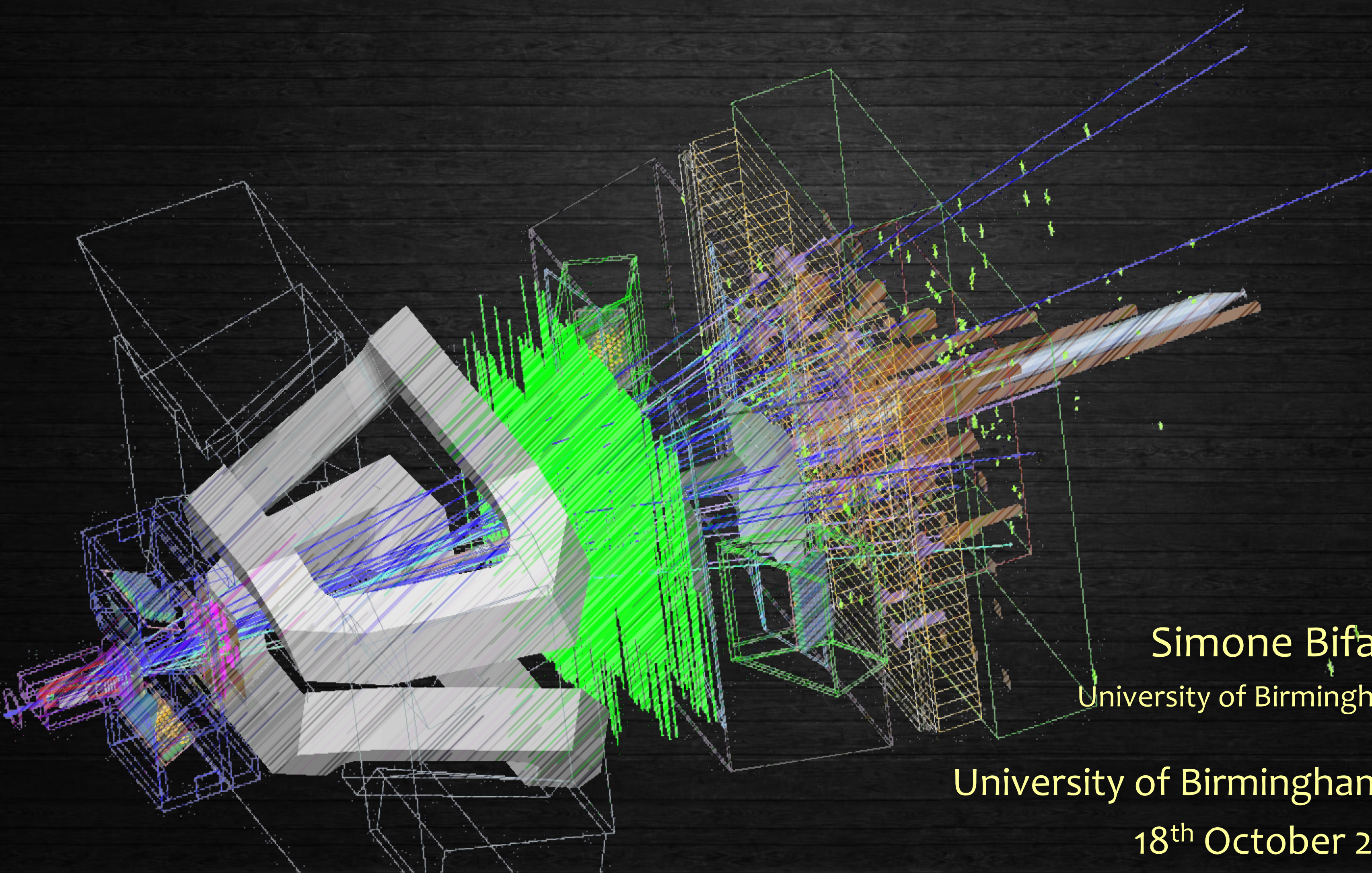
Flavour Anomalies @ LHCb



Simone Bifani
University of Birmingham (UK)

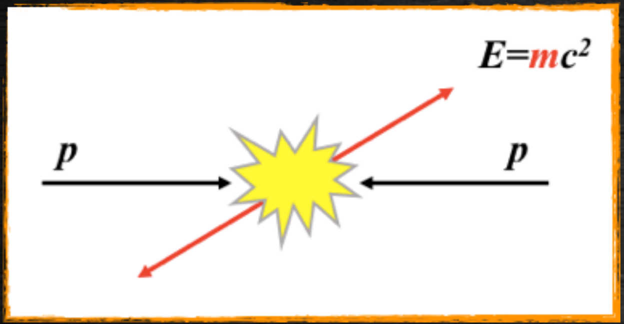
University of Birmingham - PP Seminar
18th October 2017

Outline

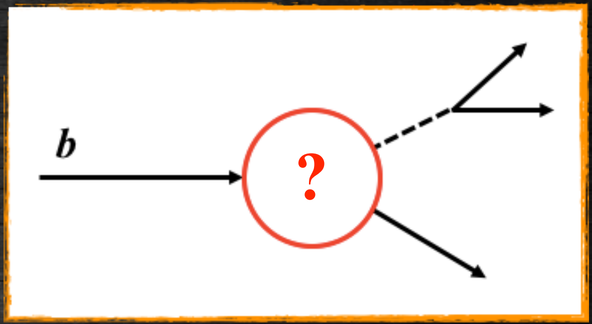
- Quest for BSM physics
- Why b-hadron decays?
- b-hadron decays @ LHCb
  - $b \to sll$
  - $b \to cl\nu$
- Outlook

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

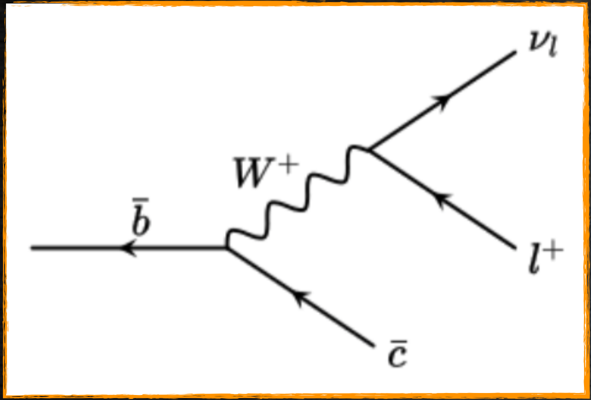
› Most of the unexpected anomalies have been neutralised by the additional statistics

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

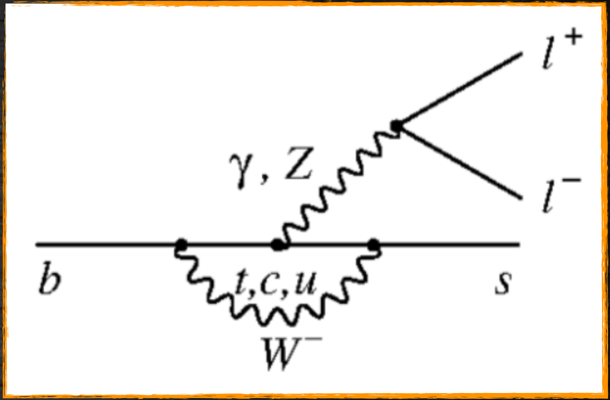
Anatomy of b-Hadron Decays

› **Flavour-Changing** quark-transitions

Charged Current (tree level)



Neutral Current (loop level)



› **FCCC well understood** in the SM

» e and μ final-states insensitive to non-SM contributions

» τ final-state sensitive to additional amplitudes

› **FCNC suppressed** in the SM

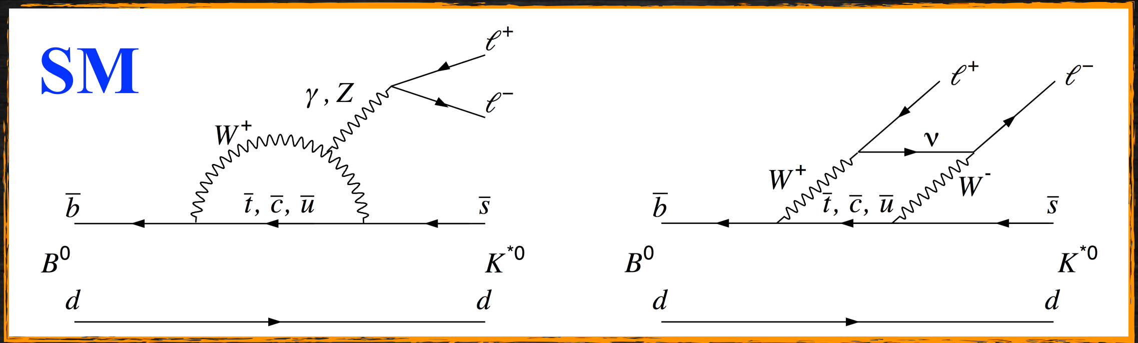
» only allowed at loop level (GIM)

» involve an off-diagonal CKM element

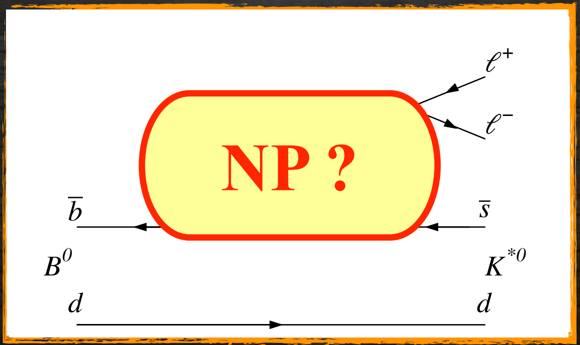
» (possibly) helicity suppressed

Why b-Hadron Decays?

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



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



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

Theoretical Framework – I

› 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 QCD, long-distance physics, depends on hadronic form-factors

0.2GeV......	4GeV......	80GeV......	~ 100 TeV ?
Λ_{QCD}	Λ_b	Λ_{EW}	Λ_{NP}
(non-perturbative regime)	(b mass)	(W mass)	(new physics scale)

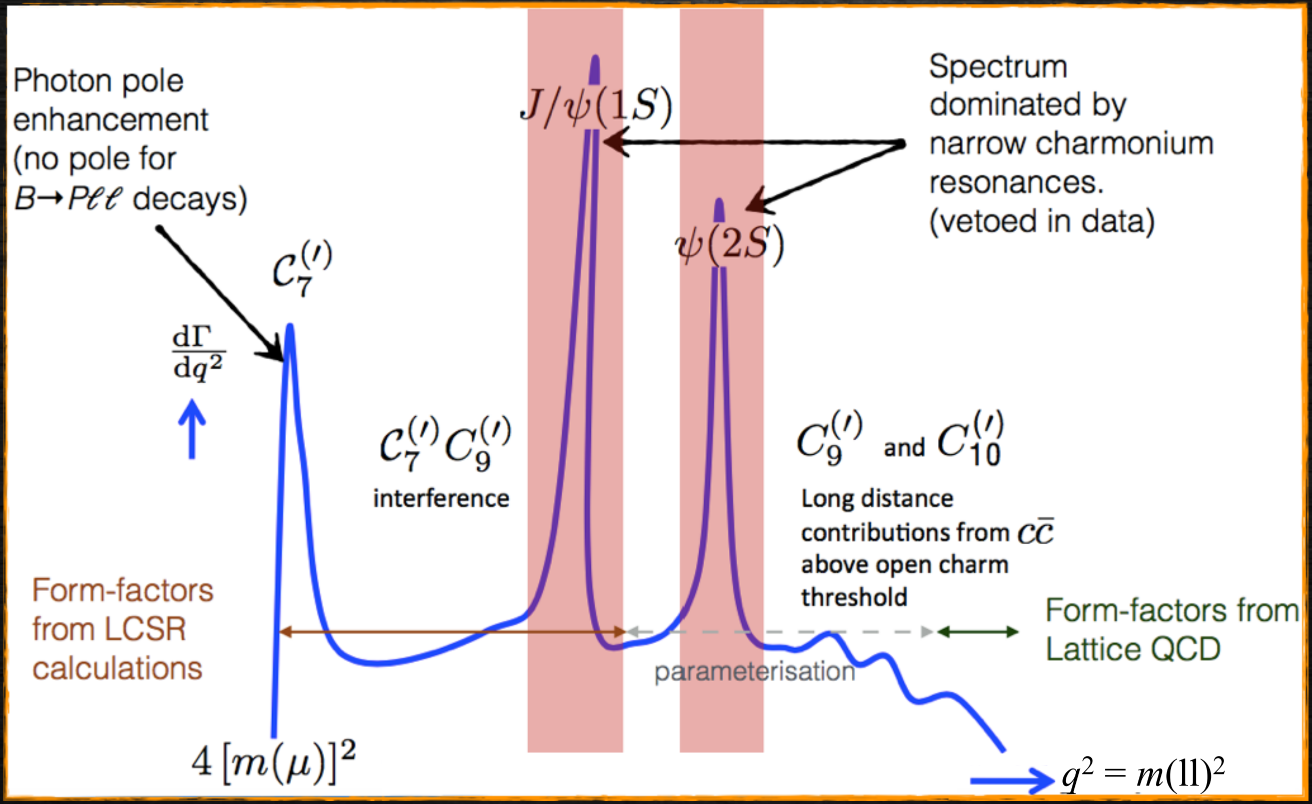
Theoretical Framework – II

› **BSM physics** can

» alter the SM operator contributions (Wilson coefficients)

» enter through new operators (right-handed O_i', $O_{S,P}$)

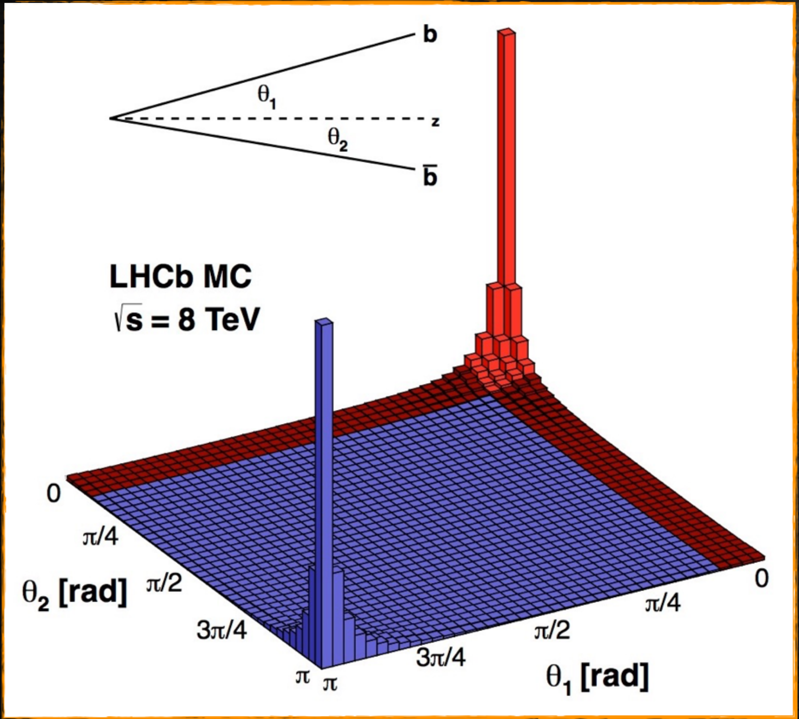
› Different q^2 regions probe different operators

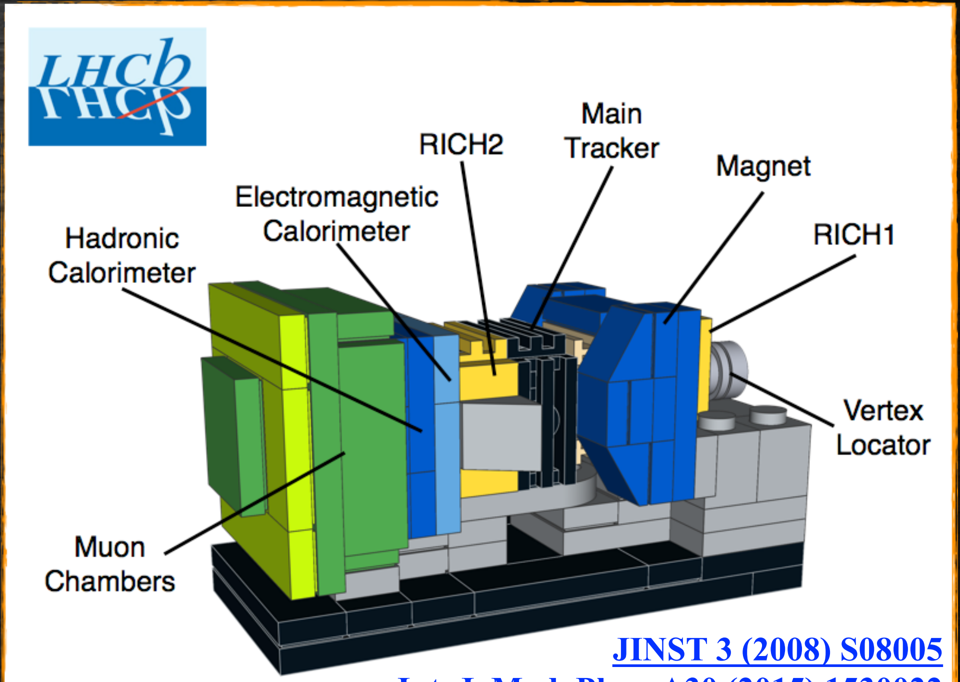


A Forward Spectrometer

› 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

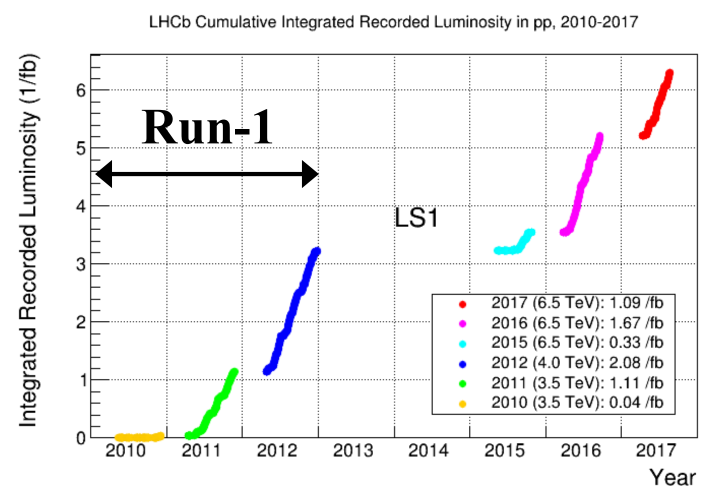


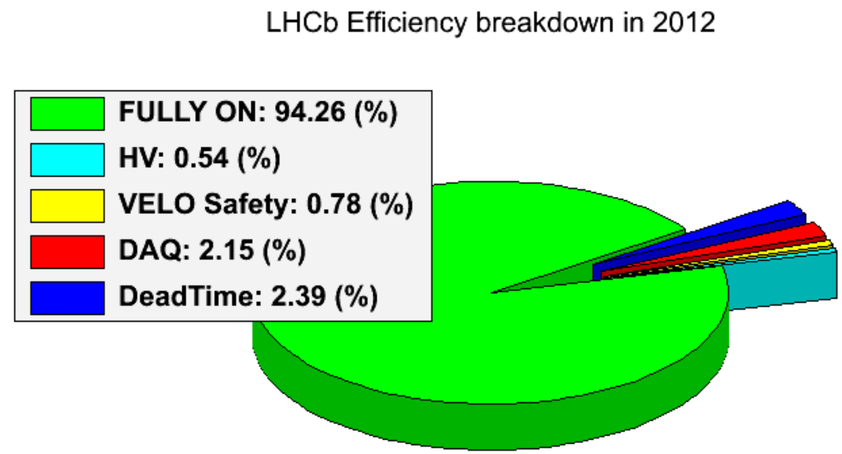


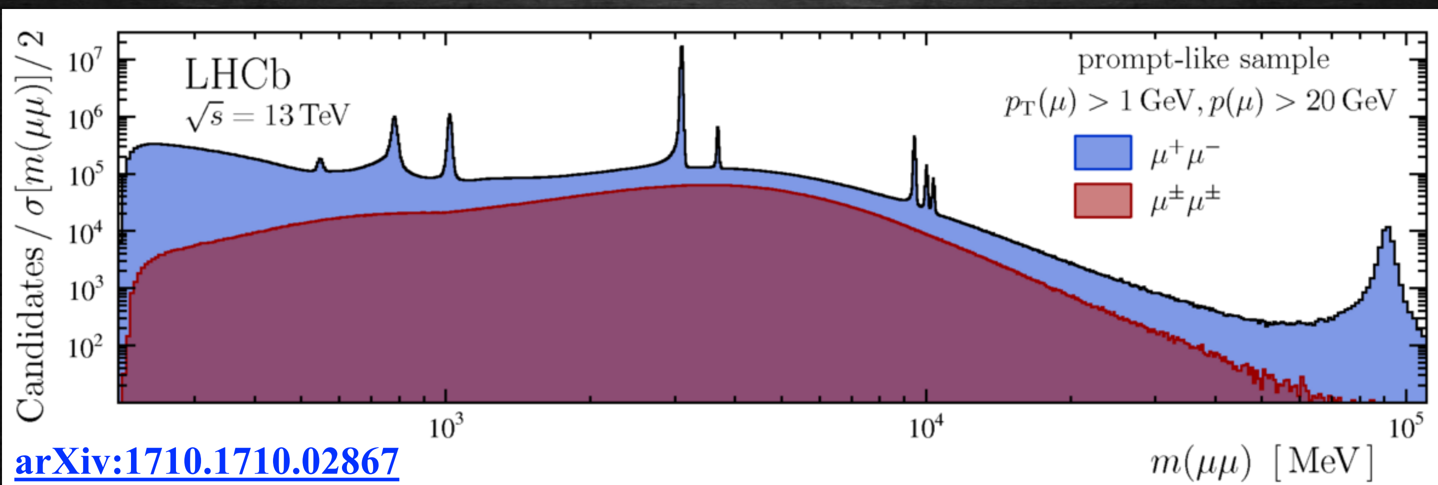
JINST 3 (2008) S08005
Int. J. Mod. Phys. A30 (2015) 1530022

Datasets

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







arXiv:1710.1710.02867

› Due to luminosity levelling, same running conditions throughout fills

Shopping List

› Three main areas of study

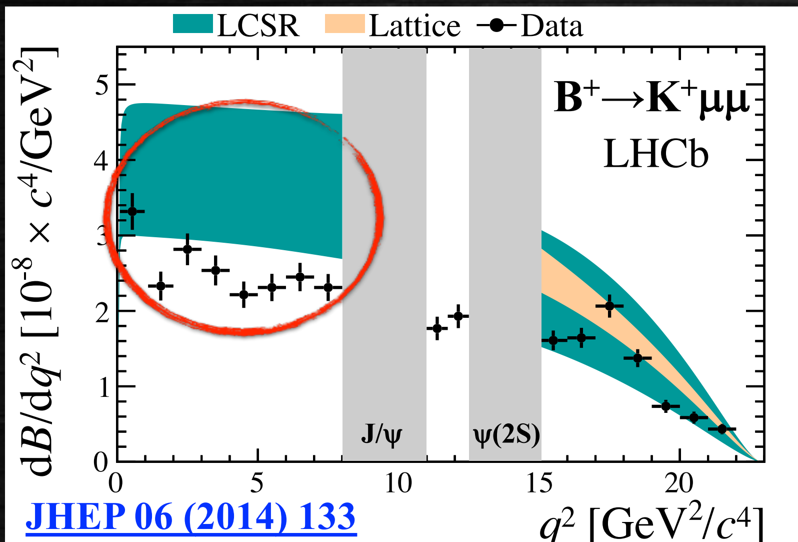
1. **Differential branching fractions** of $B^0 \to K^{(*)0}\mu\mu$, $B^+ \to K^{(*)+}\mu\mu$, $B_s \to \phi\mu\mu$, $B^+ \to \pi^+\mu\mu$ and $\Lambda_b \to \Lambda\mu\mu$
   » Presence of hadronic uncertainties in theory predictions

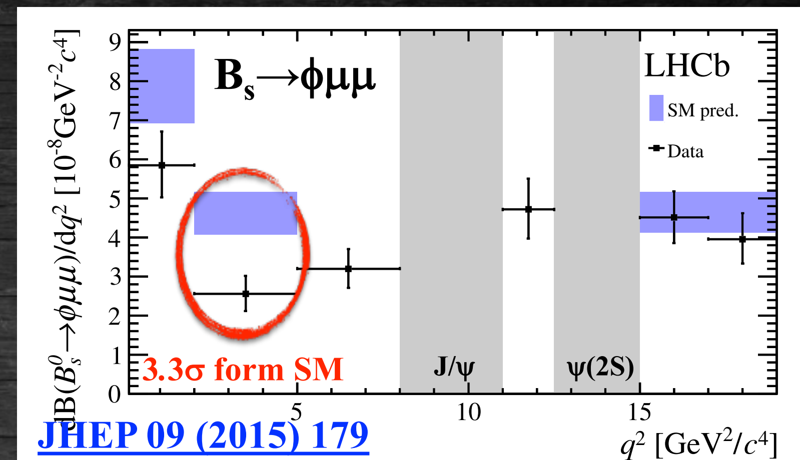
2. **Angular analyses** of $B \to K^{(*)}\mu\mu$, $B_s \to \phi\mu\mu$, $B^0 \to K^{*0}ee$ and $\Lambda_b \to \Lambda\mu\mu$
   » Define observables with smaller theory uncertainties

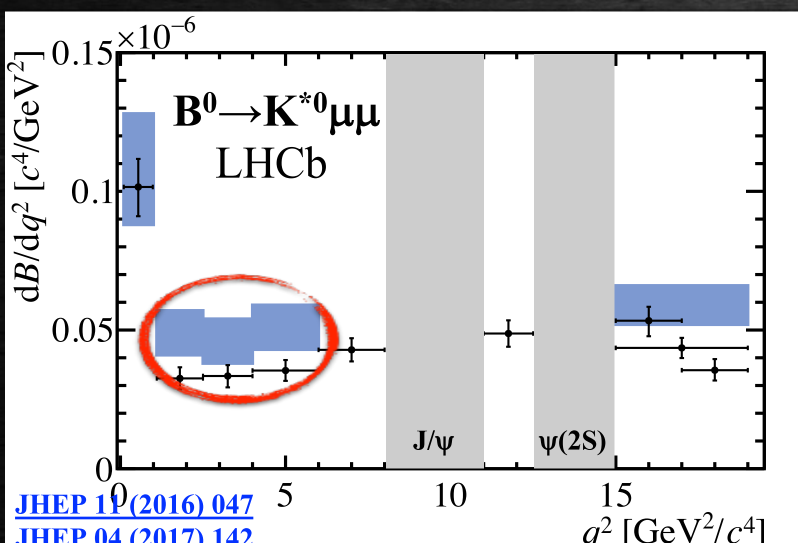
3. **Test of Lepton Universality** in $B^+ \to K^+ll$ and $B^0 \to K^{*0}ll$
   » Cancellation of hadronic uncertainties in theory predictions

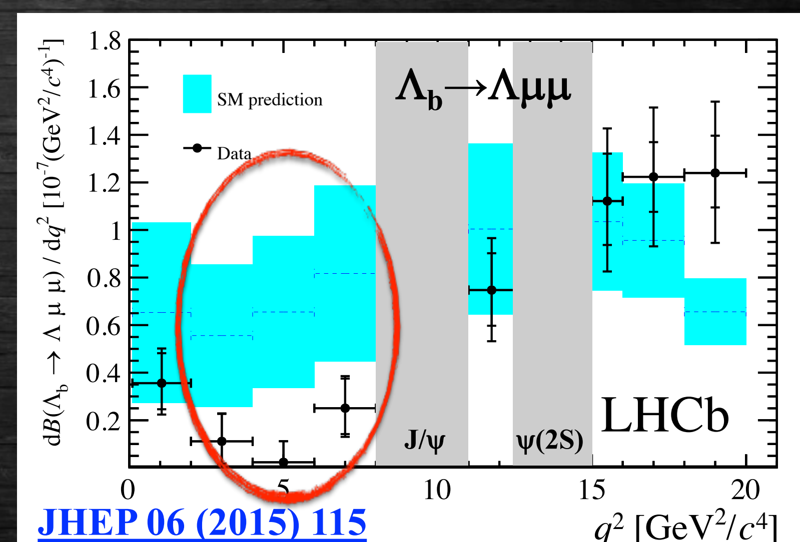
Differential Branching Fractions

› Results **consistently lower than SM predictions**



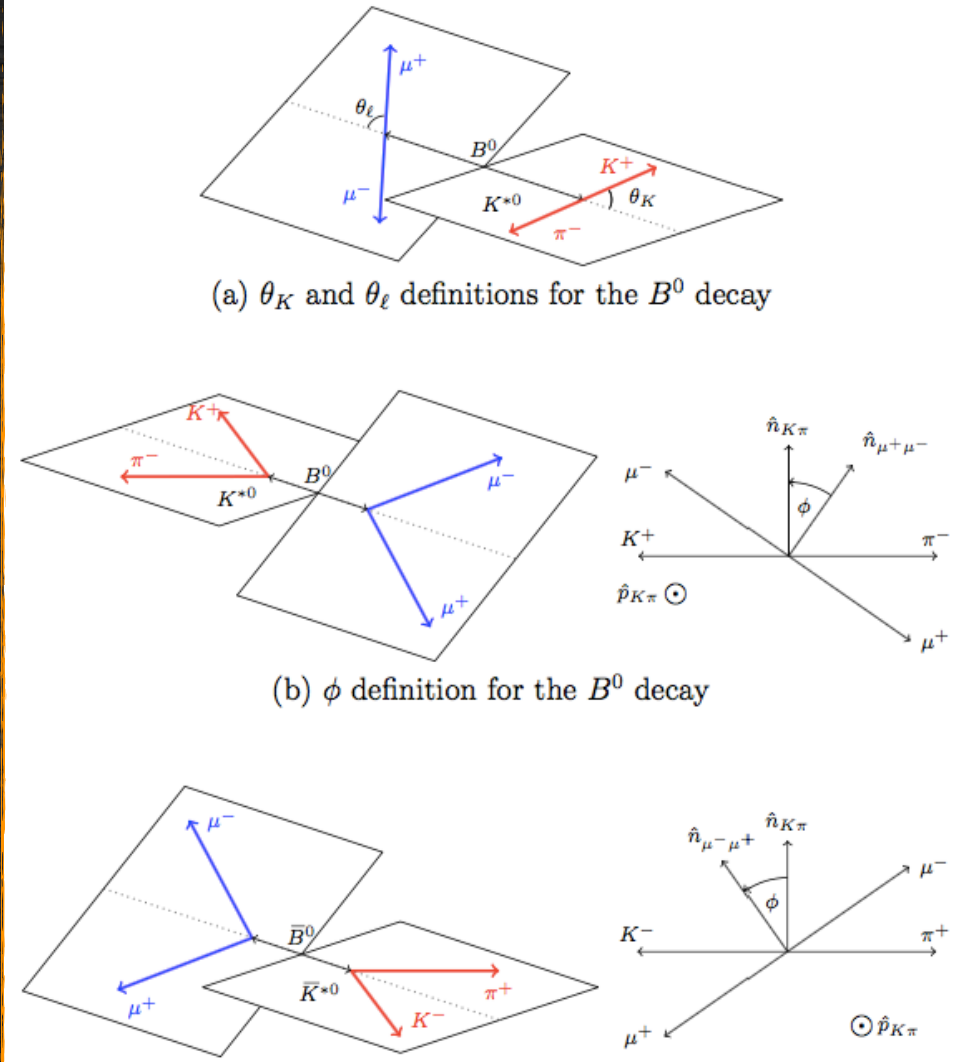






Angular Analyses – I

- **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



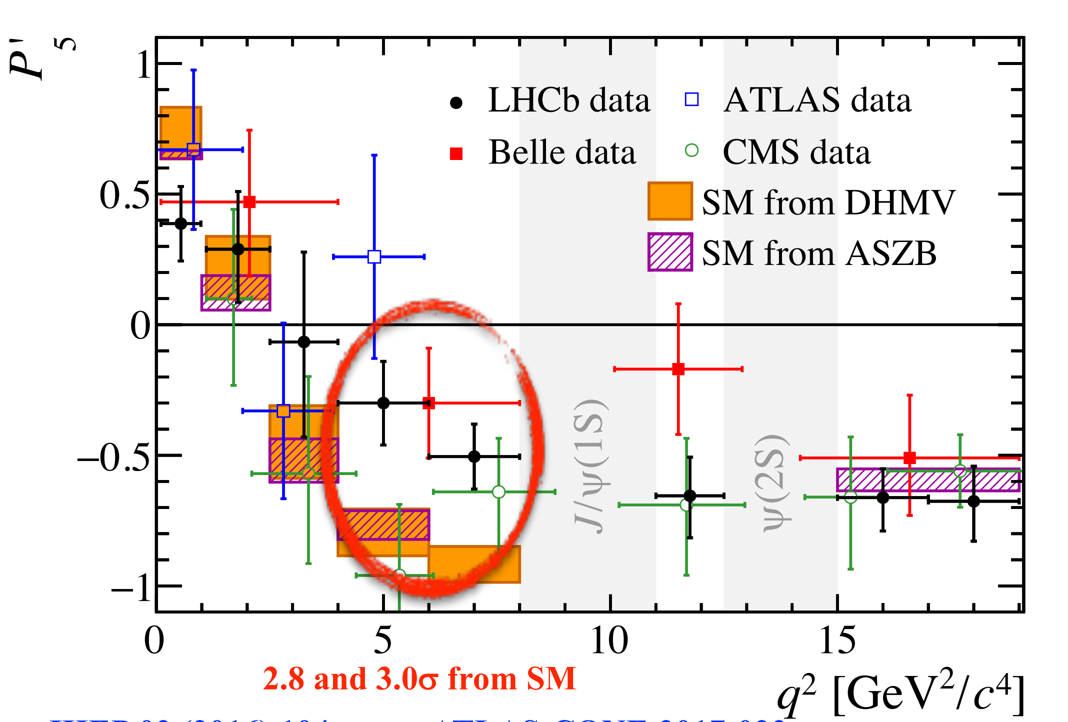
(a) θ_K and θ_ℓ definitions for the B^0 decay

(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**



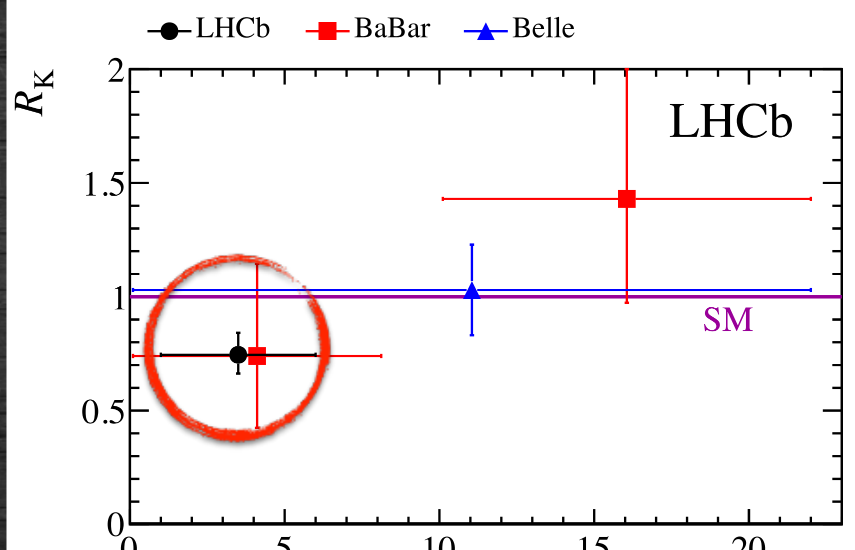
- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- arXiv:1710.02846

Test of LU – R_K

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

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

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



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

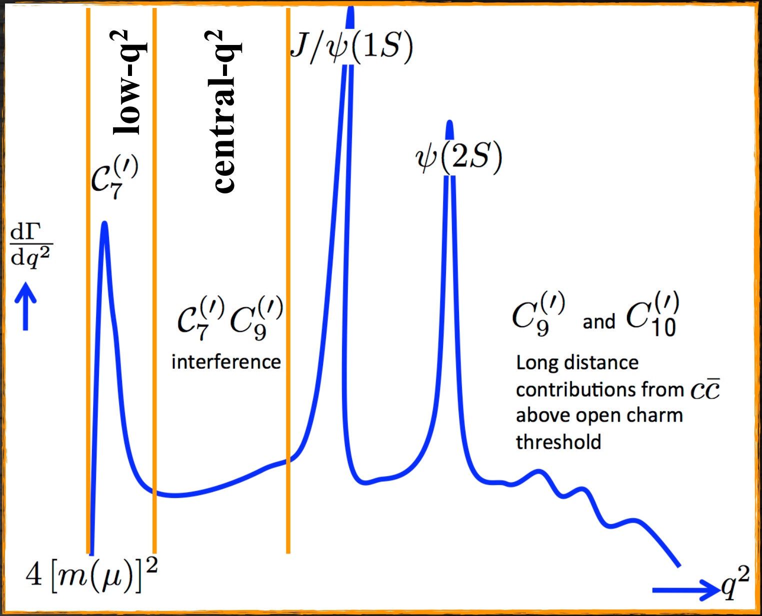
› Consistent with BF if BSM physics does not couple to electrons

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

Test of LU – $R_{K^{*0}}$

JHEP 08 (2017) 055

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



› **Two regions of q²**

» Low [0.045-1.1] GeV²/c⁴

» Central [1.1-6.0] GeV²/c⁴

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

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

› **Blind analysis** to avoid experimental biases

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

Bremsstrahlung – I

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

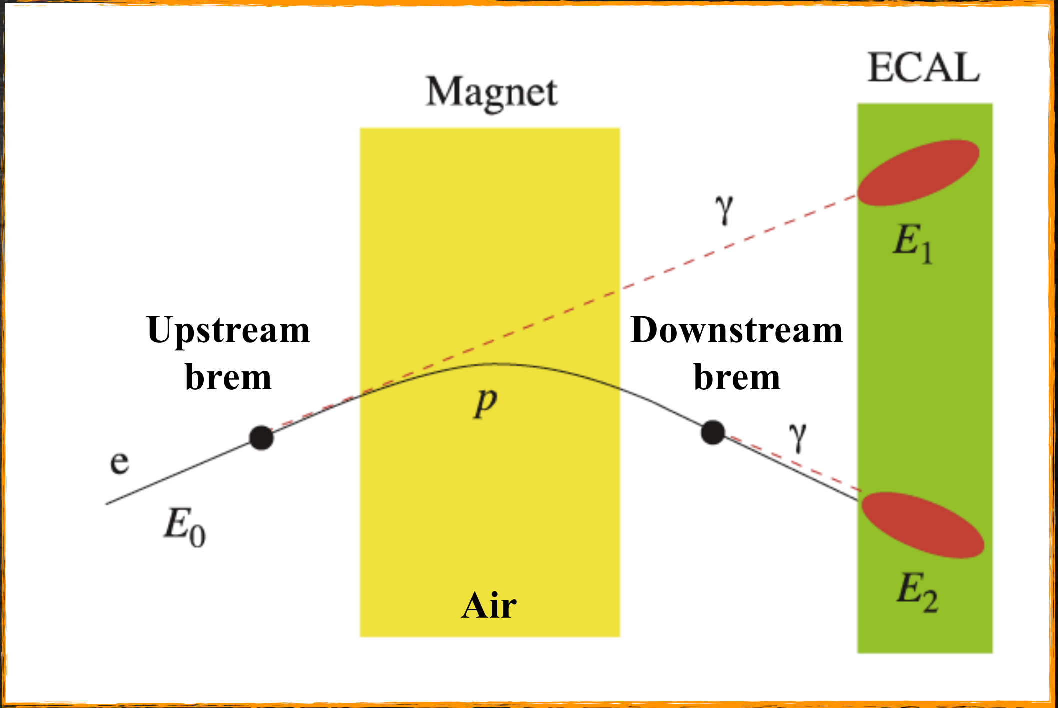
› **Two types of bremsstrahlung**

» **Downstream of the magnet**

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

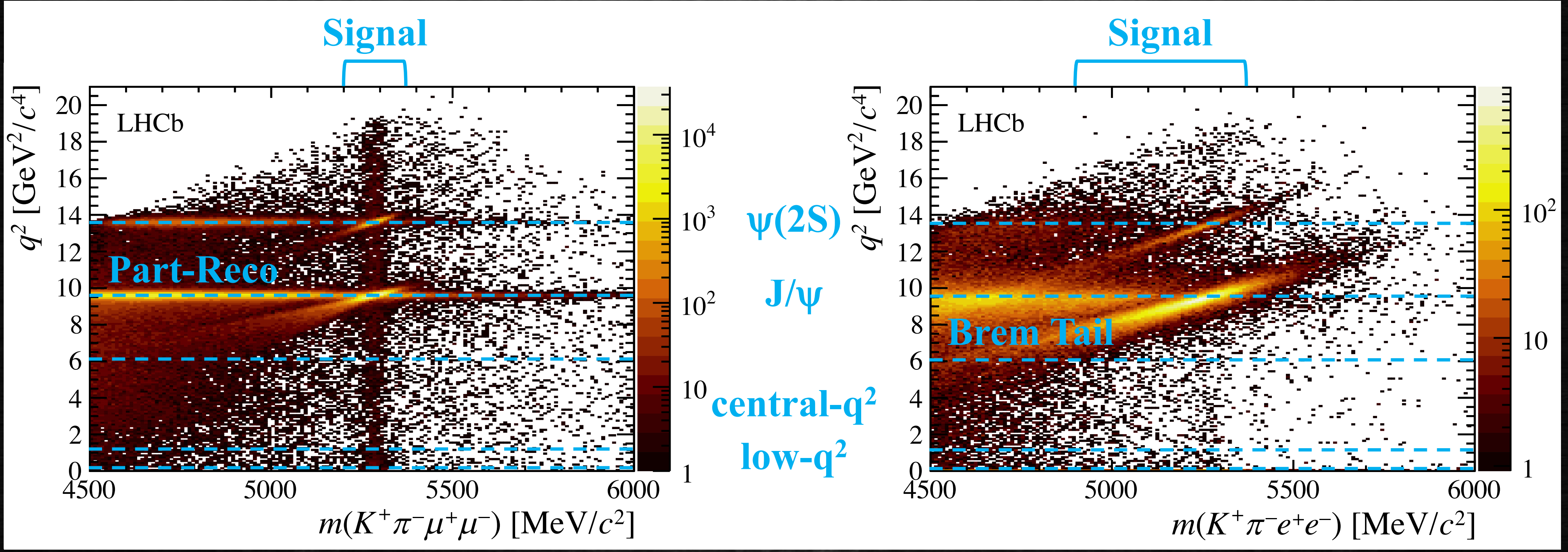
» **Upstream of the magnet**

- 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

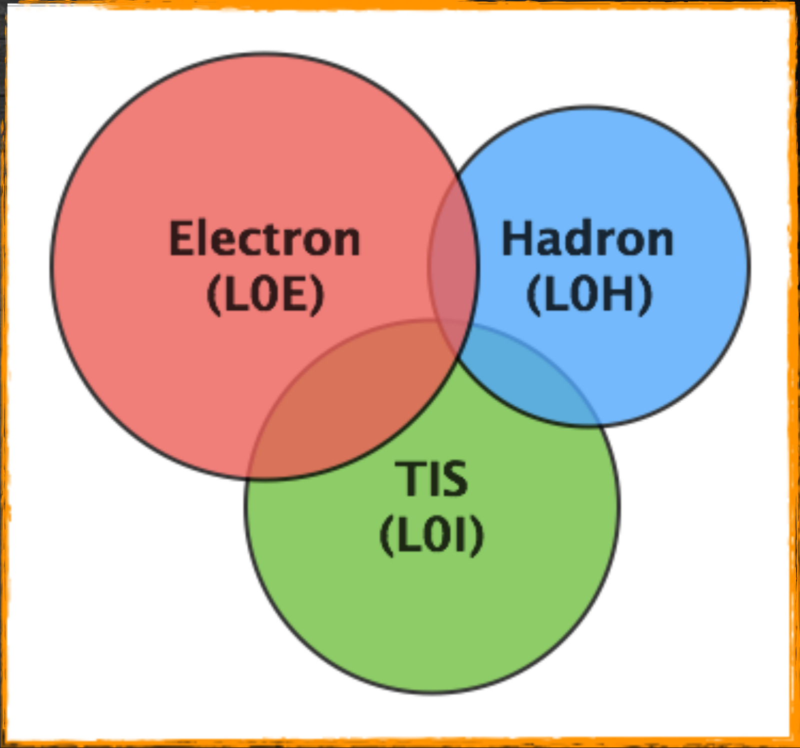


- Residual inefficiencies cause the reconstructed B mass to shift towards lower values and events to migrate in q^2

JHEP 08 (2017) 055

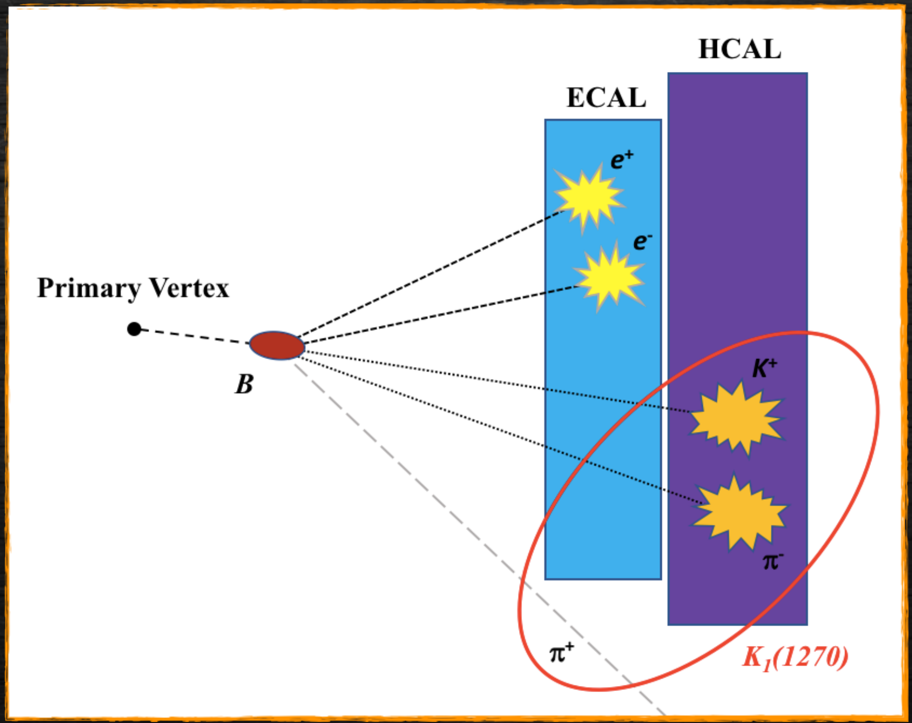
Trigger

- 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**, $p_T > 1.5\text{-}1.8$ 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 ($E_T > 2.5\text{-}3.0$ 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

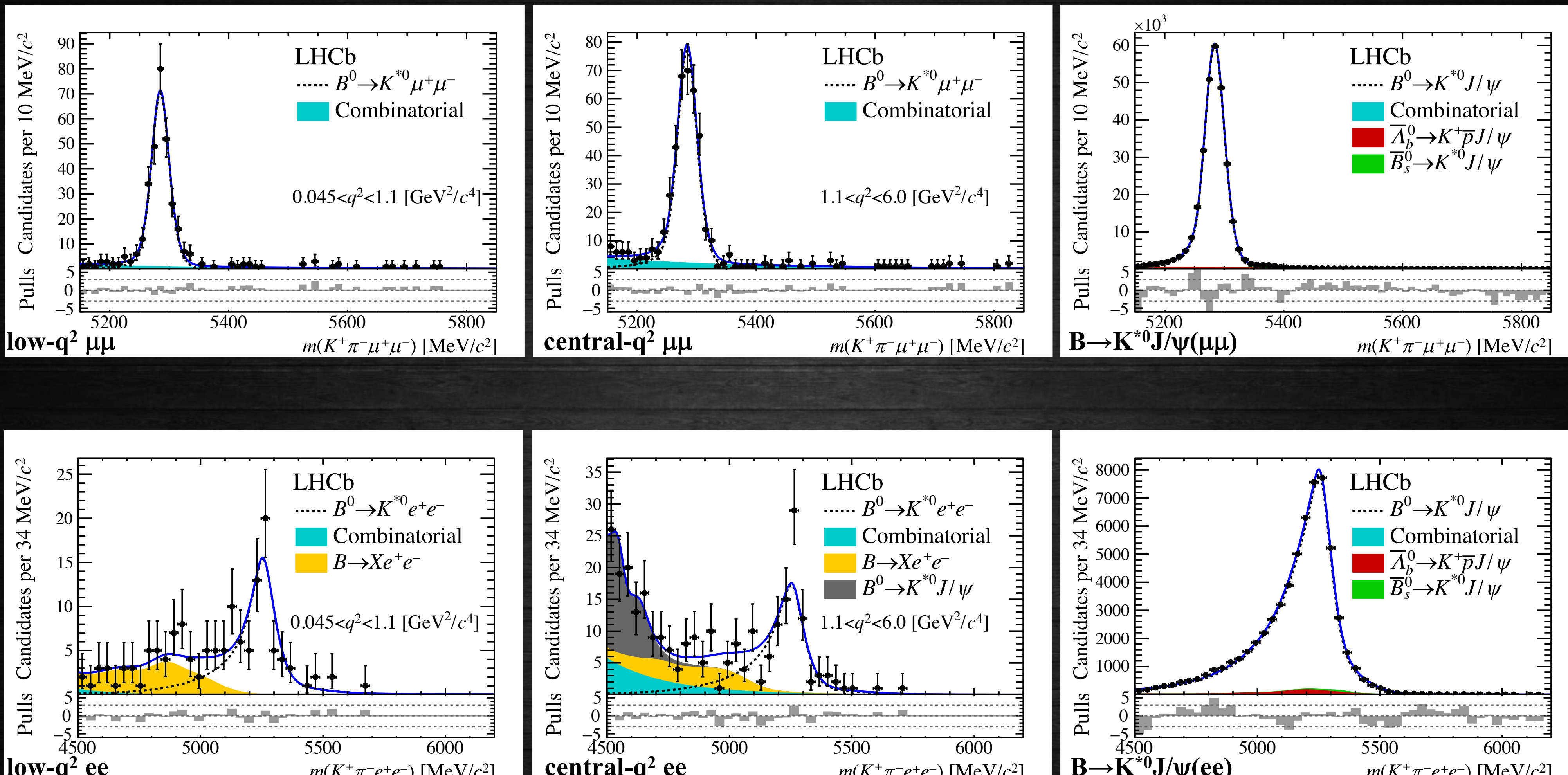


Part-Reco Background

- 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 **$B \rightarrow K_1(1270)ee$** and **$B \rightarrow K_2^*(1430)ee$**
- Modelled with a simulation cocktail or using $B^+ \rightarrow K^+\pi^+\pi^-\mu\mu$ data



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-q², respectively

JHEP 08 (2017) 055

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

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

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

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

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

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» Many experimental systematic effects much reduced

» Statistically dominated (~15%)

arXiv:1705.05802

	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	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

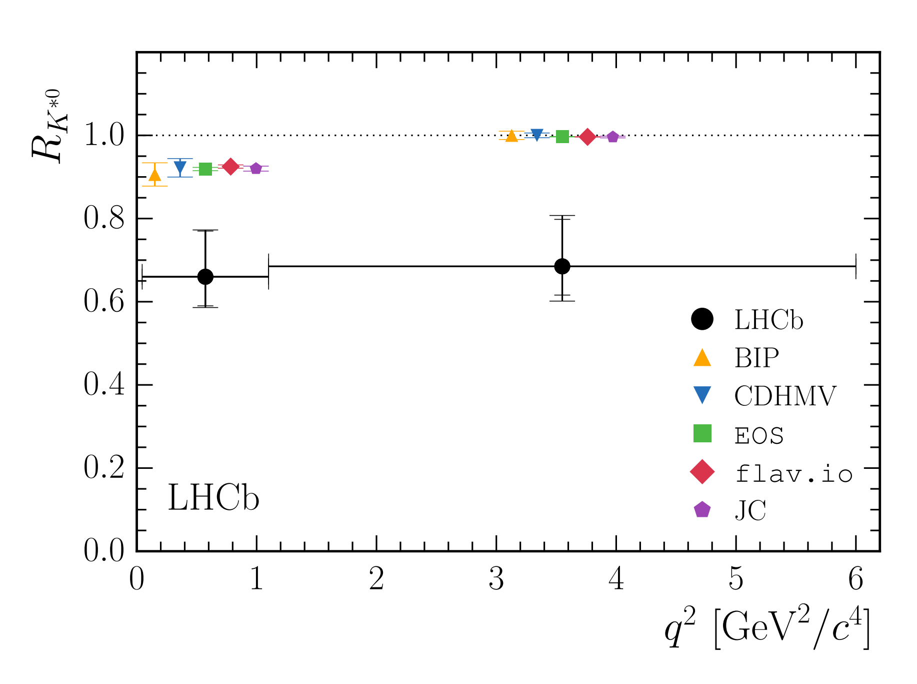
⟵ Description of brem-tail

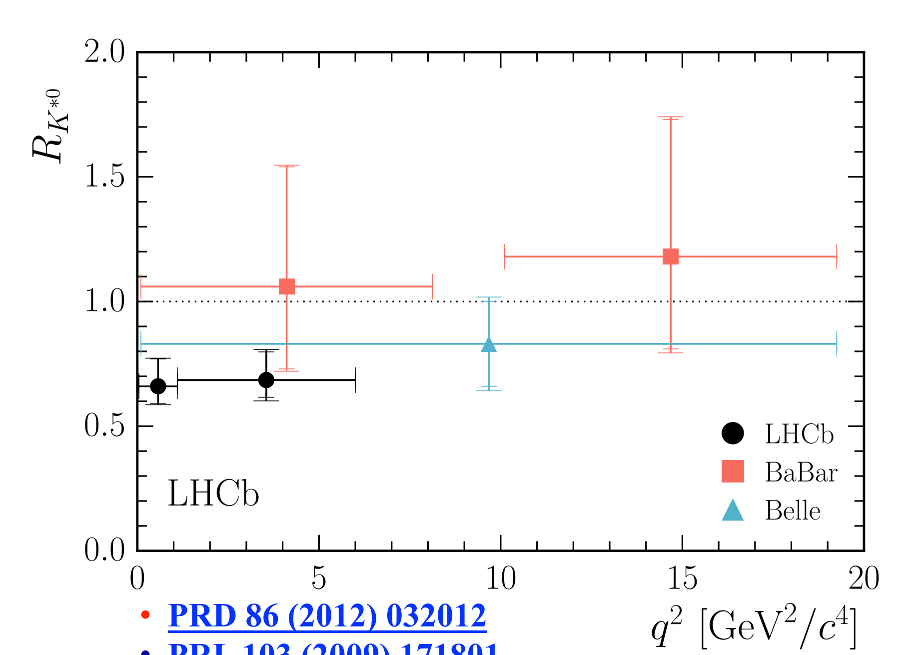
⟵ Residual background contamination due to $B^0 \to K^{*0} J/\psi(ee)$ with a $K \leftrightarrow e$ or $\pi \leftrightarrow e$ swap

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

Results

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





- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

› Compatibility with the SM prediction(s)

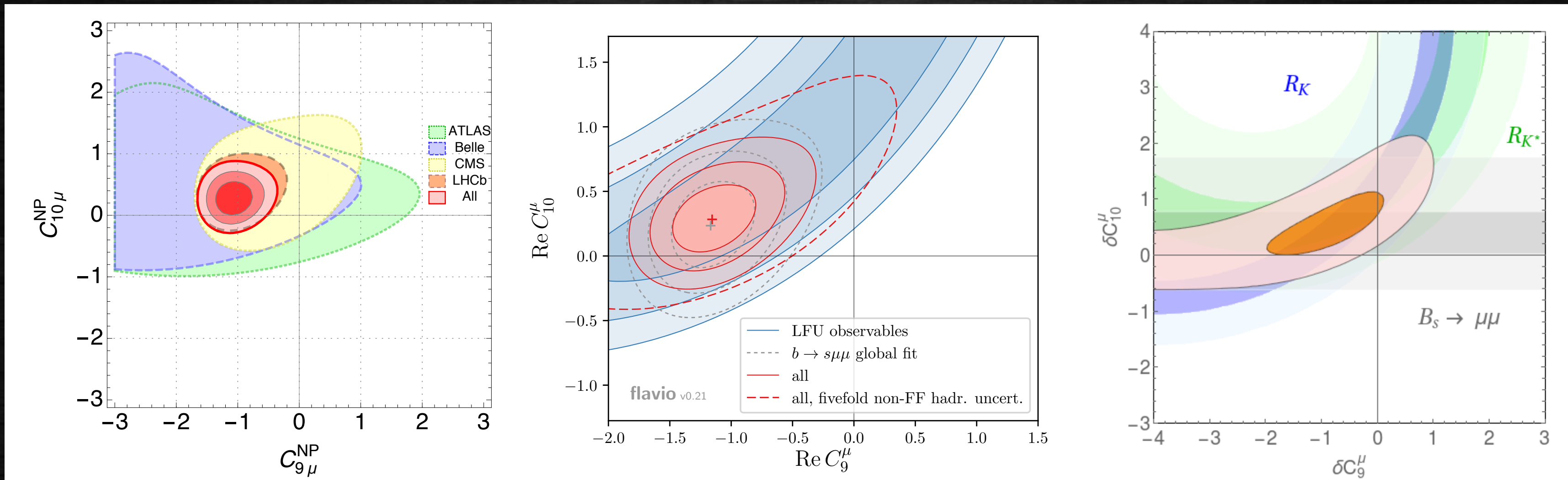
» **low-q²** 2.1-2.3 standard deviations

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

JHEP 08 (2017) 055

Global Fits – I

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



arXiv:1704.05340 arXiv:1704.05435 arXiv:1704.05446

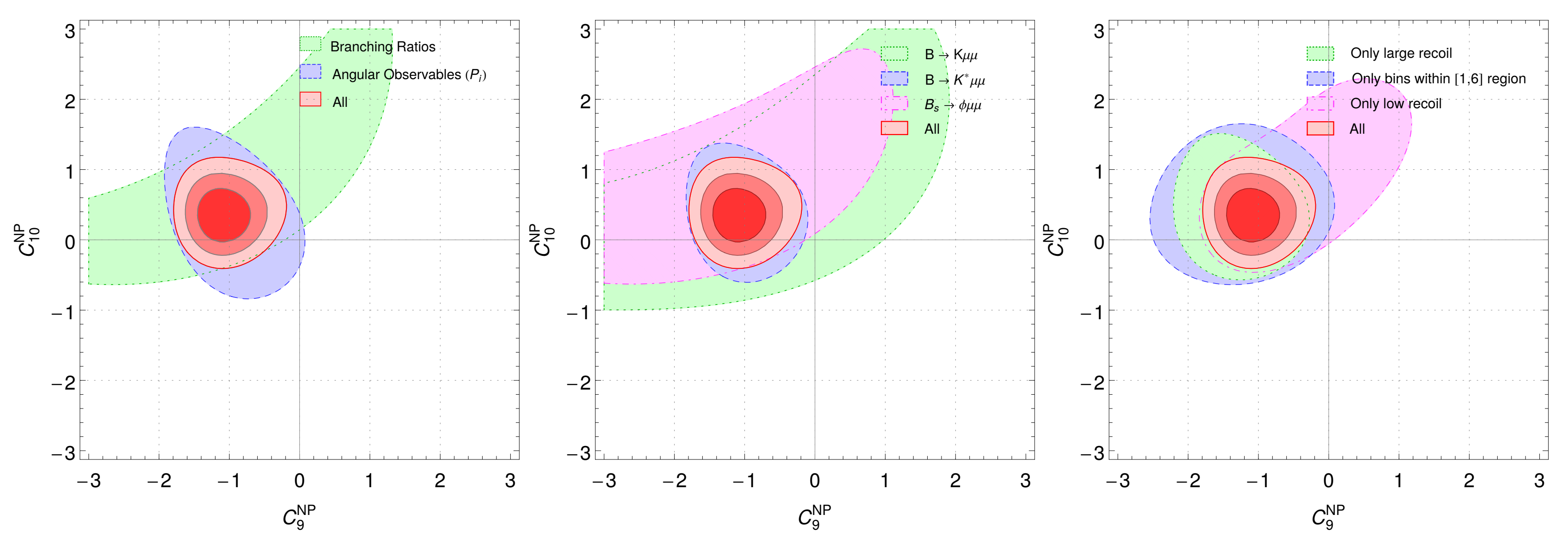
› Take into account O(100) observables from different experiments, including b→μμ, b→sll and b→sγ transitions

› 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

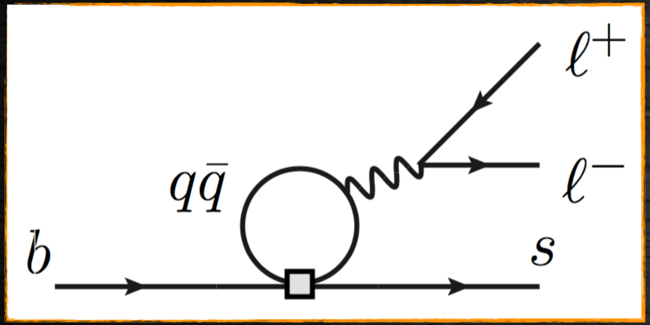


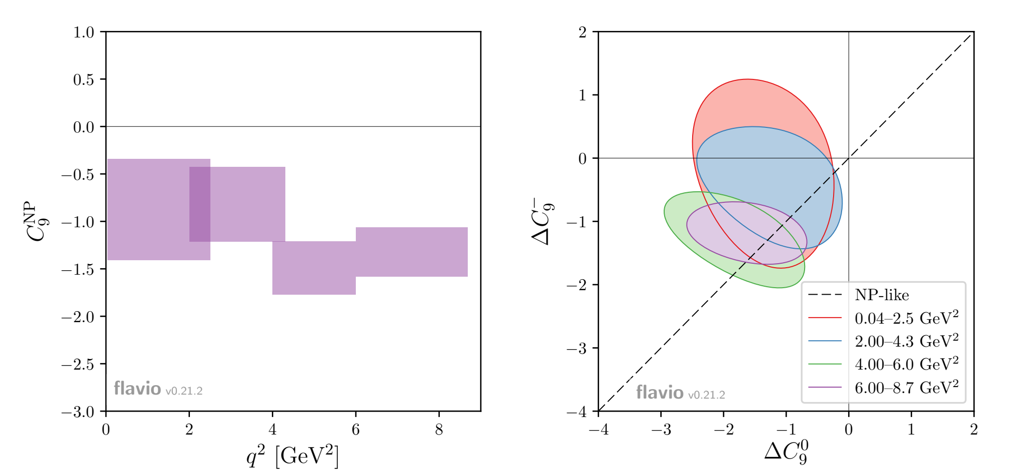
arXiv:1510.04239

- n.b. Different theory issues in each case

Controlling Charm Loops – I

- Community started to look critically at the theory predictions
- The $O_{1,2}$ operator has a component that could **mimic BSM effect** in C_9 through $c\bar{c}$ loop



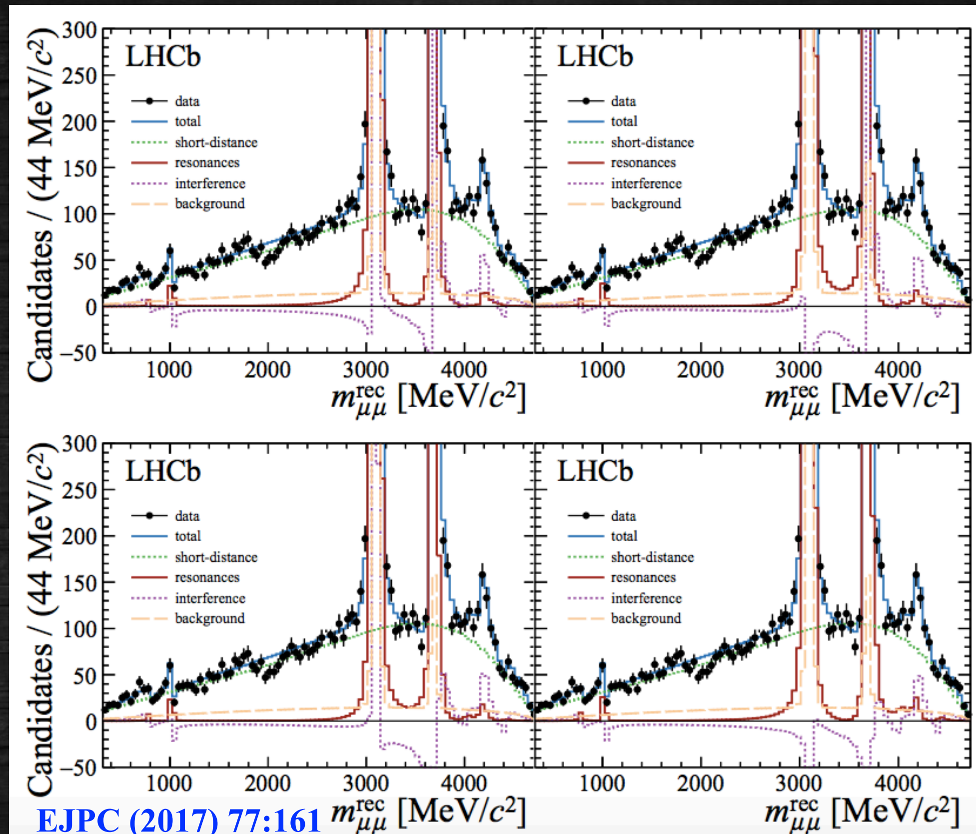


arXiv:1703.09189

- "The absence of a q^2 and helicity dependence is intriguing, but cannot exclude a hadronic effect as the origin of the apparent discrepancies"

Controlling Charm Loops – II

› **Measure interference** between penguin and $c\bar{c}$ directly from data



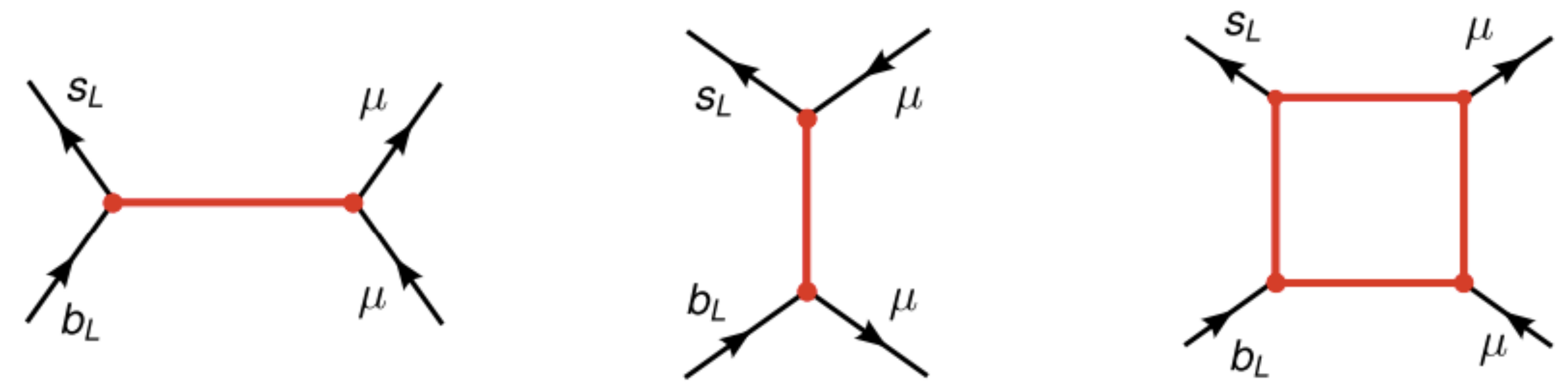
EJPC (2017) 77:161

› **$B^+ \to K^+\mu\mu$**: "The measured phases of the J/ψ and $\psi(2S)$ resonances are such that the interference with the short-distance component in dimuon mass regions far from their pole masses is small"

› **$B^0 \to K^{*0}\mu\mu$**: considerably more complex but same principle (ongoing)

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



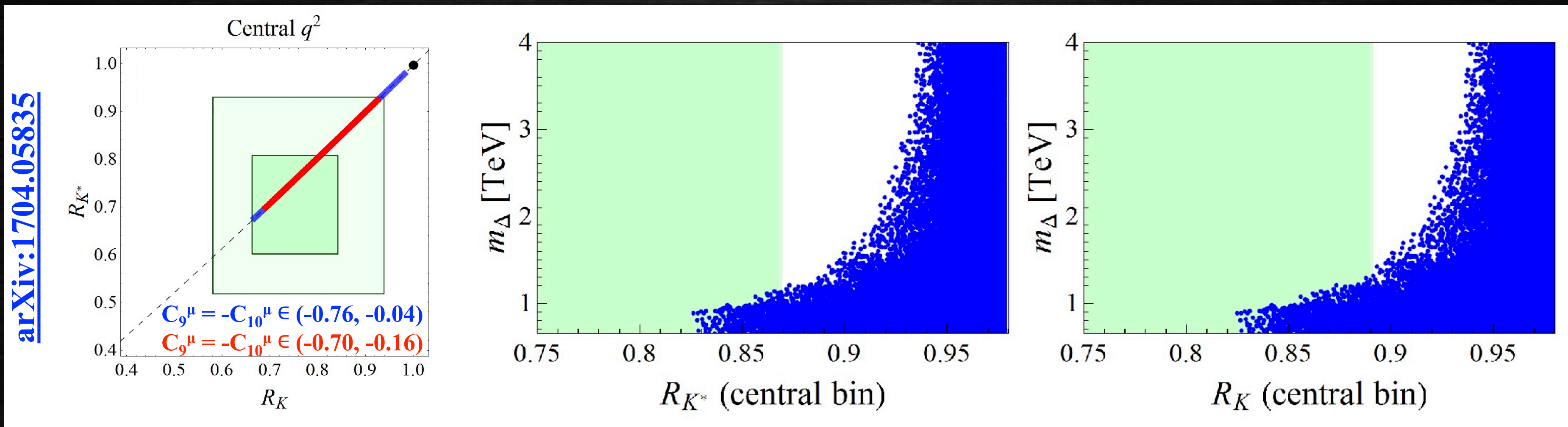
- Z'
- $SU(2)_L$ singlet or triplet

- Leptoquark
- Spin 0 or 1

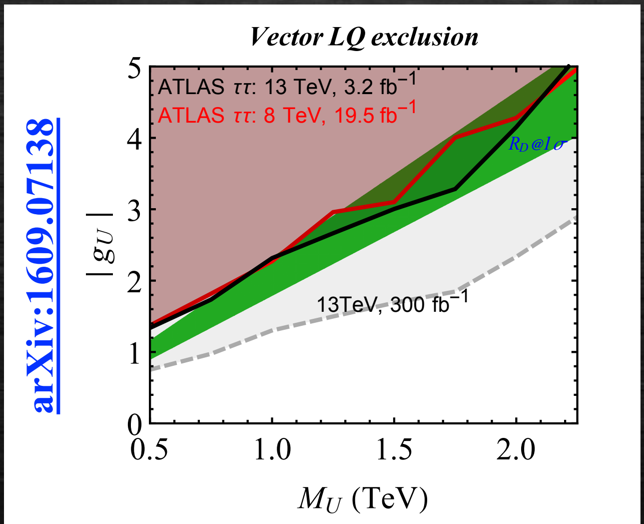
- New scalars/vectors, also leptoquarks possible

Is it a Z', a LQ or … ? – II

› e.g. Low energy scalar leptoquark



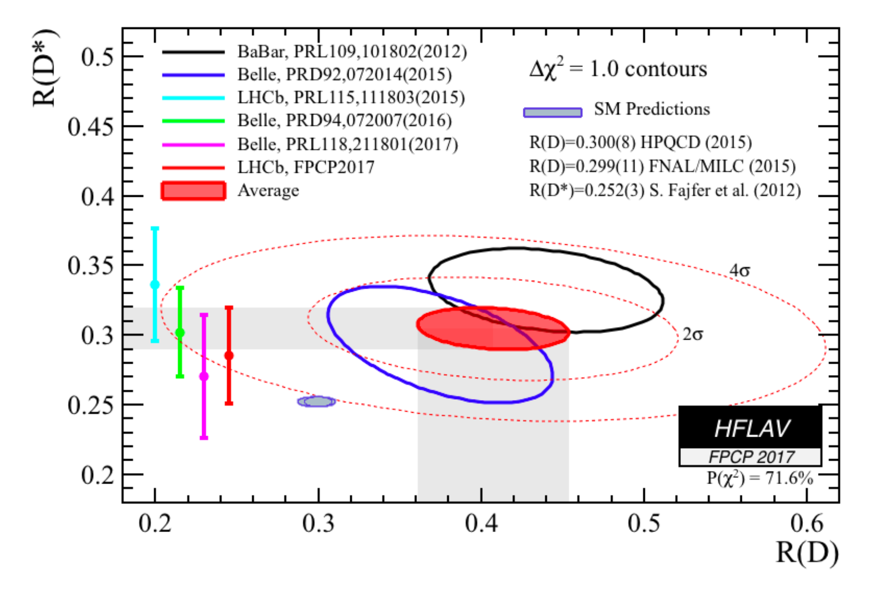
› e.g. Recast ATLAS searches of Z'→ττ



Test of LU – R_{D*}

› Anomalous effects also seen in **tree-level decays**

$$\mathcal{R}(D^{(*)-}) \equiv \mathcal{B}(B^0 \to D^{(*)-}\tau^+\nu_\tau)/\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\mu)$$
$$\mathcal{R}(D^{(*)0}) \equiv \mathcal{B}(B^- \to D^{(*)0}\tau^-\overline{\nu}_\tau)/\mathcal{B}(B^- \to D^{(*)0}\mu^-\overline{\nu}_\mu)$$



› Tau reconstructed using
- » $\tau \to \mu\nu\nu$ decays [PRL115 (2015) 111803]
- » $\tau \to 3\pi\nu$ decays [arXiv:1708.08856]

› Confirms effect seen by BaBar/Belle

› **Combined significance at 4.1σ**

› LQ models exist that are able to explain $R_{K(*)}$, R_{D*} (and $(g\text{-}2)_\mu$) [PRL 116 (2016) 141802]

Test of LU – $R_{J/\psi}$

› Anomalous effects also seen in **tree-level decays**

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\, \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\, \mu^+ \nu_\mu)}$$

› Tau reconstructed using

» $\tau \to \mu\nu\nu$ decays [LHCb-PAPER-2017-035, PRELIMINARY]

$R_{J/\psi}$ = 0.71 ± 0.17 (stat) ± 0.18 (syst)

› **Consistent with the SM (0.25-0.28) at 2σ**

Outlook – I

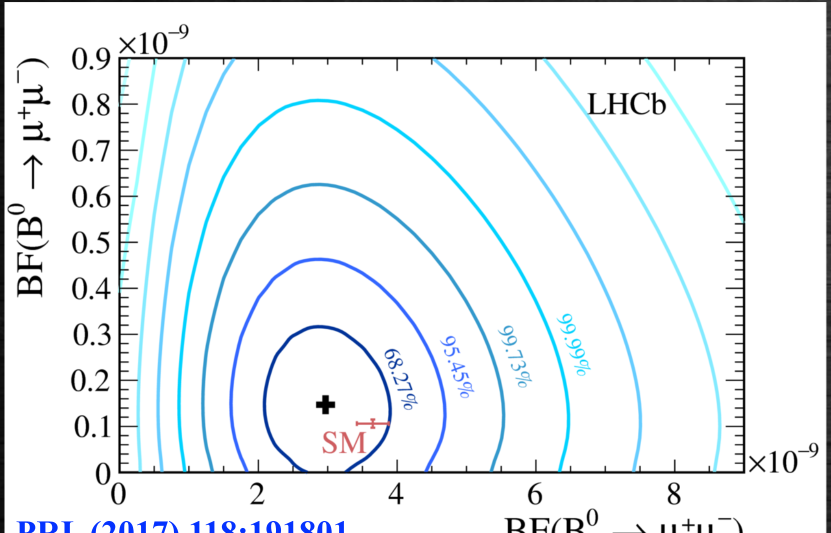
- Very lively discussion in the community, e.g. instant workshop on B anomalies just ~1 month after the $R_{K^{*0}}$ CERN seminar

- **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

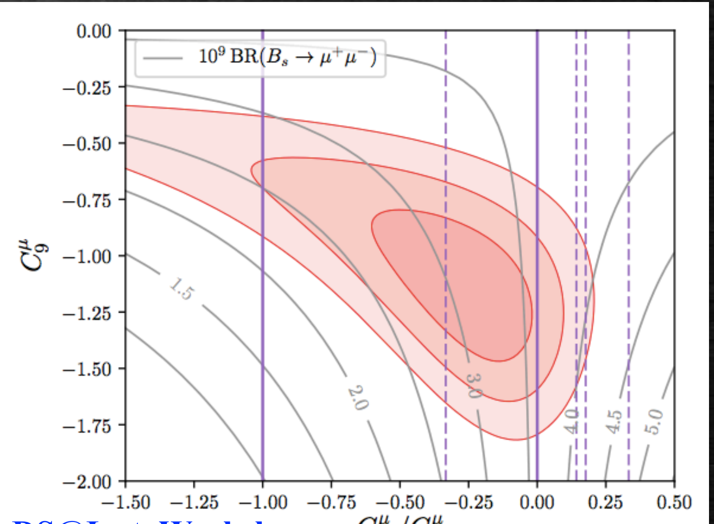
- **New measurements** also in preparation
  - **R_ϕ**: signal suppressed by f_s/f_d and BF=1/2, but narrow ϕ mass and reduced part-reco backgrounds
  - **$B^0 \to K^{*0}ee$ angular analysis** enables to form ratios of angular observables
  - **Additional final states** under study, e.g. K_S, K^{*+}, higher K^* resonances, pK

Outlook – II

- Single-particle explanations of anomalies predict $C_9^{NP} = -C_{10}^{NP}$
  → expect to see **effect in B→μμ**
- Latest LHCb measurement
  - $B_s \to \mu\mu$ established at 7.8σ
  - $BR(B^0 \to \mu\mu) < 3.4\times10^{-10}$ @ 95% CL



PRL (2017) 118:191801



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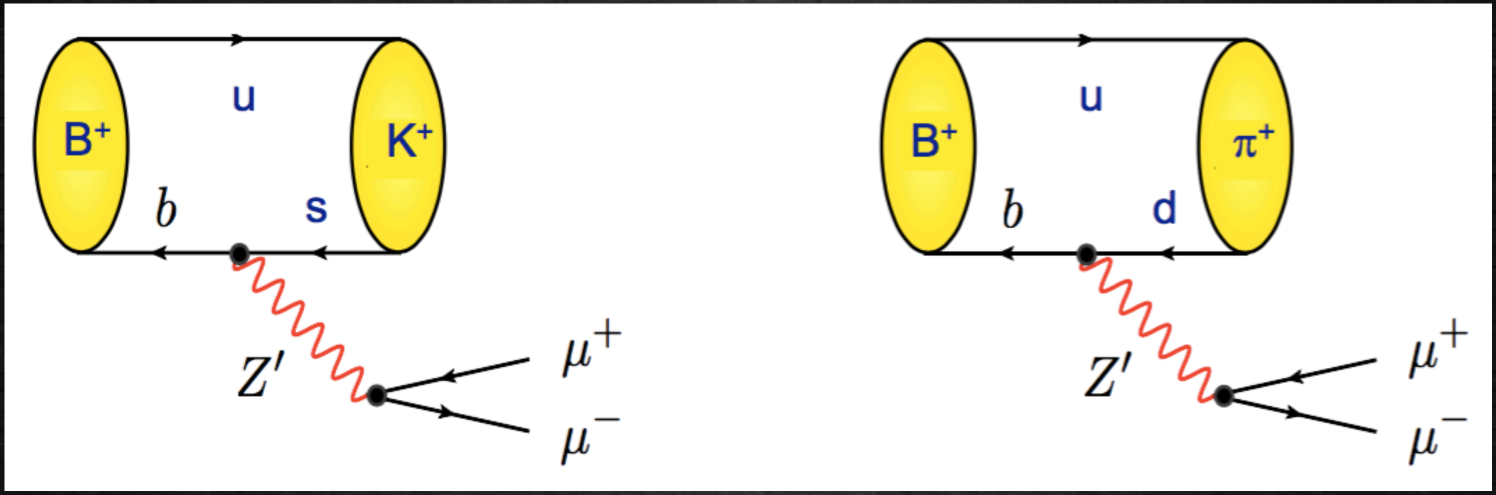
- No evidence for any deviation from SM so far, but important measurement for the future

Outlook – III

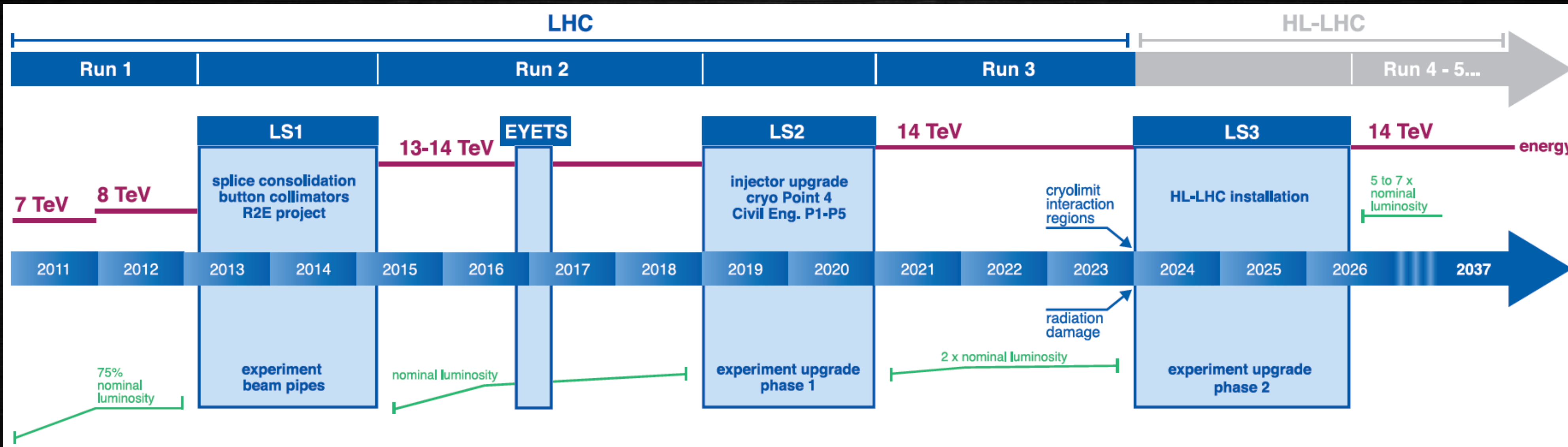
- Can try and compare b→s and **b→d transitions** e.g. to see if $R_K=R_\pi$
- Run-1+Run-2 data would give ~500 $B^+\to\pi^+\mu\mu$ events

  → with $R_K=R_\pi$ expect ~50 $B^+\to\pi^+ee$ events (might be able to see decay)



- LQ could presumably give diagrams with different b→d suppression and/or different lepton flavours

LHCb Upgrade



› During LS2 the detector will be upgraded to run at a 5 times larger instantaneous-luminosity and collect a total of O(50) fb^{-1} in **Run-3** [CERN-LHCC-2012-007]

› The upgrade detector will record data without any hardware-based online-selection and adopt a full online-reconstruction

› EoI for a **Phase-II upgrade** of LHCb to take full advantage of the flavour-physics opportunities at the HL-LHC [CERN-LHCC-2017-003]

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