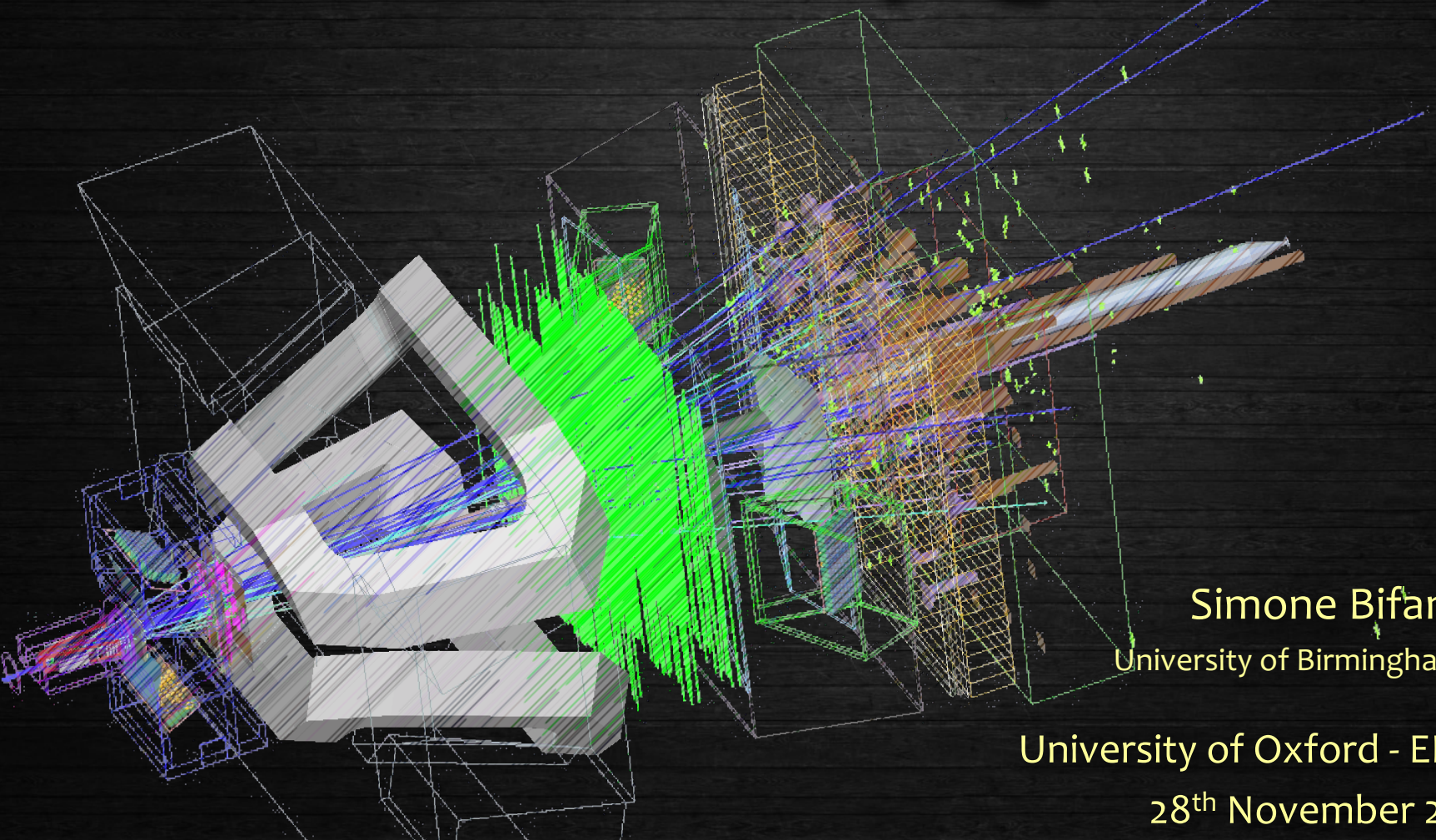
Tests of Lepton Universality @ LHCb



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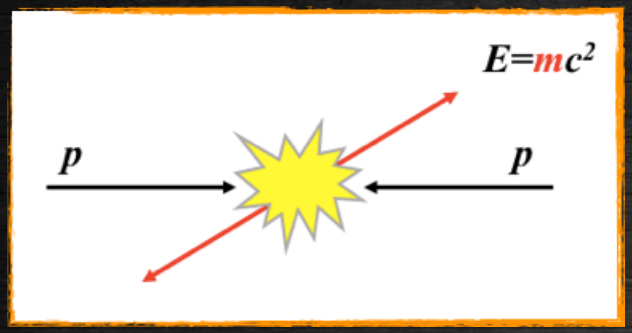
University of Oxford - EPP Seminar
28th November 2017

Outline

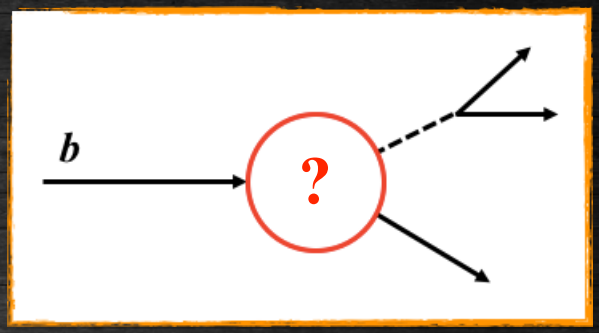
- Quest for BSM physics
- Why b-hadron decays?
- Rare b-hadron decays @ LHCb
  - Flavour anomalies
  - Tests of lepton universality
- Outlook and Summary

Quest for Physics Beyond SM

› Current state of affairs



Direct production
› simpler to interpret
› probes masses <E



Indirect production
› model-dependent interpretation
› probes very-high mases

› **No evidence** of new heavy on-shell particles below ~2 TeV

… except for a very much Standard Model Higgs-like scalar at 125GeV

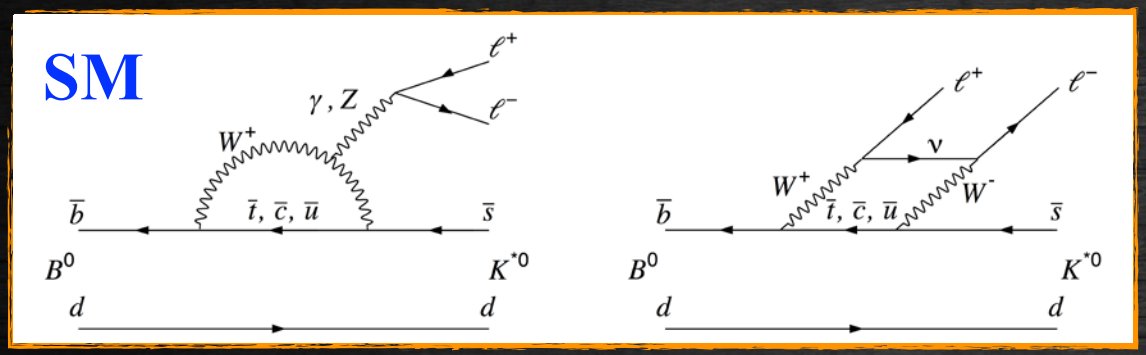
› Most of the unexpected anomalies have been neutralised by the additional statistics

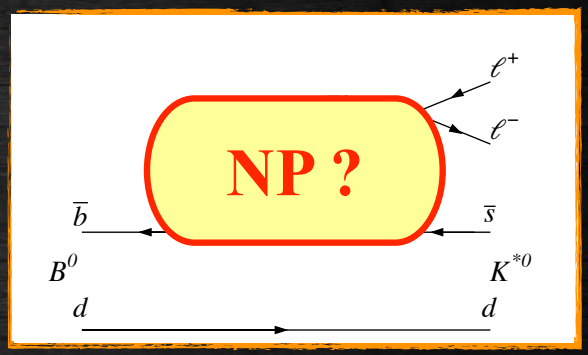
… all but the **anomalies in b-hadron decays**

Why b-Hadron Decays?

› In presence of sizeable SM contributions, BSM effects might be hidden

› Instead, look at suppressed decays e.g. b→sll **Flavour-Changing Neutral-Current 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 decays can place **strong constraints** on many BSM models by probing energy scales higher than those accessible with direct searches

Theoretical Framework

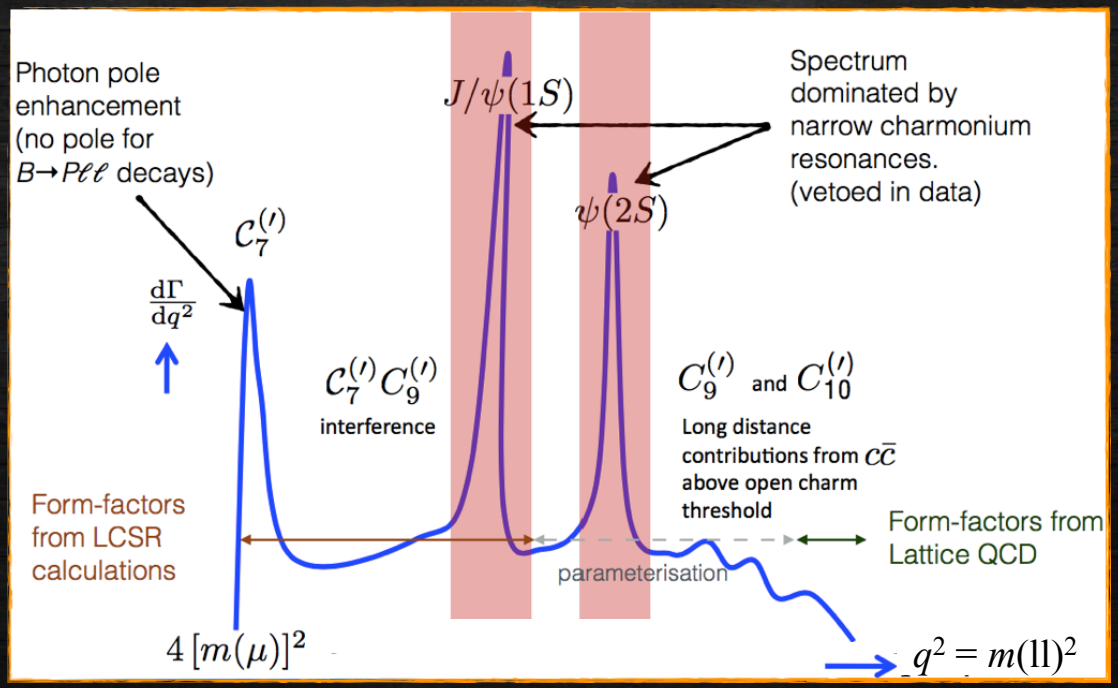
› FCNC **effective Hamiltonian** described by Operator Product Expansion

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left-handed part}} + \underbrace{\mathcal{C}_i'(\mu)\mathcal{O}_i'(\mu)}_{\text{right-handed part suppressed in SM}}]$$

i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

» C_i (**Wilson coefficients**): perturbative, short-distance physics, sensitive to $E>\Lambda_{EW}$

» O_i (**Operators**): non-perturbative, long-distance physics, depend on hadronic FF



A Forward Spectrometer

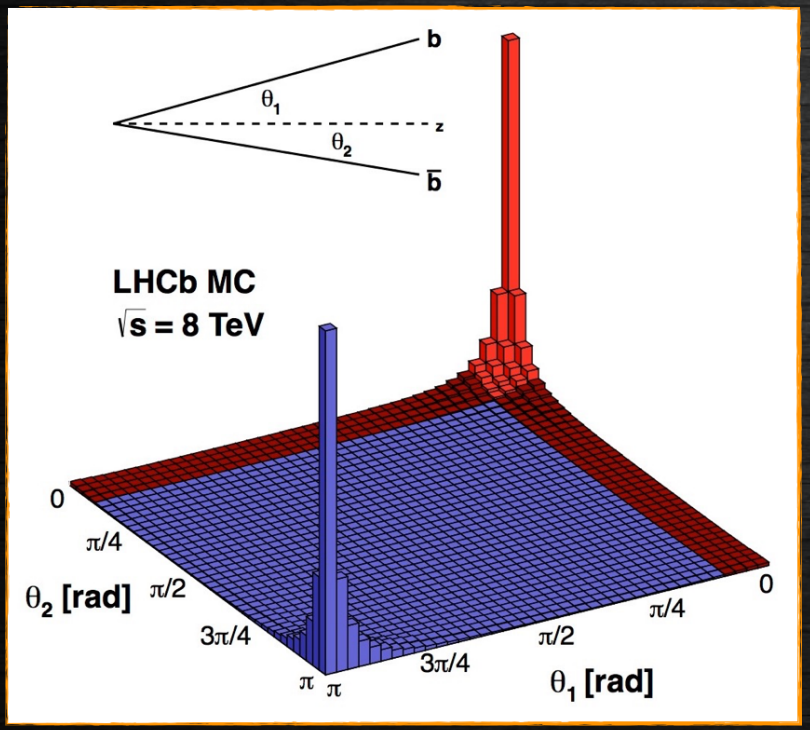
› Optimized for beauty and charm physics at large pseudorapidity ($2<\eta<5$)

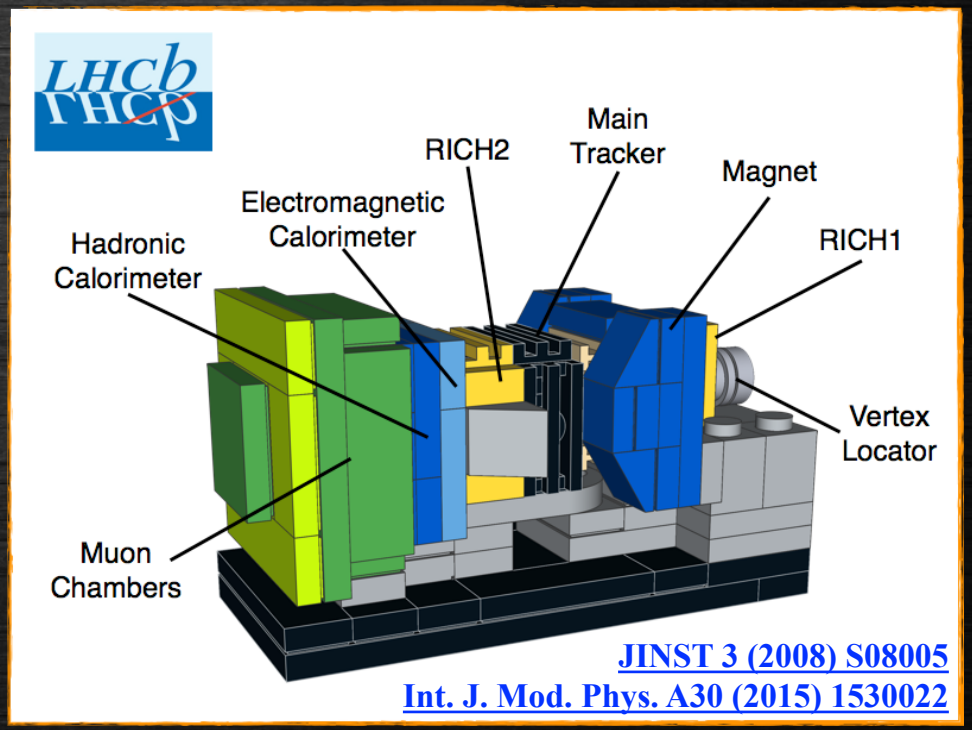
» **Trigger:** >95% (60-70%) efficient for muons (electrons)

» **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

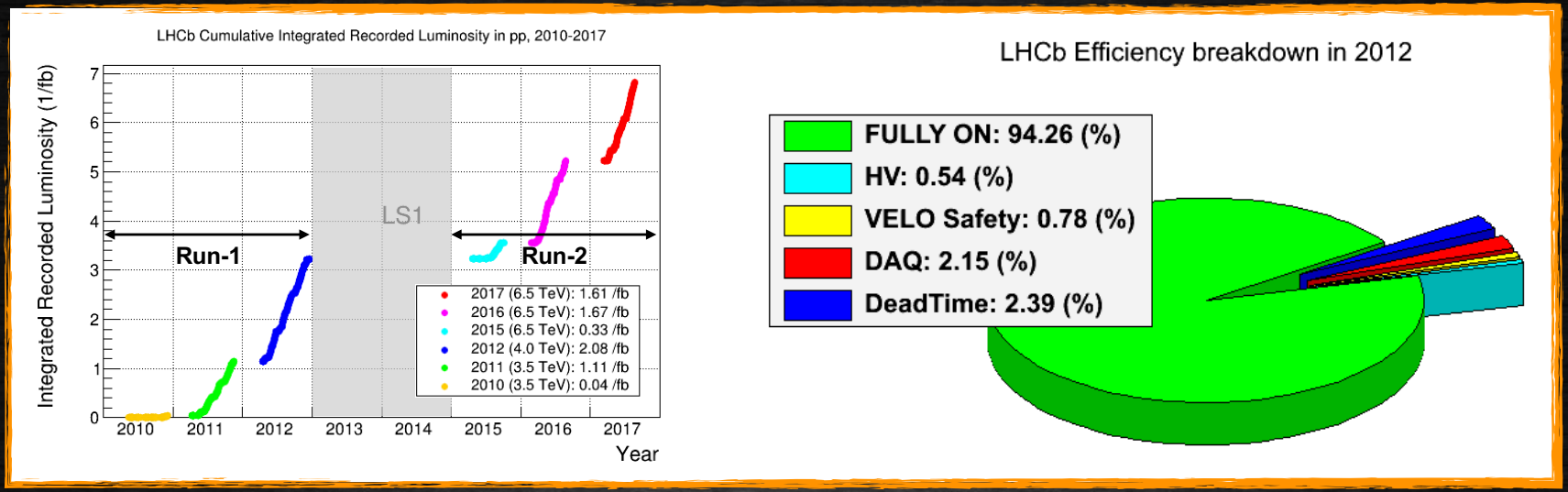


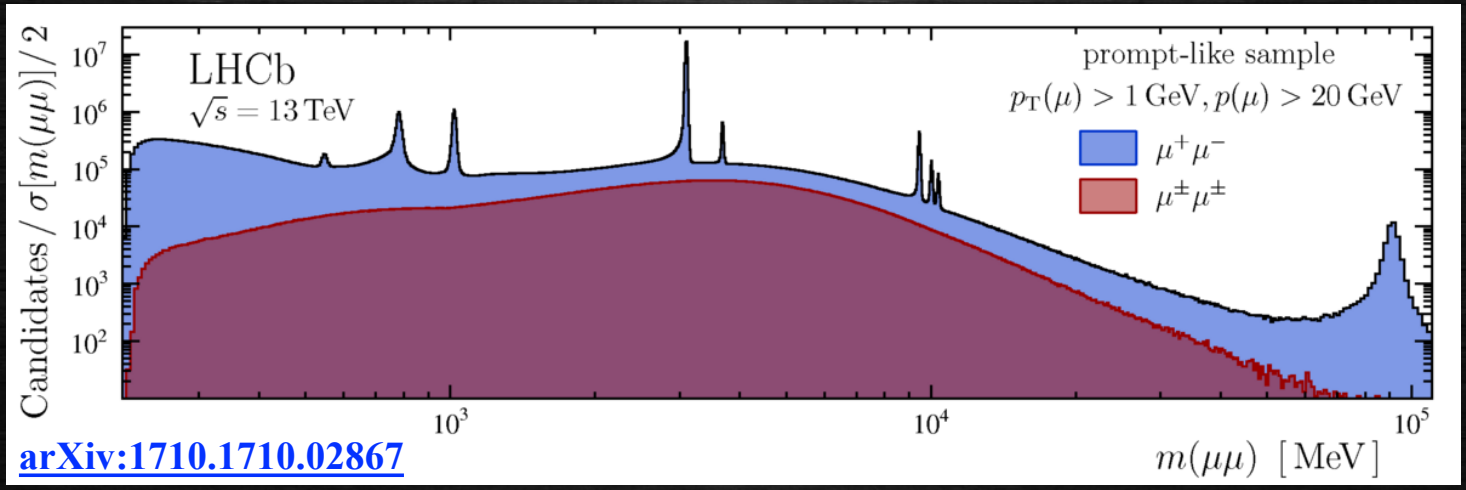


JINST 3 (2008) S08005
Int. J. Mod. Phys. A30 (2015) 1530022

Datasets

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





arXiv:1710.1710.02867

› Due to luminosity levelling, same running conditions throughout fills

Rare b-Hadron Decays @ LHCb

› Three main areas of study

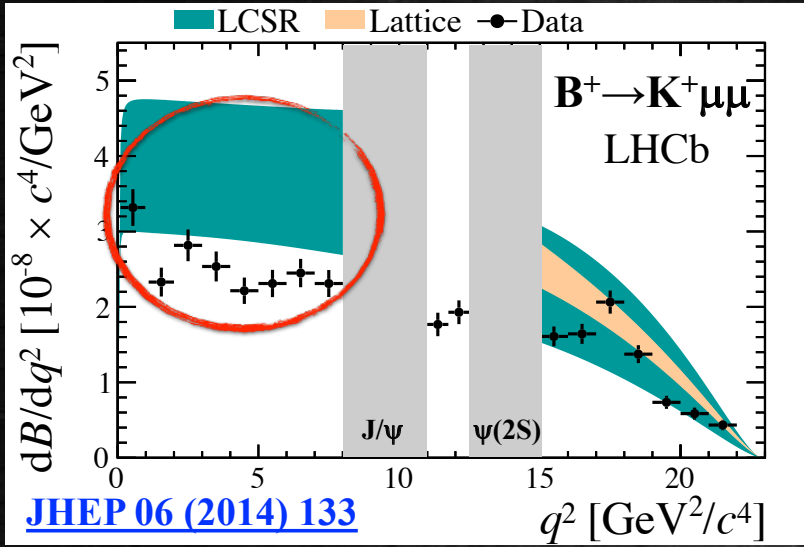
1. **Differential branching fractions** of $B^0 \to K^{(*)0}\mu\mu$, $B^+ \to K^{(*)+}\mu\mu$, $B_s \to \phi\mu\mu$, $B^+ \to \pi^+\mu\mu$ and $\Lambda_b \to \Lambda\mu\mu$
   » Presence of hadronic uncertainties in theory predictions

2. **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

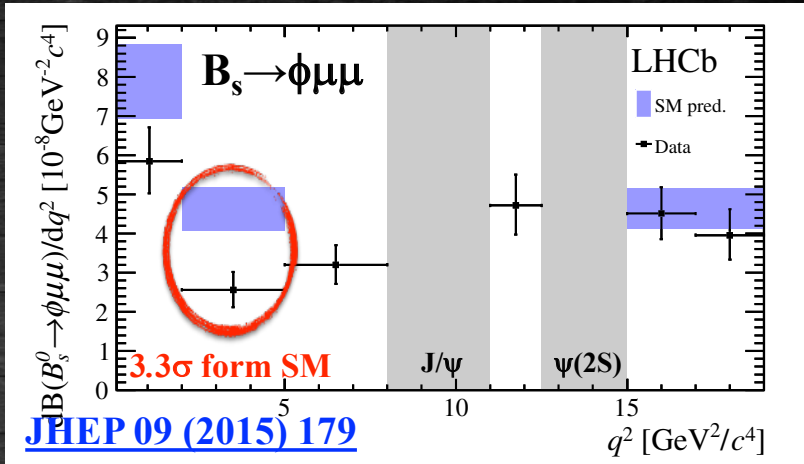
3. **Tests of Lepton Universality** in $B^+ \to K^+ll$ and $B^0 \to K^{*0}ll$
   » Cancellation of hadronic uncertainties in theory predictions

Differential Branching Fractions

› Results **consistently lower than SM predictions**



JHEP 06 (2014) 133



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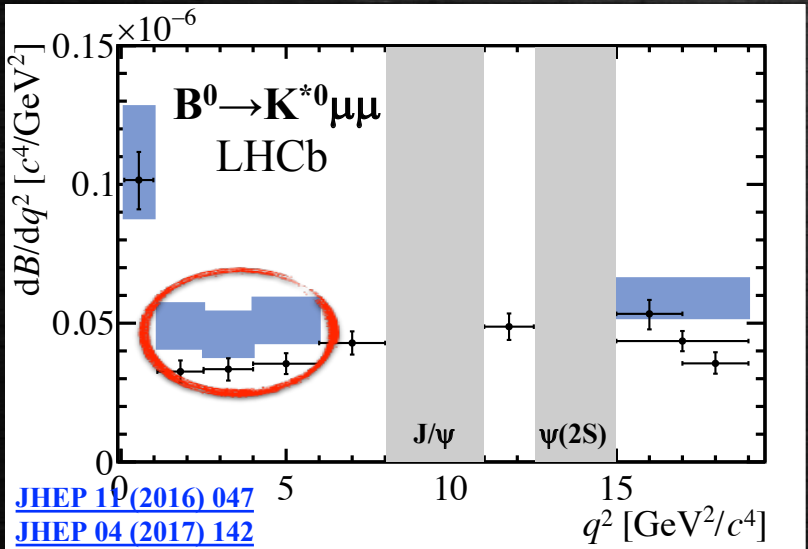

JHEP 11 (2016) 047
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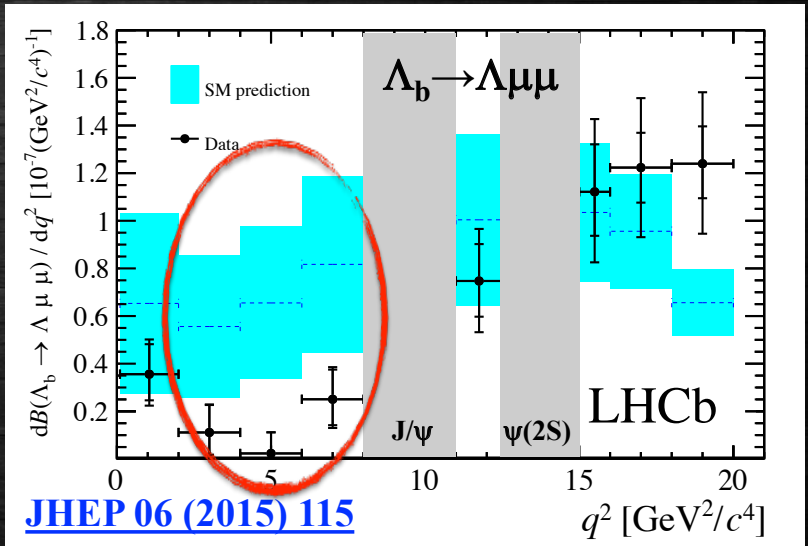
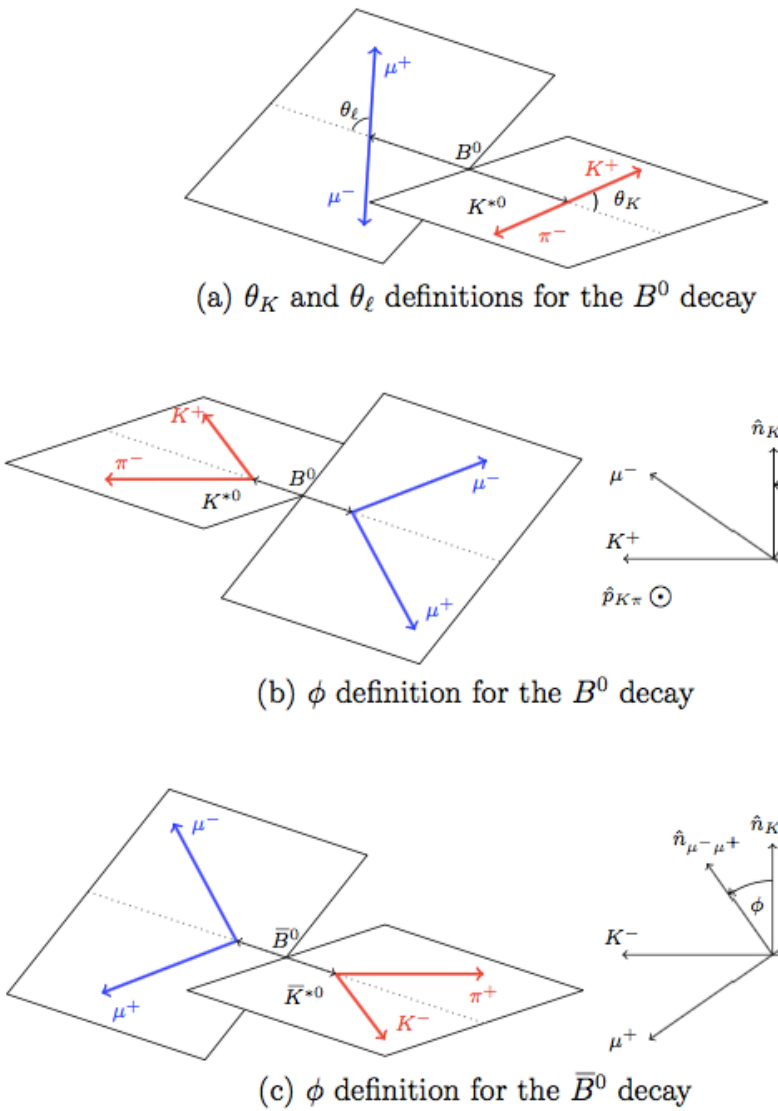


JHEP 06 (2015) 115

Angular Analyses – I

- **Four-body** final states
- System described by **three angles** and the **di-lepton invariant mass squared**, q^2
- Complex angular distribution that provides **many observables sensitive to different types of BSM physics**
- Each observable depends on different Wilson coefficients and form-factors



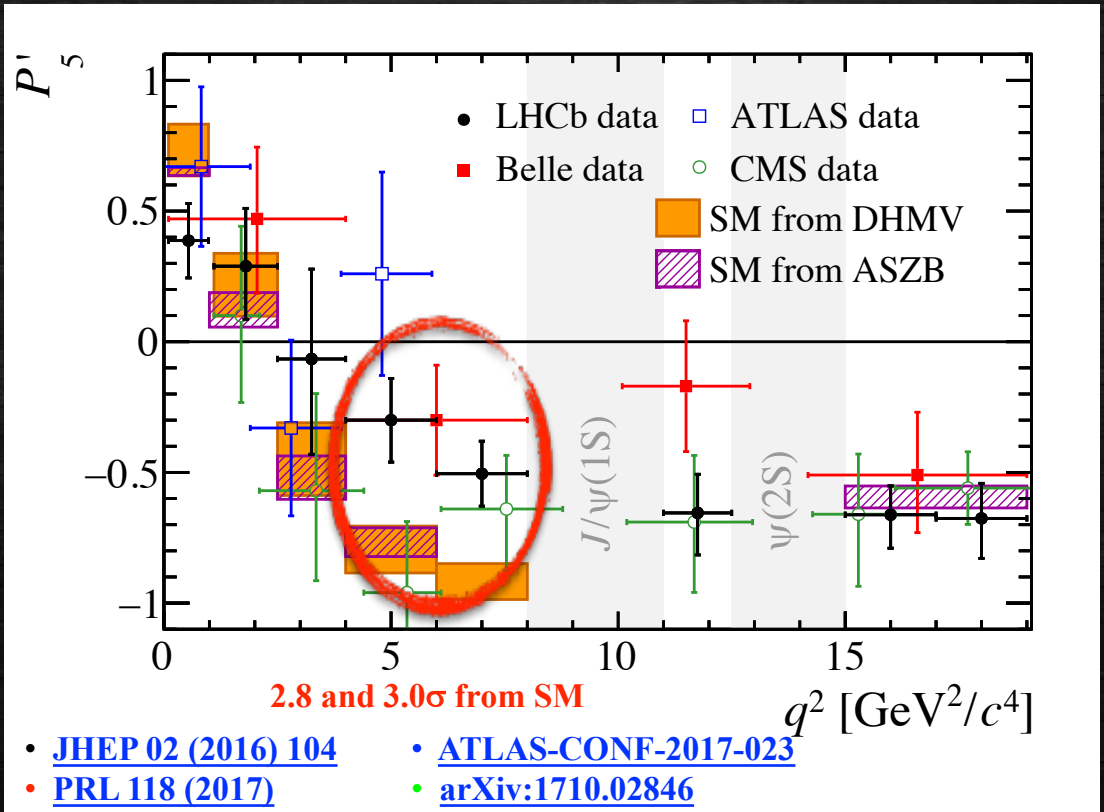
(a) θ_K and θ_ℓ definitions for the B^0 decay

(b) ϕ definition for the B^0 decay

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

Angular Analyses – II

- First **full angular analysis** of $B^0 \to K^{*0}\mu\mu$: measured all CP-averaged angular terms and CP-asymmetries
- Vast majority of observables in agreement with SM predictions giving confidence in theory control of relevant form-factors
- Can construct **less form-factor dependent ratios of observables**



Tests of LU

› **Ratios of branching fractions** are powerful tests of LU as experimental systematics are reduced and theoretical uncertainties largely cancel

$$R_H = \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\, dq^2}$$

› **Determined experimentally as double ratios** to further reduce experimental systematic effects

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

› Extremely challenging due to differences in the way muons and electrons "interact" with the detector

› Selection as similar as possible between μμ and ee

› Simulation tuned as much as possible with data

Tests of LU – R_K

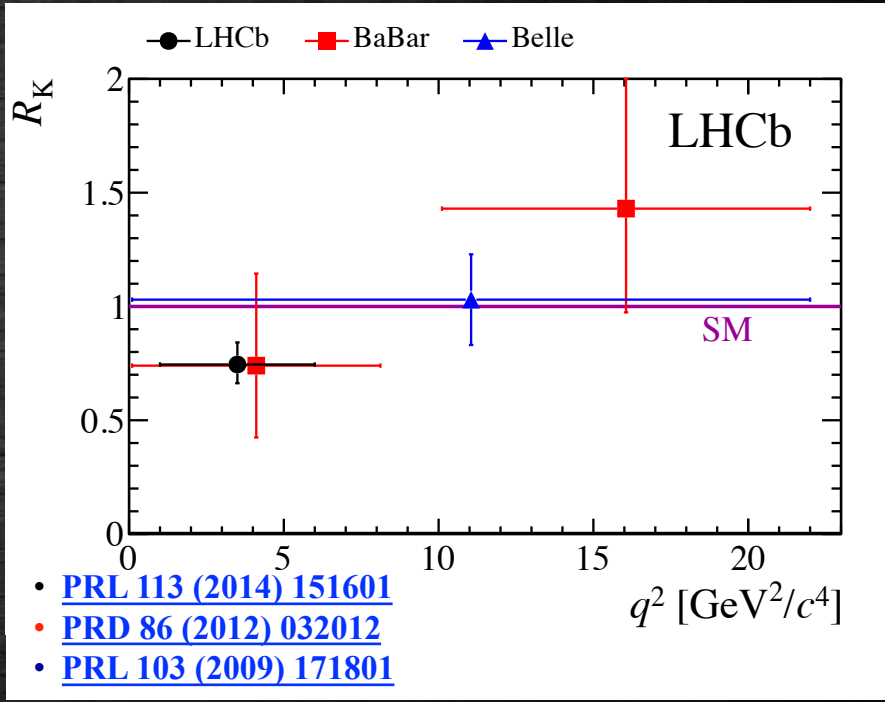
› Test of LU with **$B^+ \to K^+ll$** decays manifests a **tension with the SM at 2.6σ**

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

› **One region of q^2**

»Central [1.0-6.0] GeV²/c⁴

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



› Consistent with BF if BSM physics does not couple to electrons

› **Observation of LU violation would be a clear sign of BSM physics**

Tests of LU – $R_{K^{*0}}$

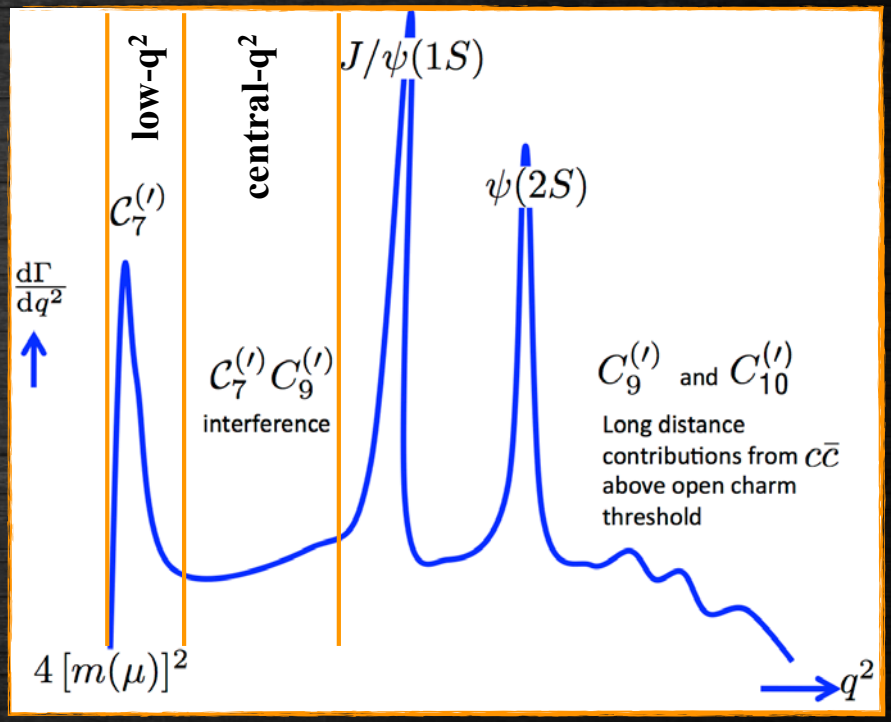
› Test of LU with **$B^0 \to K^{*0} ll$**

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

› **Two regions of q^2**

» Low [0.045-1.1] GeV²/c⁴

» Central [1.1-6.0] GeV²/c⁴



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

› **Blind analysis** to avoid experimental biases

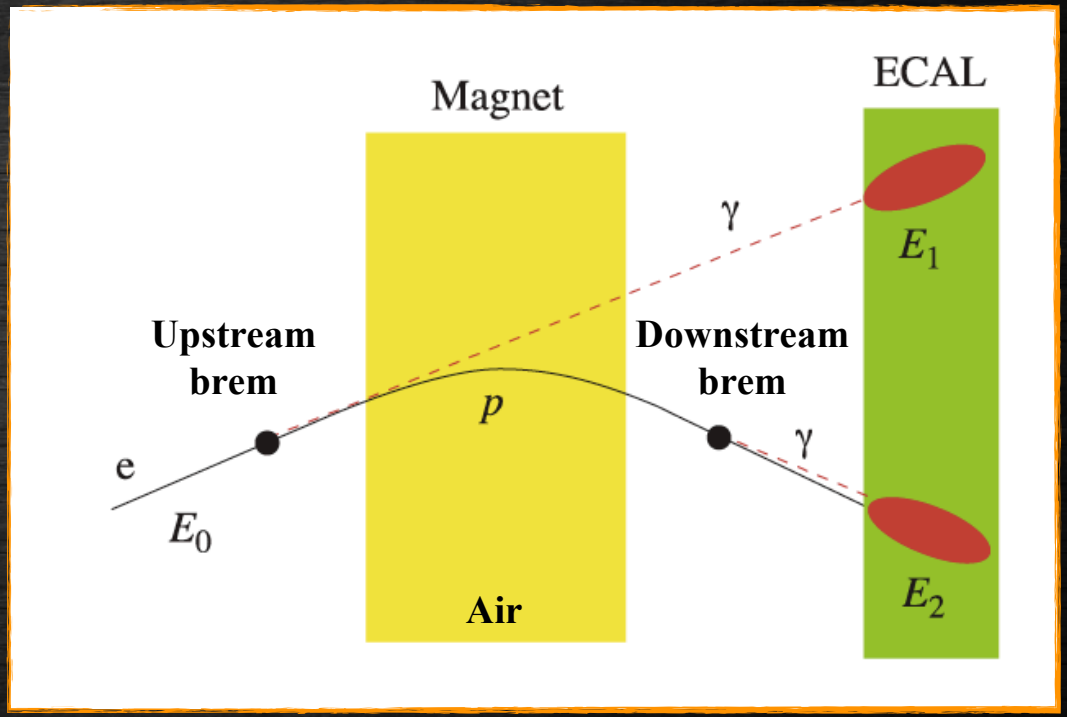
Bremsstrahlung – I

› 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

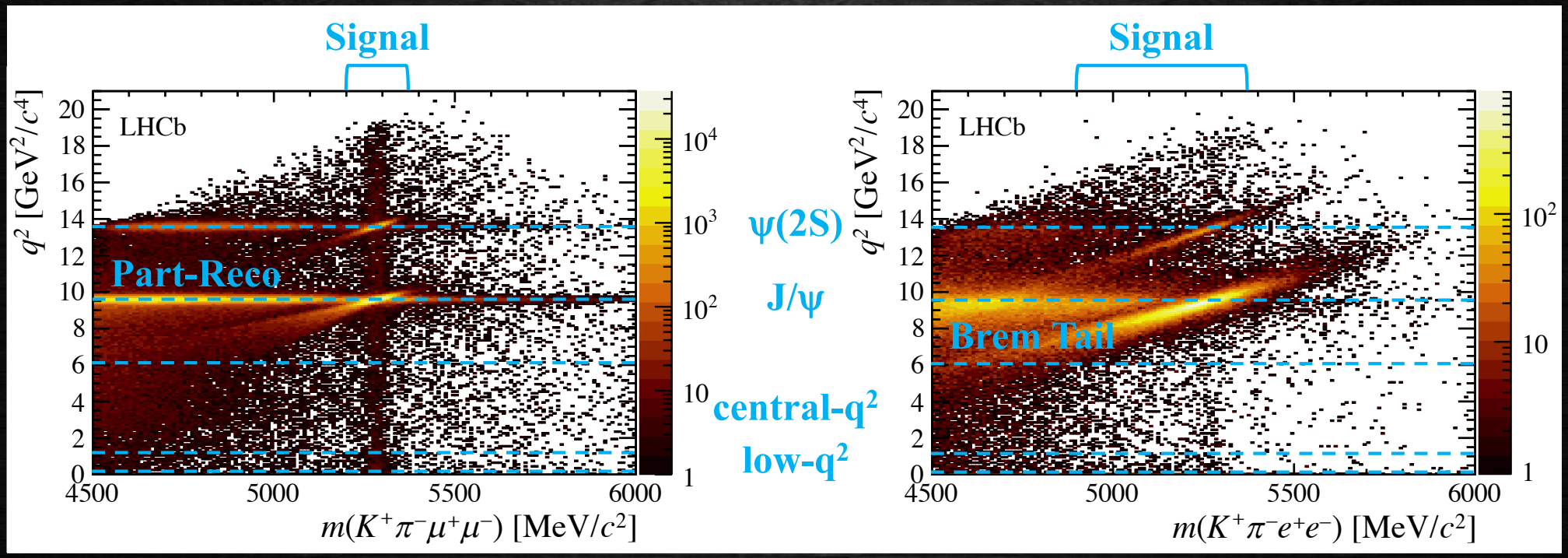
» **Upstream of the magnet**
- photon energy in different calorimeter cells than electron
- momentum evaluated after bremsstrahlung



Bremsstrahlung – II

› A **recovery procedure** is in place to improve the momentum reconstruction

› Events categorised depending on the number of recovered brem γs

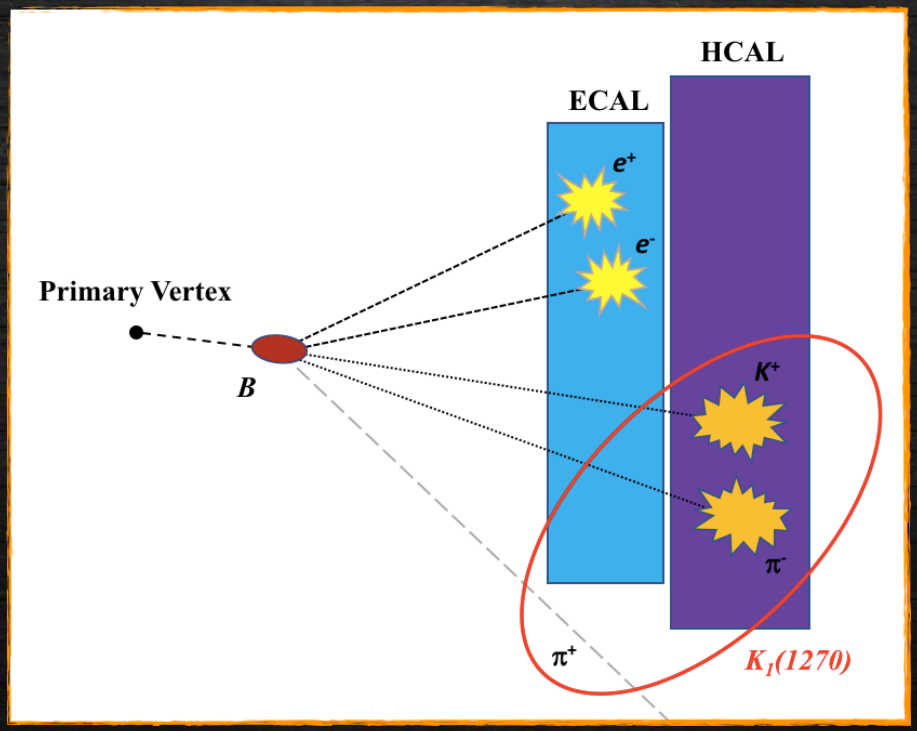


› Residual inefficiencies cause the reconstructed B mass to shift towards lower values and events to migrate in q^2

JHEP 08 (2017) 055

Part-Reco Background

- 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 **$B \to K_2^*(1430)ee$**
- Modelled with a simulation cocktail or using $B^+ \to K^+\pi^+\pi^-\mu\mu$ data



Trigger

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

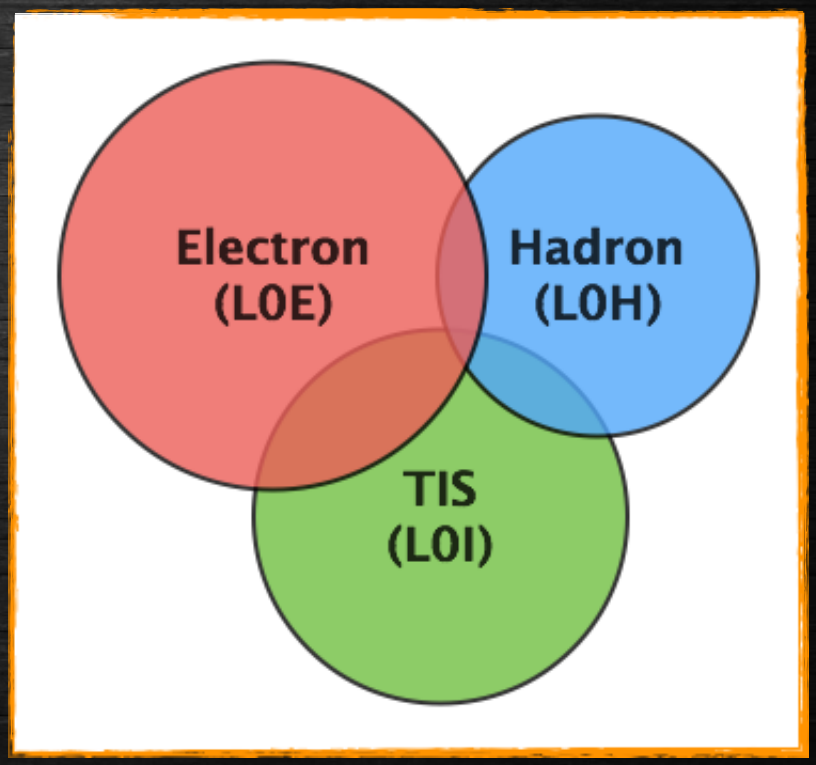
› Due to higher occupancy of the calorimeters compared to the muon stations, hardware thresholds on the electron E_T are higher than on the muon p_T (**L0 Muon**, p_T > 1.5-1.8 GeV)

› To partially mitigate this effect, **3 exclusive trigger categories** are defined for the electron sample

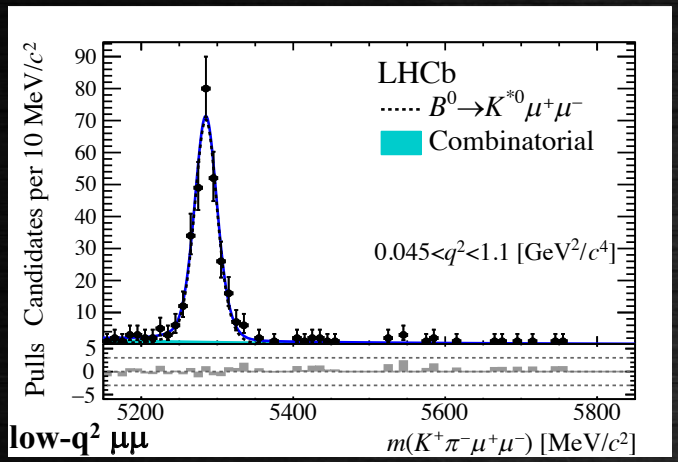
» **L0 Electron**: electron trigger fired by clusters associated to at least one of the two electrons (E_T > 2.5-3.0 GeV)

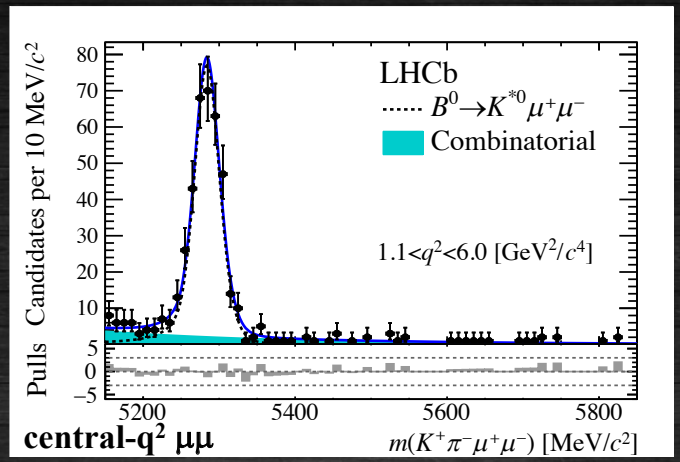
» **L0 Hadron**: hadron trigger fired by clusters associated to at least one of the K^{*0} decay products (E_T > 3.5 GeV)

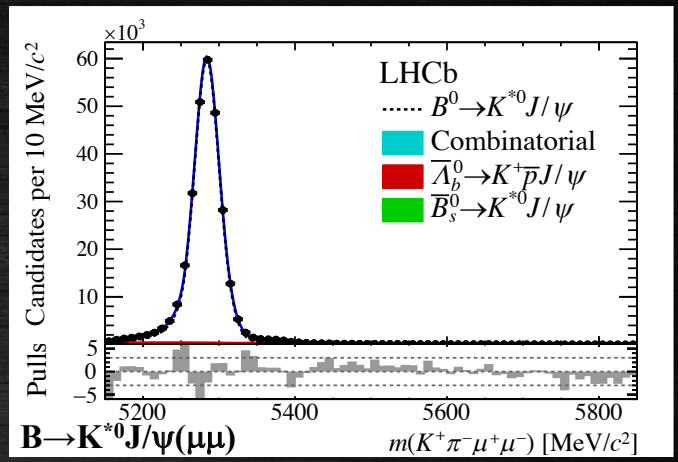
» **L0 TIS**: any trigger fired by particles in the event not associated to the signal candidate

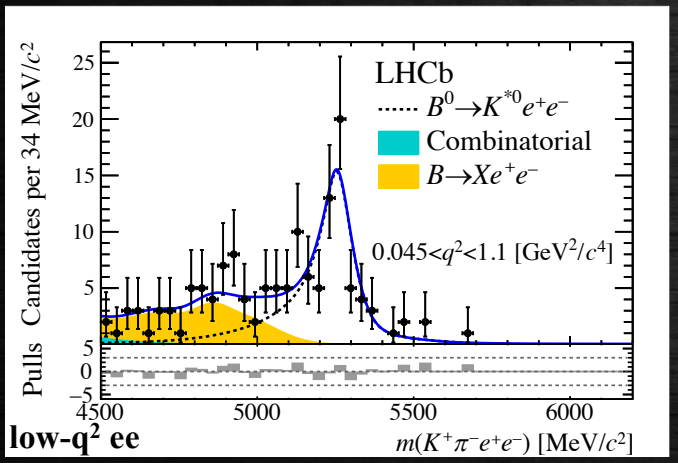


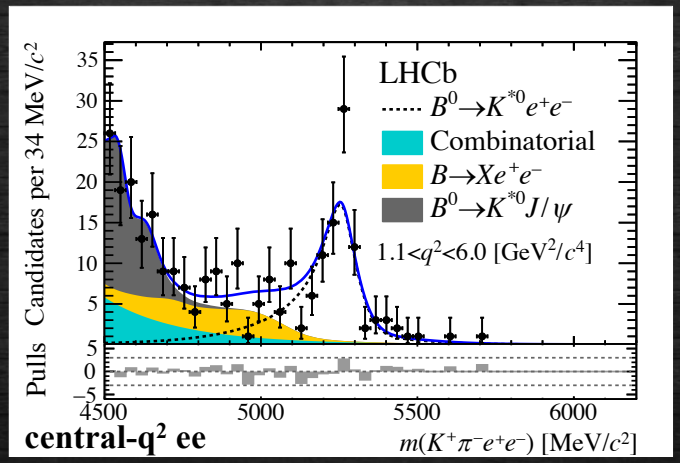
Fit Results

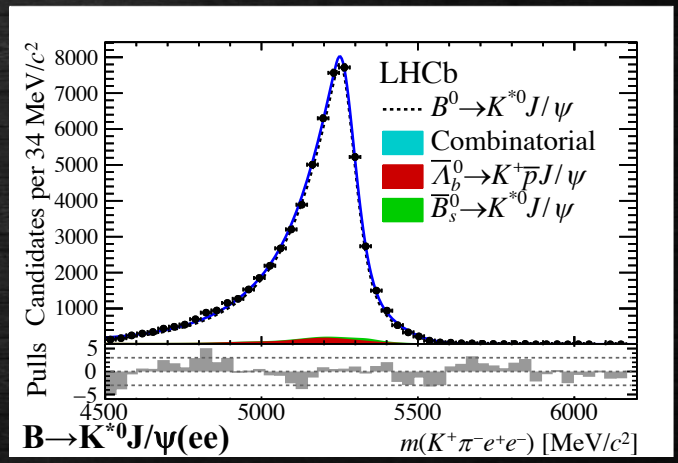












› In total, about 290 (90) and 350 (110) $B^0 \to K^{*0}\mu\mu$ ($B^0 \to K^{*0}ee$) candidates at low- and central-q^2, respectively

JHEP 08 (2017) 055

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

Cross-Checks

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

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))} = 1.043 \pm 0.006 \pm 0.045$$

Compatible with unity and independent of the decay kinematics and event track multiplicity

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

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

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

Compatible with the expectations

› **BR($B^0 \to K^{*0}\mu\mu$)** in good agreement with [JHEP 04 (2017) 142]

› Relative population of **bremsstrahlung categories** consistent between data and simulation

› When **corrections to simulations** are not accounted for, the efficiency ratio changes by less than 5%

JHEP 08 (2017) 055

Systematics

JHEP 08 (2017) 055

› $R_{K^{*0}}$ determined as a double ratio

» Many experimental systematic effects much reduced

» Statistically dominated (~15%)

	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	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
$r_{J/\psi}$ ratio	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

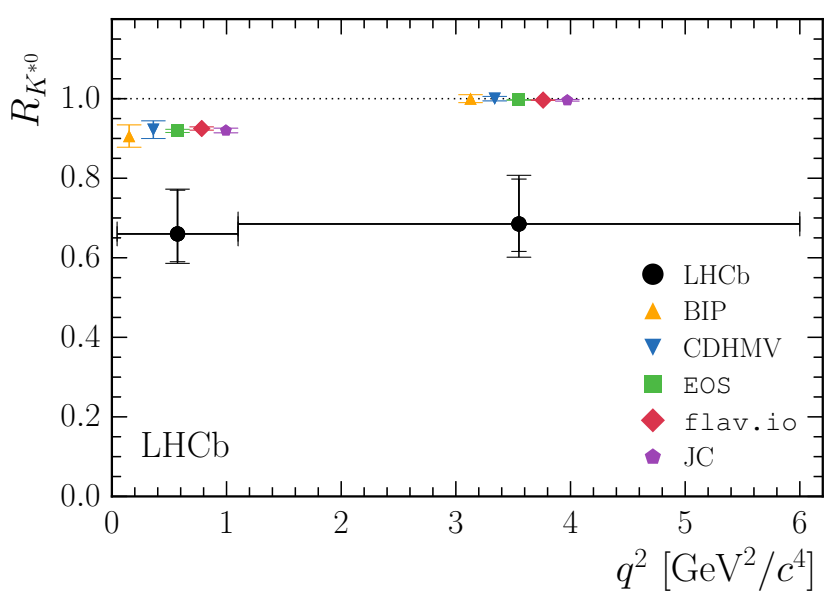
⟵ Description of brem-tail

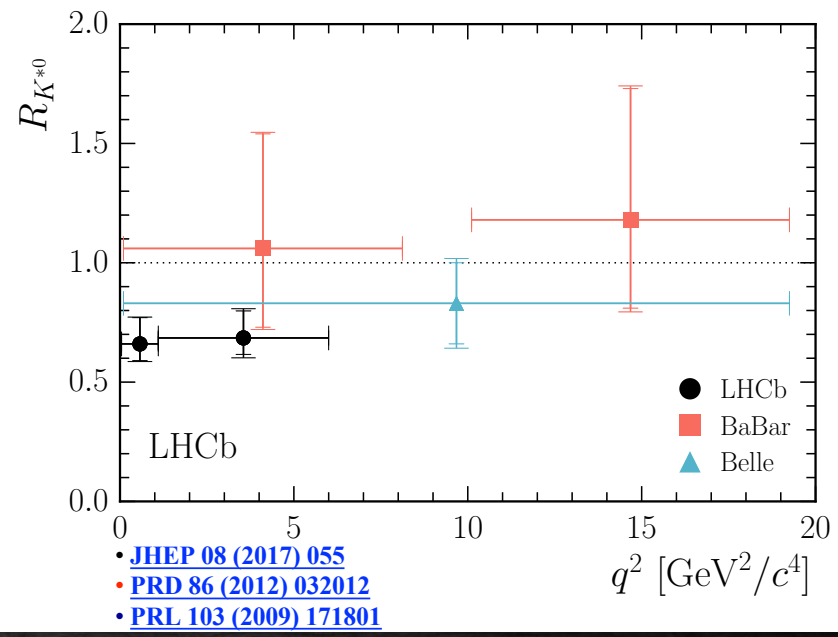
⟵ Residual background contamination due to $B^0 \to K^{*0} J/\psi(ee)$ with a $K \leftrightarrow e$ or $\pi \leftrightarrow e$ swap

› Total systematic uncertainty of 4-6% and 6-8% at low- and central-q^2

Results

$$R_{K^{*0}} = \begin{cases} 0.66\,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4 \\ 0.69\,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0\ \text{GeV}^2/c^4 \end{cases}$$





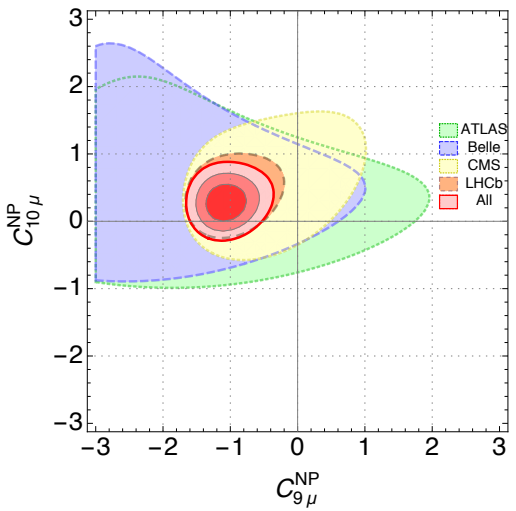
› Compatibility with the SM prediction(s)

» **low-q²** 2.1-2.3 standard deviations

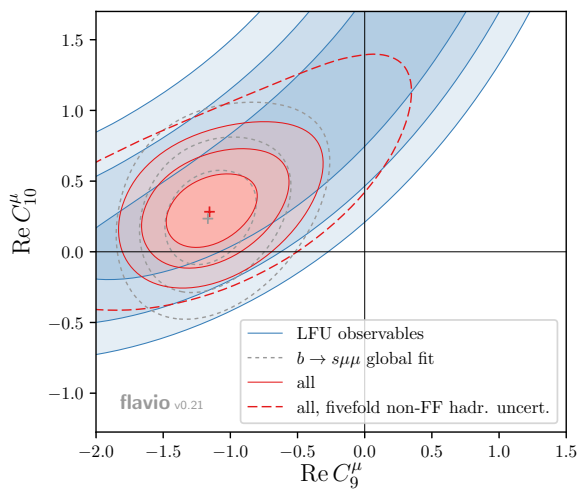
» **central-q²** 2.4-2.5 standard deviations

Global Fits – I

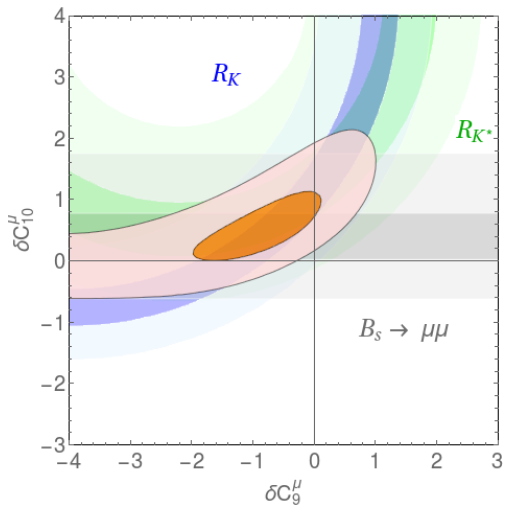
› Several attempts to interpret results by performing **global fits to data**



arXiv:1704.05340



arXiv:1704.05435



arXiv:1704.05446

› Take into account O(100) observables from different experiments, including b→μμ, b→sll and b→sγ transitions

› All global fits require an **additional contribution wrt the SM to accommodate the data, with a preference for BSM physics in C_9 at 3-5σ**

› **Or is this a problem with the understanding of QCD?**
e.g. Correct estimate of the contribution from charm loops?

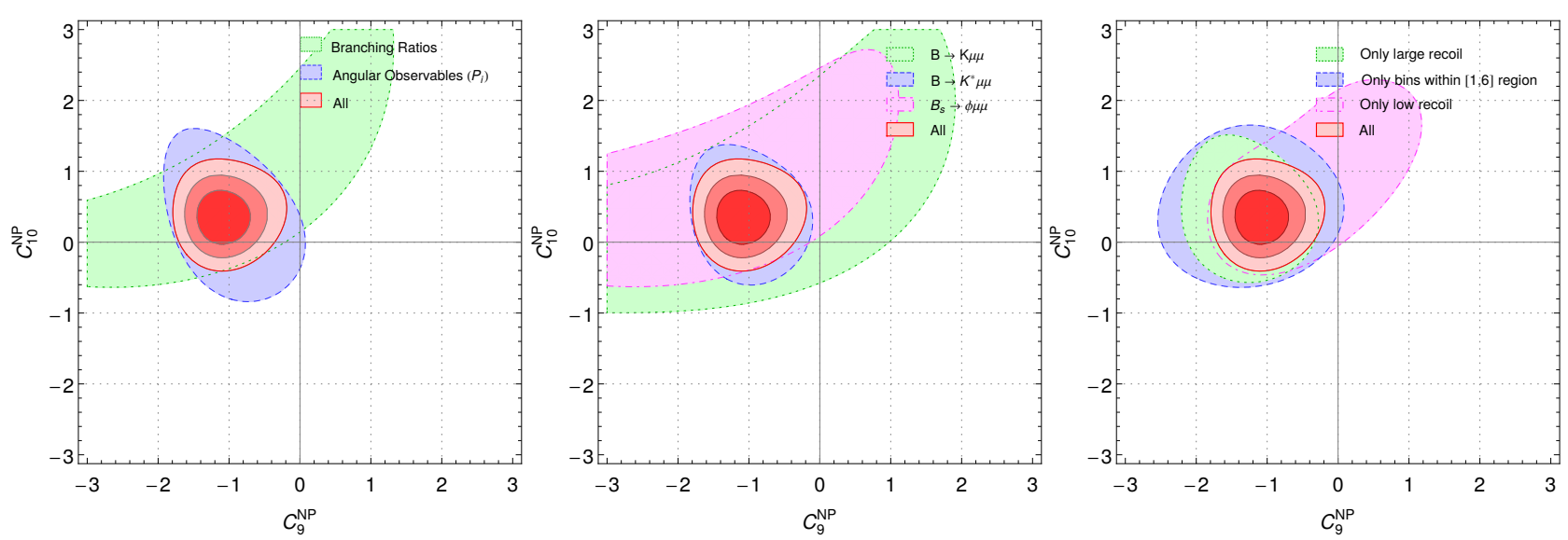
Global Fits – II

› **Good consistency among different fits**

» BFs and Angular Observables

» Different modes

» Different q^2 regions

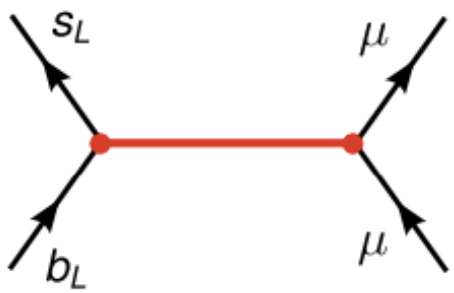


arXiv:1510.04239

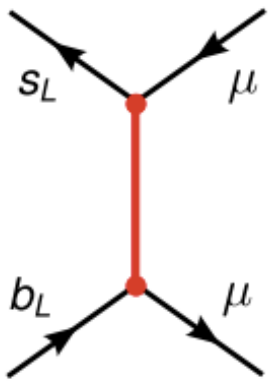
› n.b. Different theory issues in each case

Is it a Z', a LQ or … ? – I

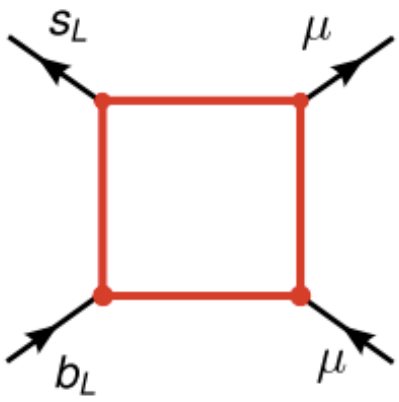
› Models containing a **new heavy gauge boson** or **leptoquarks** have been proposed to explain the anomalies in the flavour sector



- Z'
- $SU(2)_L$ singlet or triplet



- Leptoquark
- Spin 0 or 1

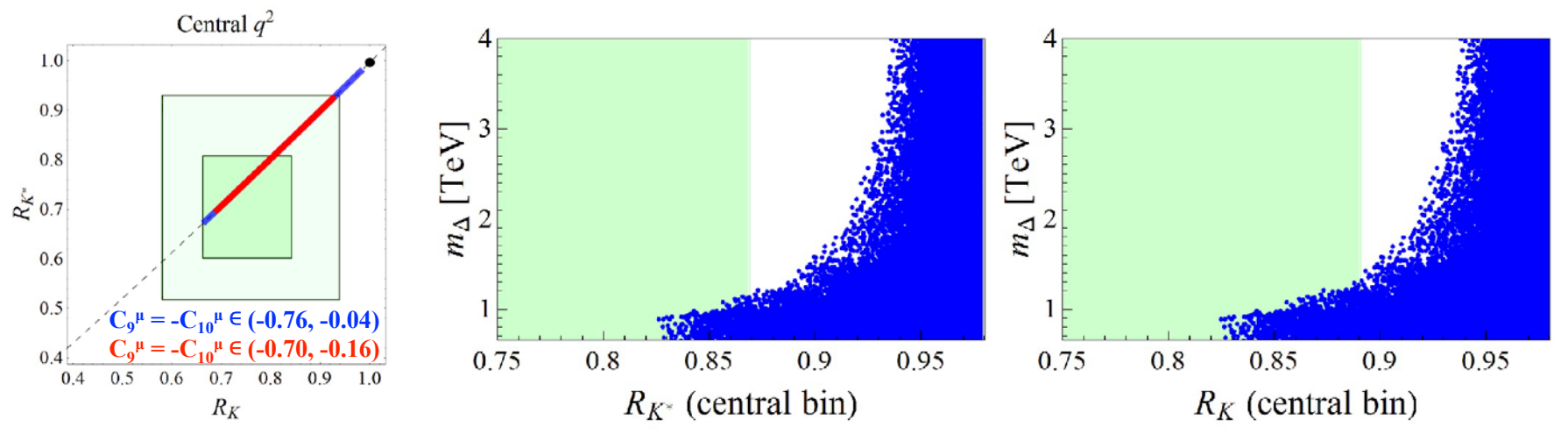


- New scalars/vectors, also leptoquarks possible

Is it a Z', a LQ or … ? – II

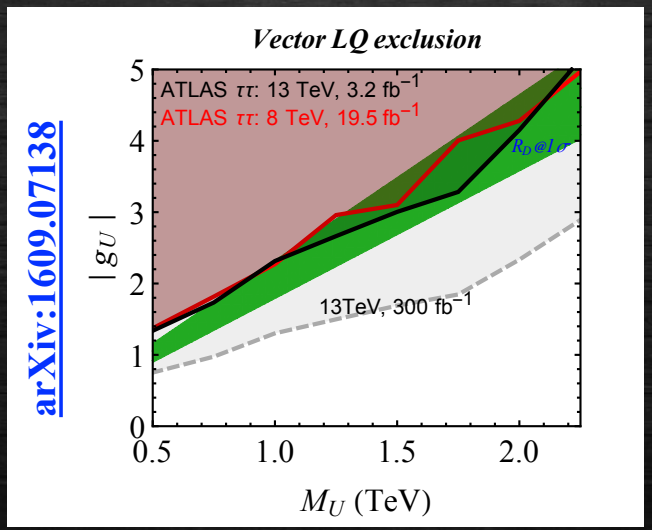
› e.g. Low energy scalar leptoquark

arXiv:1704.05835



› e.g. Recast ATLAS searches of Z'→ττ

arXiv:1609.07138



Outlook

› Very lively discussion in the community, e.g. instant workshop on B anomalies just ~1 month after the $R_{K^{*0}}$ CERN seminar

› **Updated measurements** with ~½ Run-2 data

» **$B^0 \to K^{*0}\mu\mu$ angular analysis**: ~√2 improvement in precision

» **R_K**: ~1.8 improvement in precision

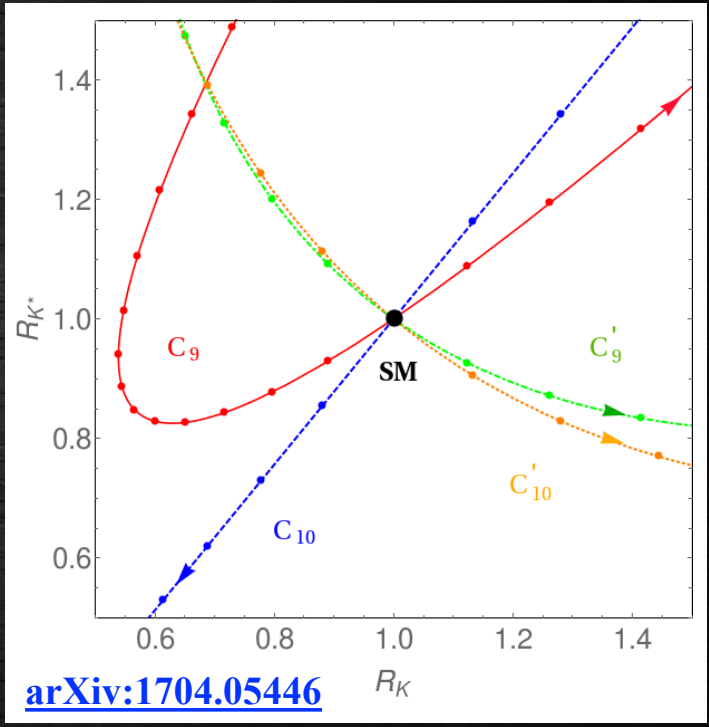
» **$R_{K^{*0}}$** : ~√2 improvement in precision

› **New measurements** also in preparation

» **$B^0 \to K^{*0}ee$ angular analysis** enables tests of LU using angular observables

» **R_ϕ**: signal suppressed by f_s/f_d and BF=1/2, but narrow ϕ mass and reduced backgrounds

» **Additional final states** under study, e.g. K_S, K^{*+}, higher K^* resonances, Λ, pK



Summary

- Interesting set of anomalies observed in b-hadron decays by LHCb
- If taken together this is probably the largest "coherent" set of BSM effects in the present data

- Near-term updates should clarify the experimental situation and can help constrain some of the theoretical issues
- Wide range of measurements will be added to broaden the constraints on any BSM physics model

- The full Run-2 dataset will give a factor ~5 more statistics than Run-1 on the timescale that Belle-II will start its physics run