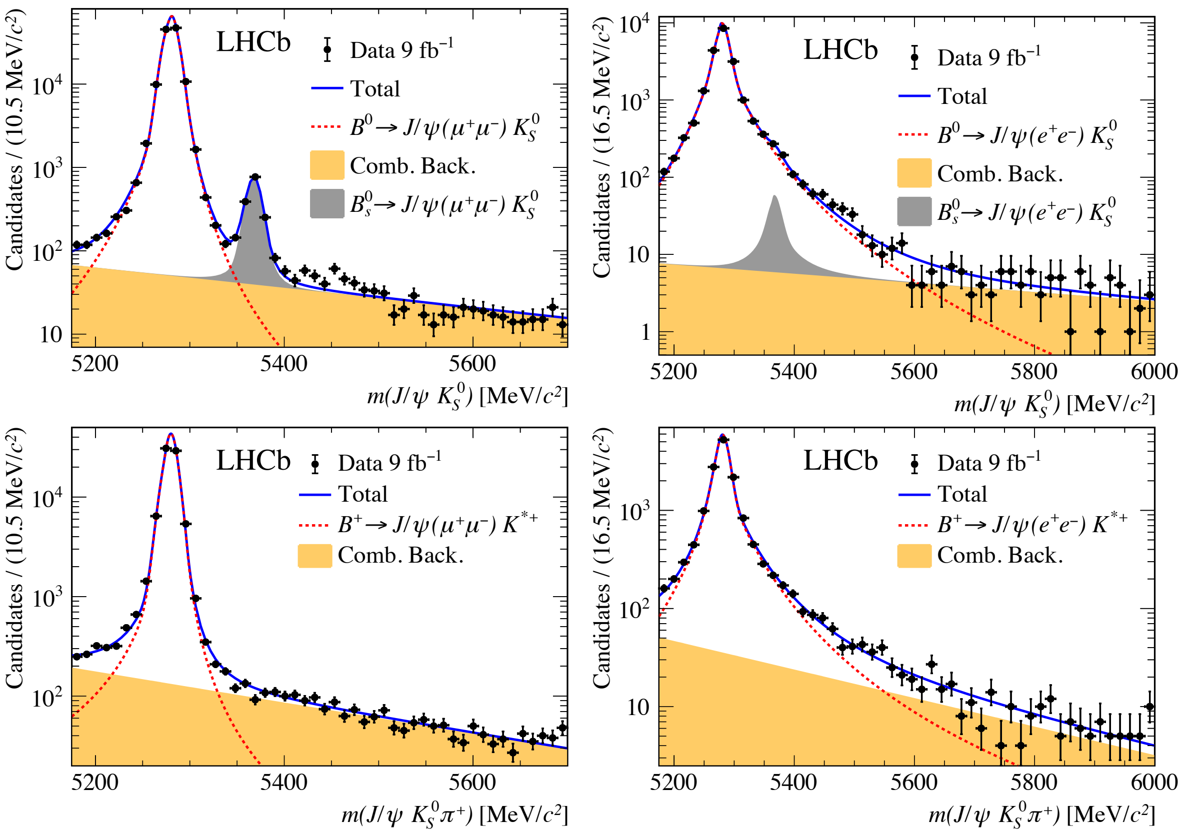

HARRY CLIFF
WAS MACHT
DAS QUARK IM
APFELKUCHEN?
»Dieses Buch ist
ein wilder Ritt durch
die faszinierenden
Gefilde der
Teilchenphysik.«
Heino Falcke
Auf der Suche nach dem Rezept
für unser Universum
dtv

Backup

Maximum likelihood fits

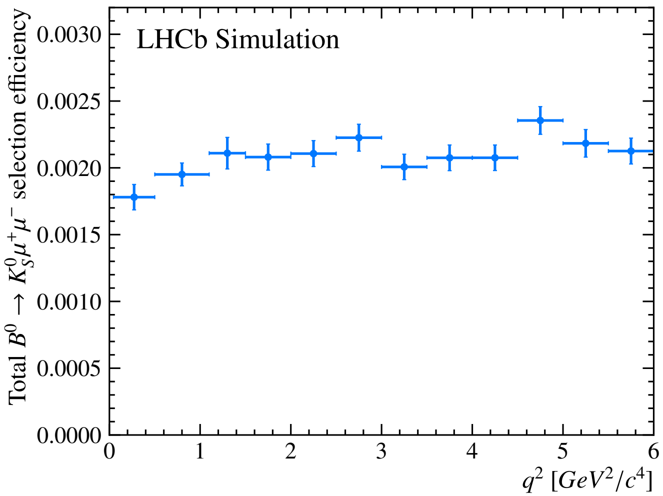
Yields of **control modes** extracted using maximum likelihood fits:

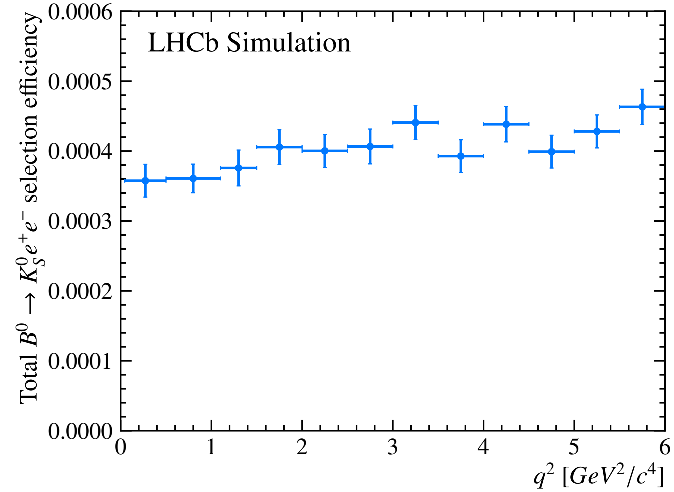
- Resolution improved by constraining J/ψ and K_S^0 mass
- Parameters of control mode PDFs determined from simulation with mean mass and mass resolution allowed to float in fit to data

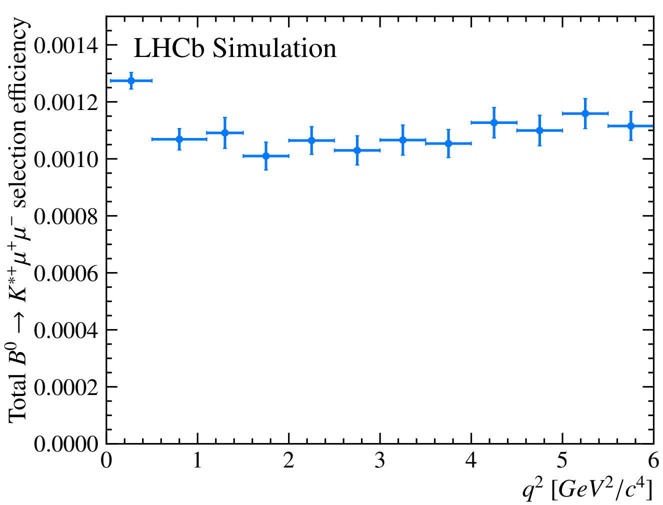


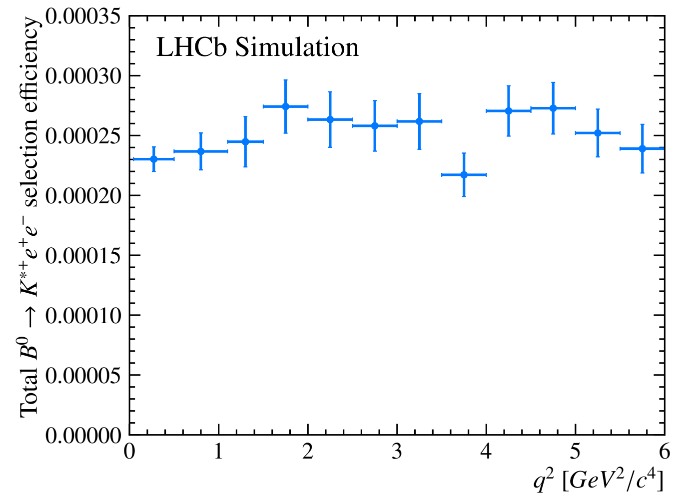
Decay	Yield
$B^0 \to J/\psi(\mu^+\mu^-)K_S^0$	118,750 ± 360
$B^0 \to J/\psi(e^+e^-)K_S^0$	21,080 ± 170
$B^+ \to J/\psi(\mu^+\mu^-)K^{*+}$	75,420 ± 290,
$B^+ \to J/\psi(e^+e^-)K^{*+}$	14,330 ± 170

Efficiencies

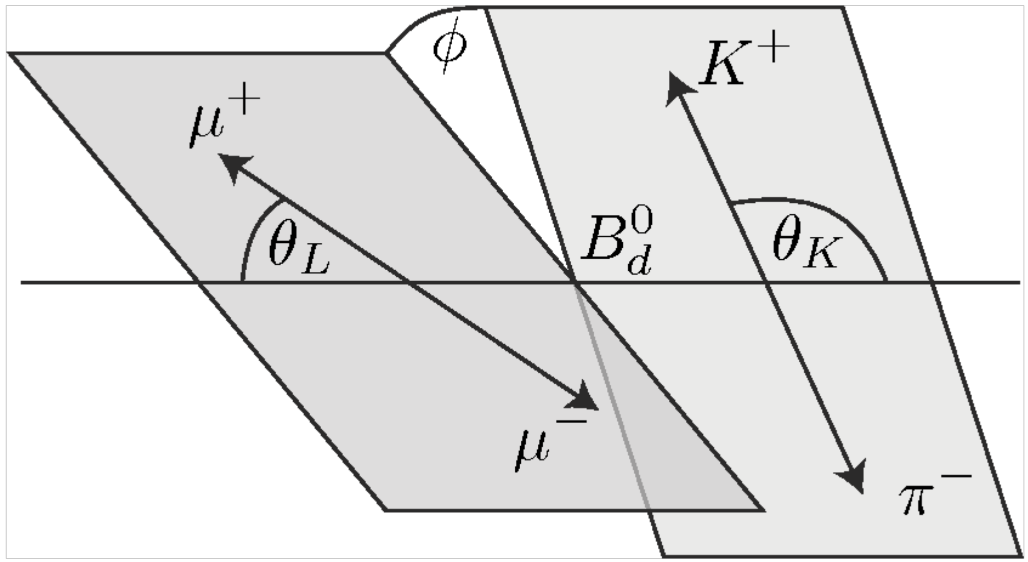








Angular Distributions

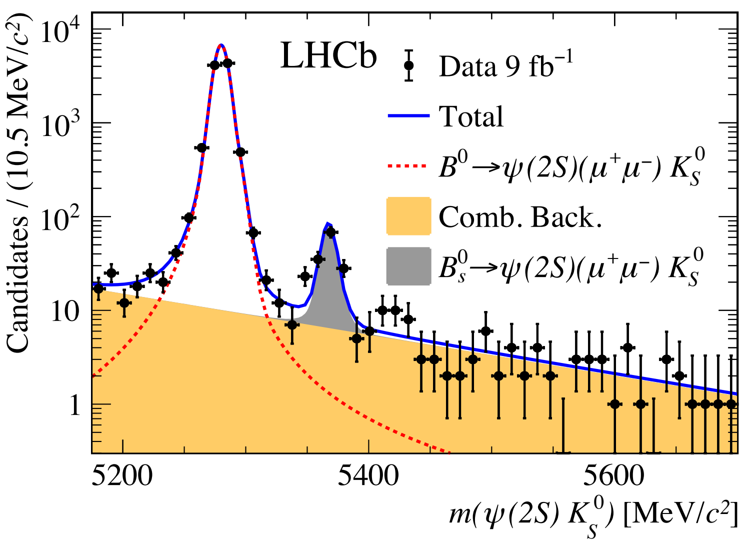


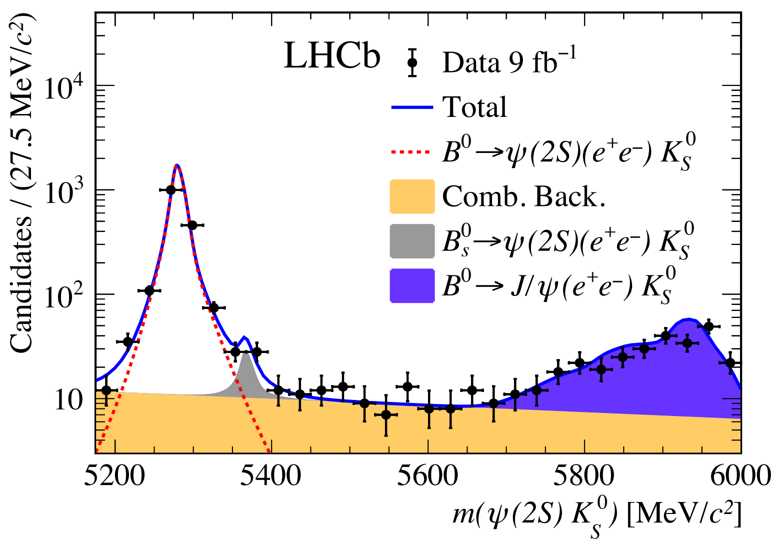
$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2\,d\vec{\Omega}}\Big|_P = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\rm L})\sin^2\theta_K + F_{\rm L}\cos^2\theta_K + \frac{1}{4}(1-F_{\rm L})\sin^2\theta_K\cos 2\theta_l$$
$$- F_{\rm L}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos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

Validation

Method validated by measuring double ratio:

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





Finding:

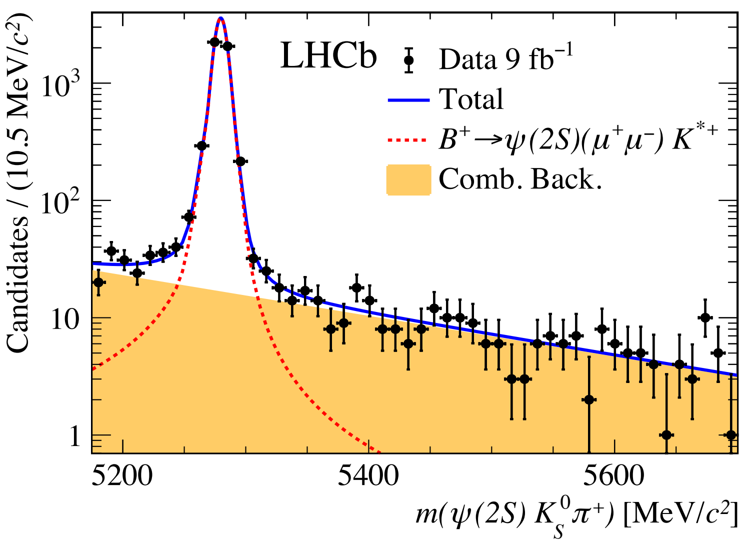
$$R^{-1}_{\psi(2S)K^0_S} = 1.014 \pm 0.030\,(\text{stat.}) \pm 0.020\,(\text{syst.})$$

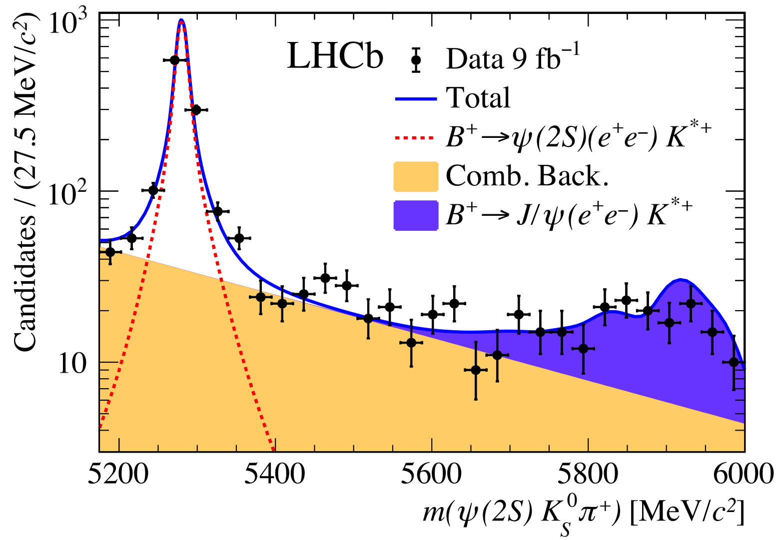
Consistent with unity.

Validation

Method validated by measuring double ratio:

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





Finding:

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

Consistent with unity.

Results: Combination

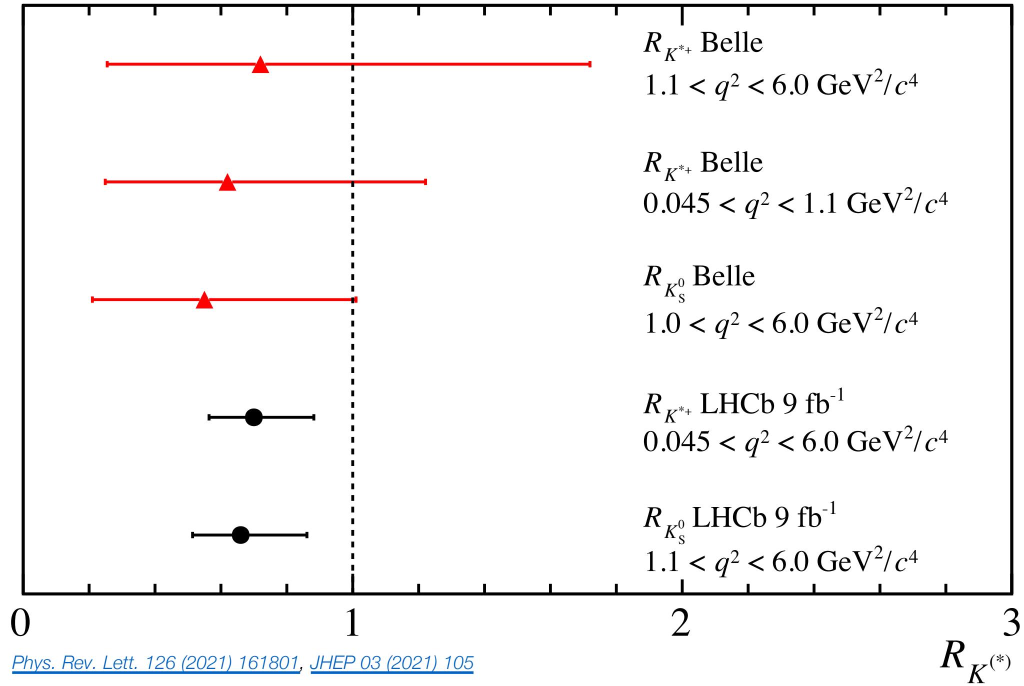
Two results combined to evaluate total significance with respect to the SM:

- 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

Effective lifetime – control fit