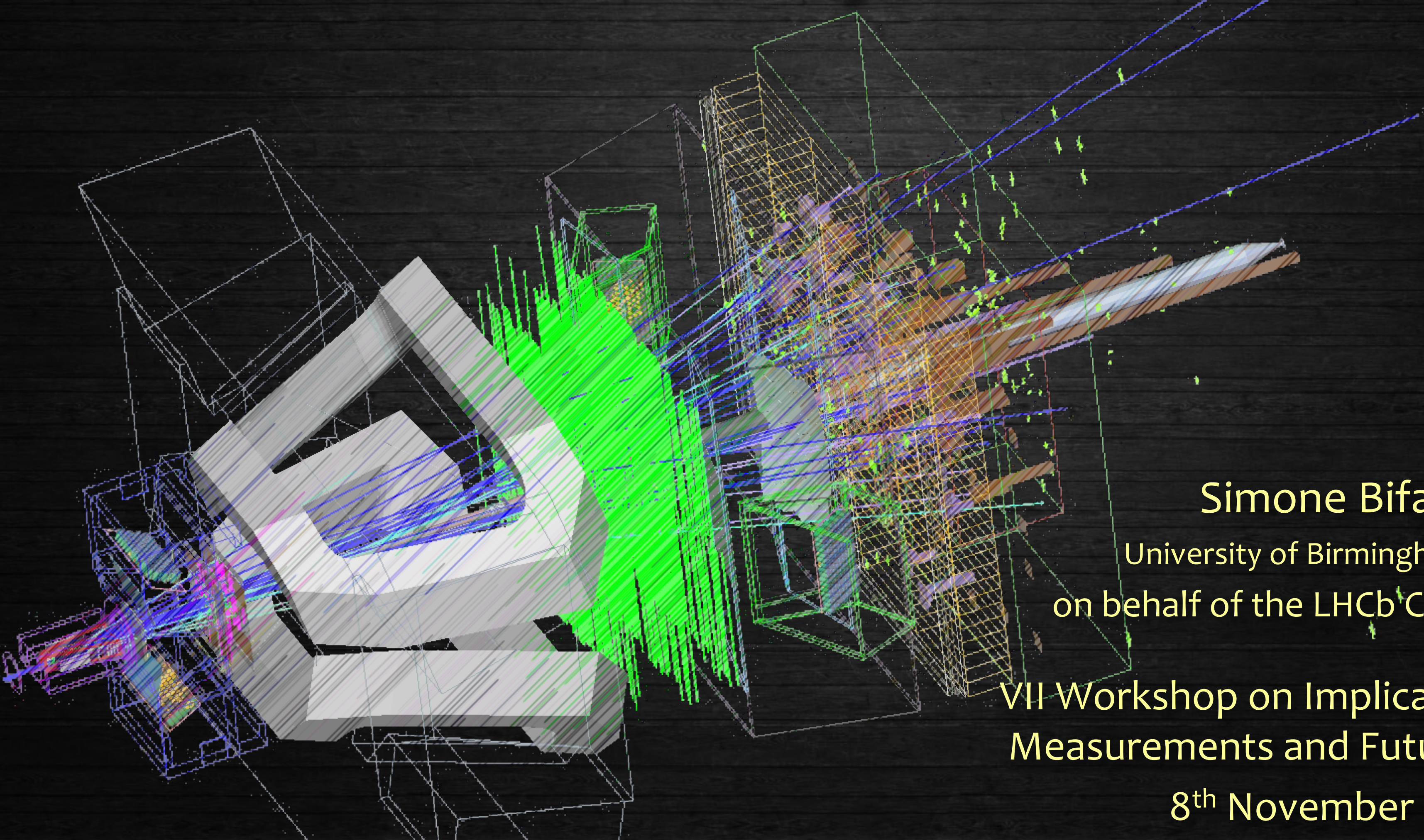
Experimental Overview of Rare Decays at LHCb



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on behalf of the LHCb Collaboration

VII Workshop on Implications of LHCb Measurements and Future Prospects

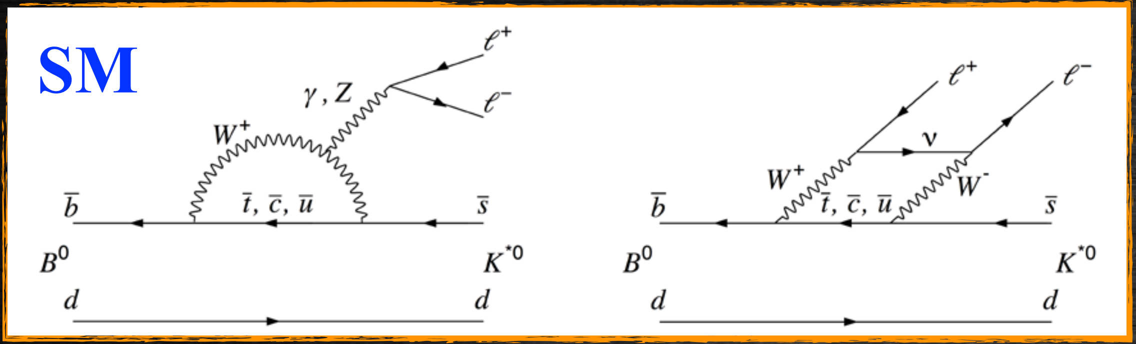
8th November 2017

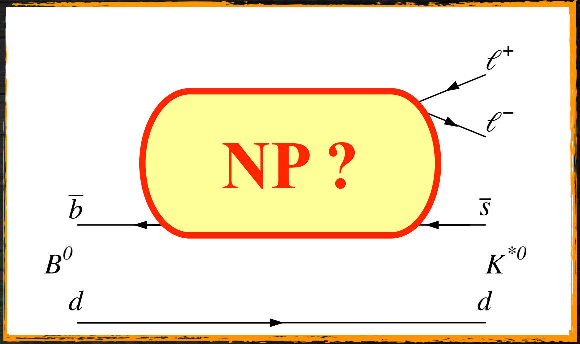
Outline

- Why rare decays?
- Rare decays @ LHCb
  - Beauty
  - Charm
  - Strange
- Summary and Outlook

Why Rare Decays?

- In presence of sizeable SM contributions, BSM effects might be hidden
- Instead, look at suppressed decays e.g. b→sll **Flavour Changing 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

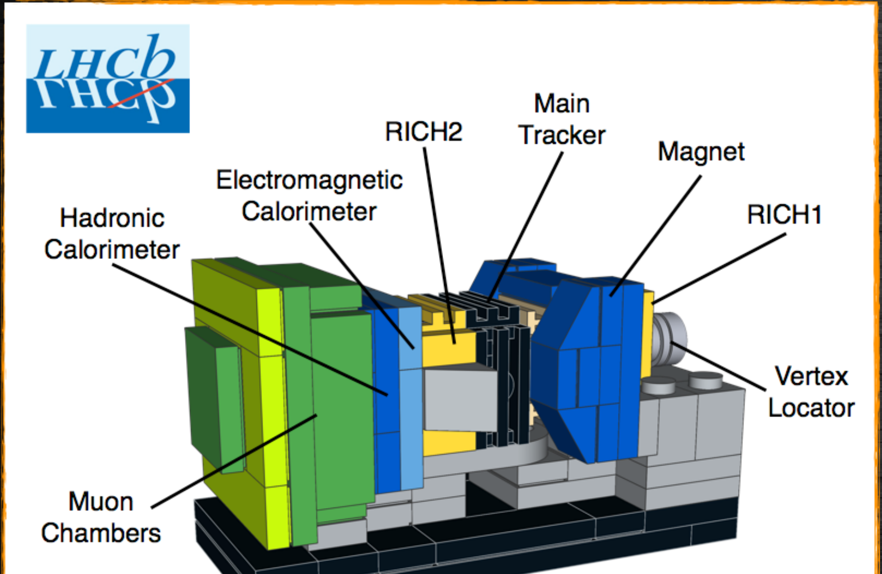
- Rare decays can place **strong constraints** on many BSM models by probing energy scales higher than those accessible with direct searches

Today's Shopping List

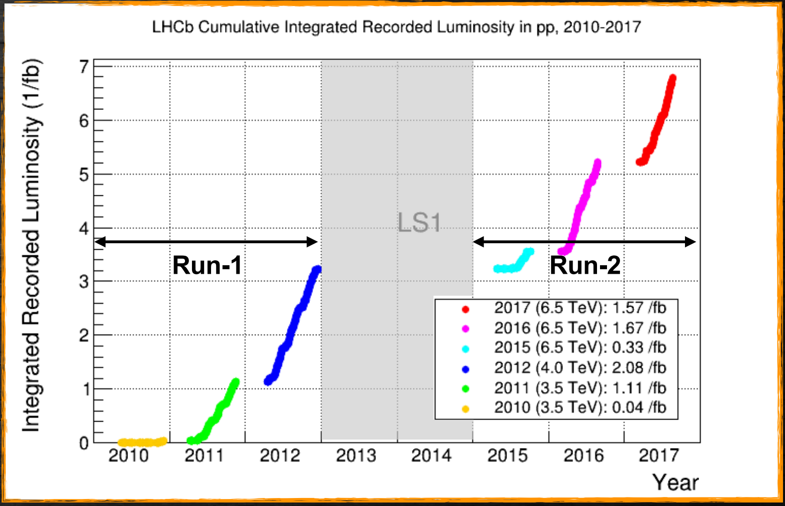
- Many **new results** since last LHCb Implication Workshop
- **Beauty**
  - $R_{K^{*0}}$ [JHEP 08 (2017) 055]
  - $B^+ \to K^+ \mu\mu$ [EPJC 77 (2017) 161]
  - $B^+ \to K^+ \chi(\mu\mu)$ [PRD 95 (2017) 071101] (see C.Vazquez Sierra's talk)
  - $B_{(s)} \to \mu\mu$ [PRL 118 (2017) 191801]
  - $B_{(s)} \to \tau\tau$ [PRL 118 (2017) 251802]
  - $B_{(s)} \to e\mu$ [arXiv:1710.04111]
  - $\Lambda_b \to ph\,\mu\mu$ [JHEP 06 (2017) 108, JHEP 04 (2017) 029]
- **Charm**
  - $D^0 \to hh\,\mu\mu$ [arXiv:1707.08377]
  - $\Lambda_c \to p\,\mu\mu$ [LHCb-PAPER-2017-039] (see also J.Brodzicka's talk)
- **Strange**
  - $K_S \to \mu\mu$ [EPJC 77 (2017) 678]

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:** >90% μ, e and K ID for 1–5% misID from π

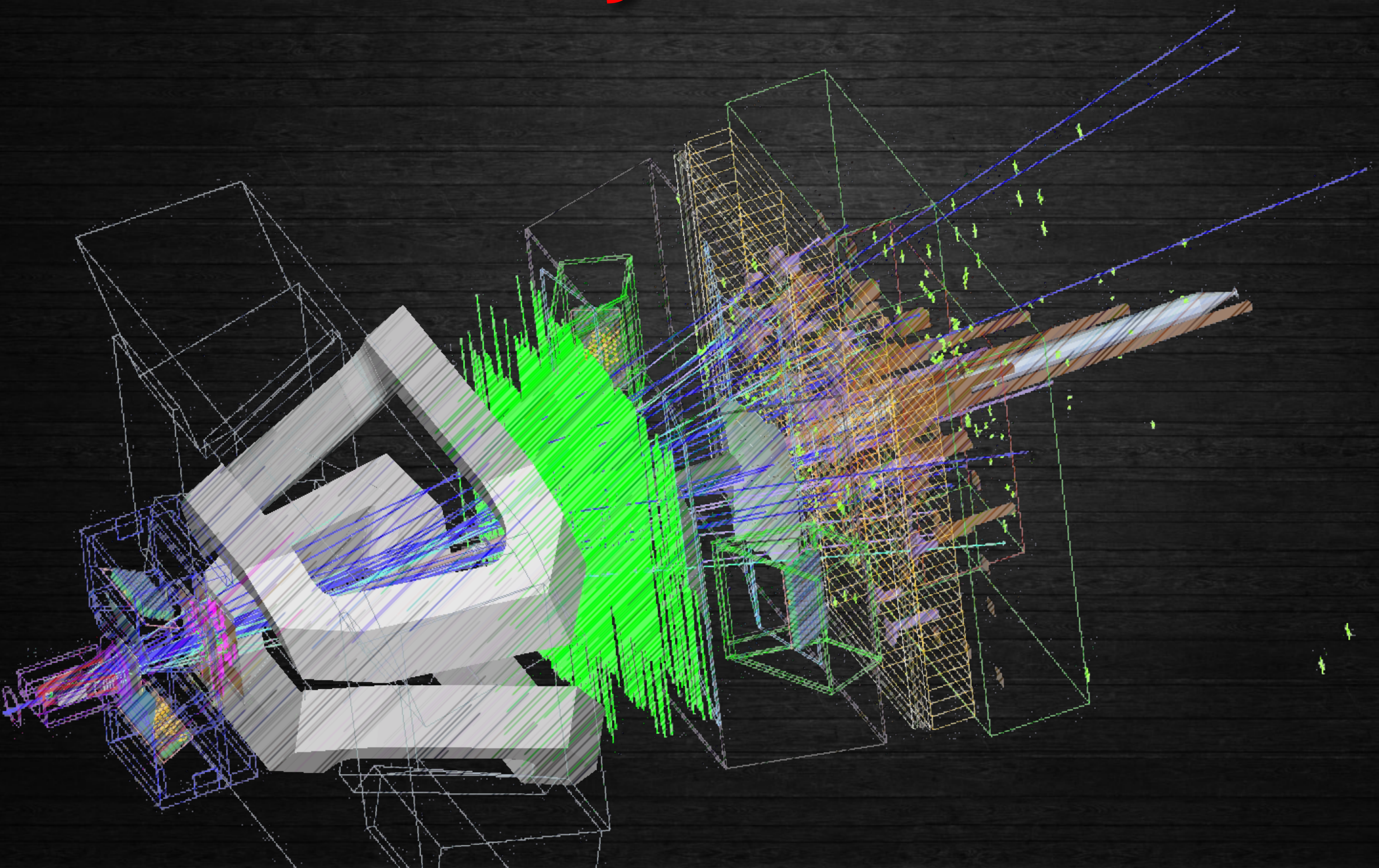


JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022



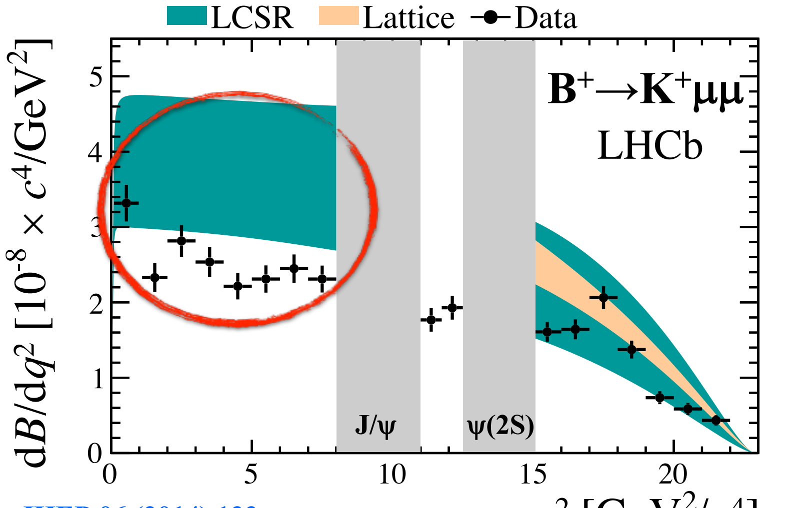
- Analyses presented today based on **Run-1** and/or **Run-2** datasets

Beauty

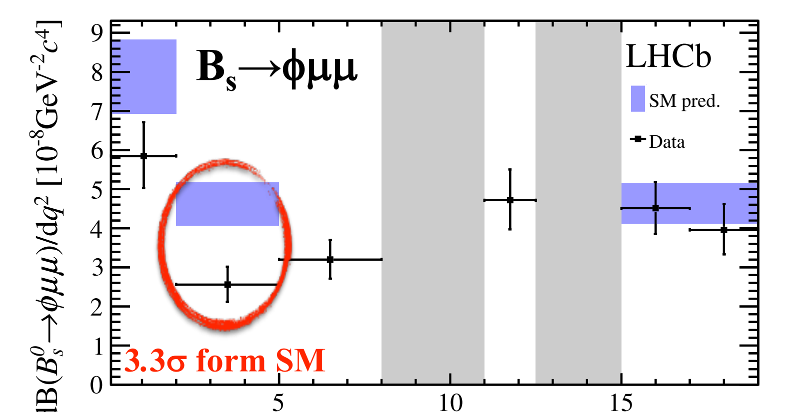


b-Hadron Anomalies

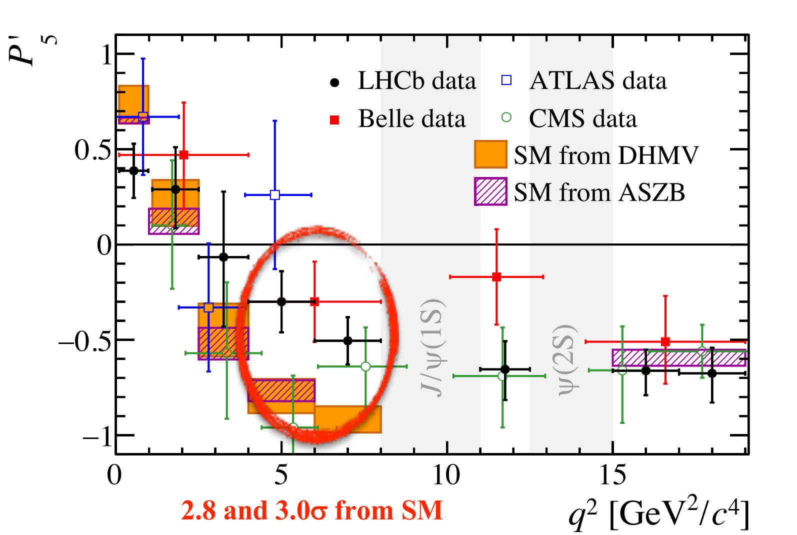
› **Intriguing anomalies** in rare decays of b-hadrons emerged in recent years



JHEP 06 (2014) 133



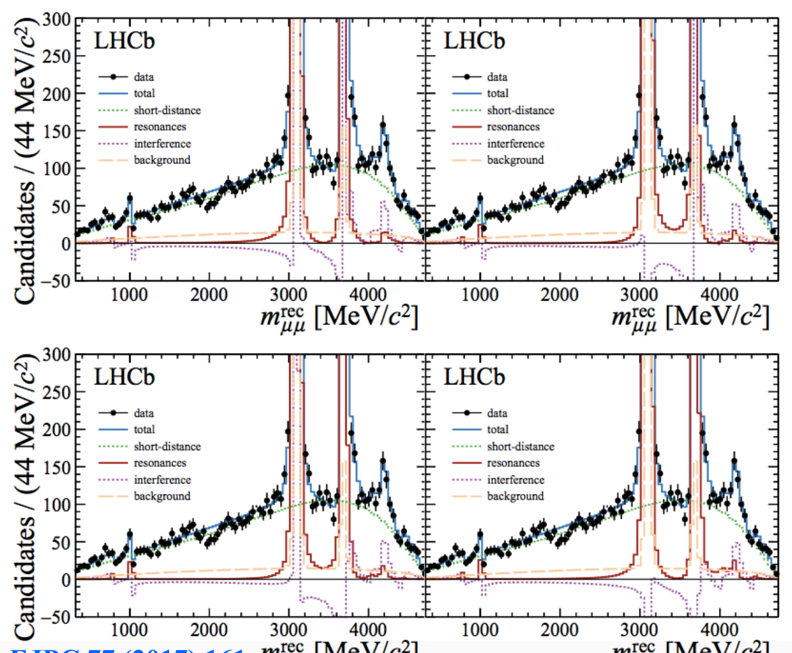
JHEP 09 (2015) 179



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

Controlling Charm Loops

- **Or is this a problem with the understanding of QCD?** e.g. Correct estimate of the contribution from charm loops?
- **Measure interference** between penguin and $c\bar{c}$ from data

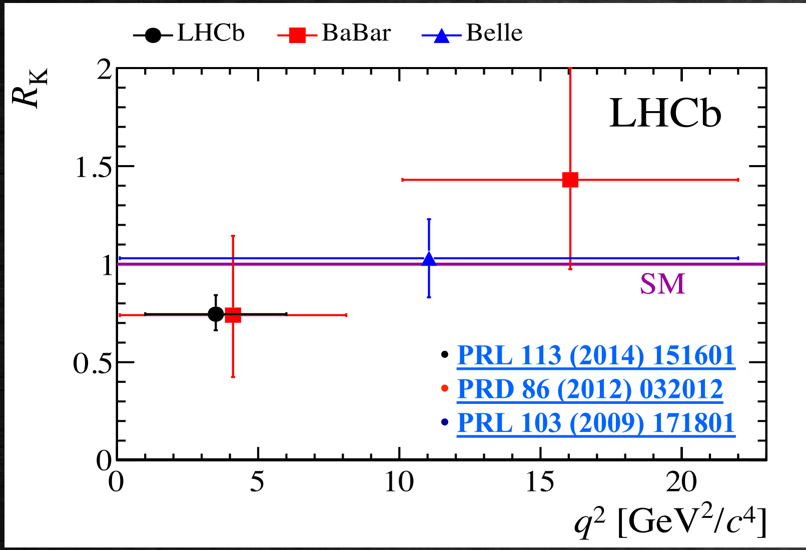


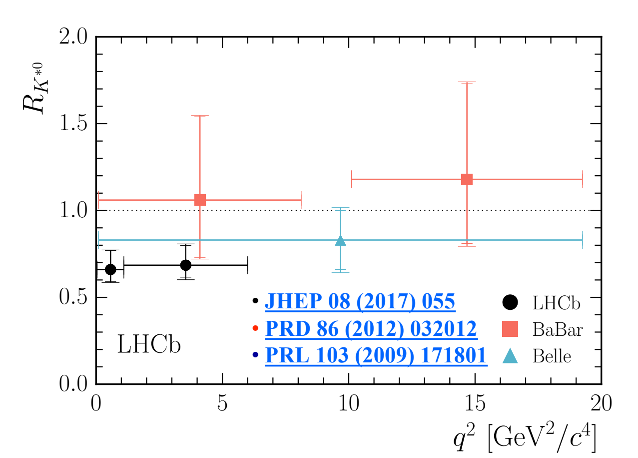
EJPC 77 (2017) 161

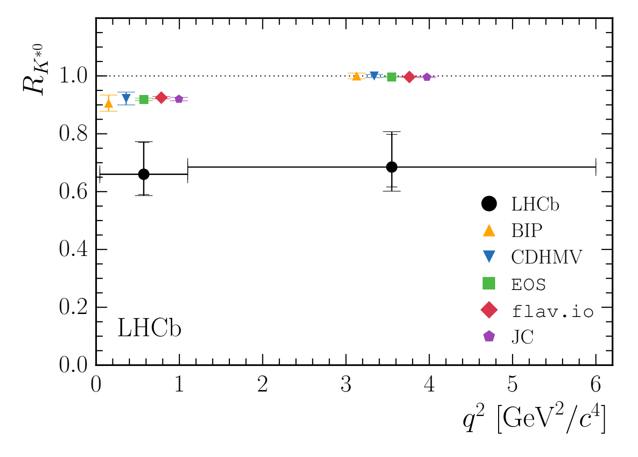
- **$B^+ \to K^+\mu\mu$:** "The measured phases of the J/ψ and $\psi(2S)$ resonances are such that the interference with the short-distance component in dimuon mass regions far from their pole masses is small"
- **$B^0 \to K^{*0}\mu\mu$:** see G.J.Pomery and A.Mauri's talks

Tests of Lepton Universality

- **Ratios of branching fractions** are powerful tests of LU as experimental systematics are reduced and theoretical uncertainties largely cancel
- Extremely challenging due to differences in the way muons and electrons "interact" with the detector



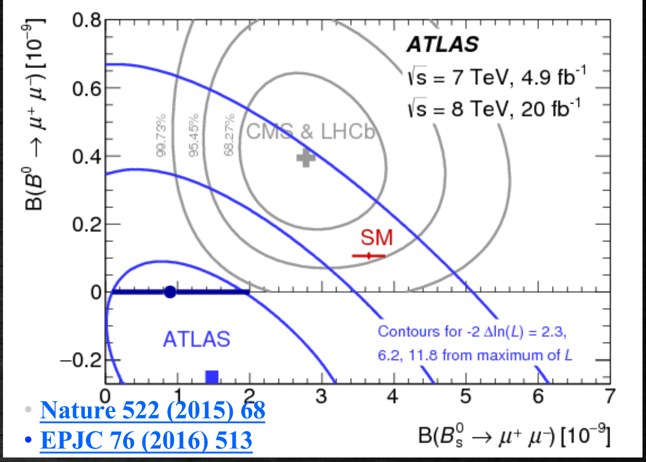




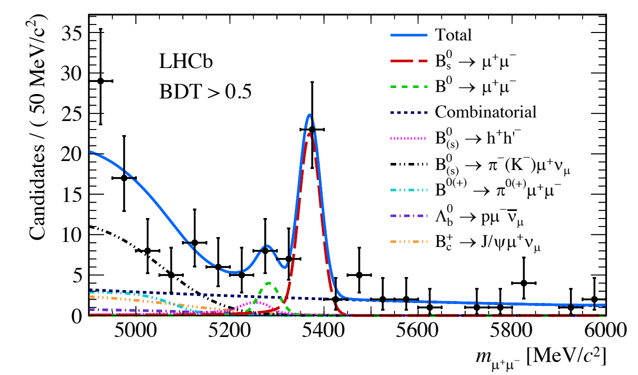
- Compatibility with the SM prediction(s)
  - **R_K** 2.6σ
  - **$R_{K^{*0}}$ low-q^2** 2.1-2.3σ
  - **$R_{K^{*0}}$ central-q^2** 2.4-2.5σ

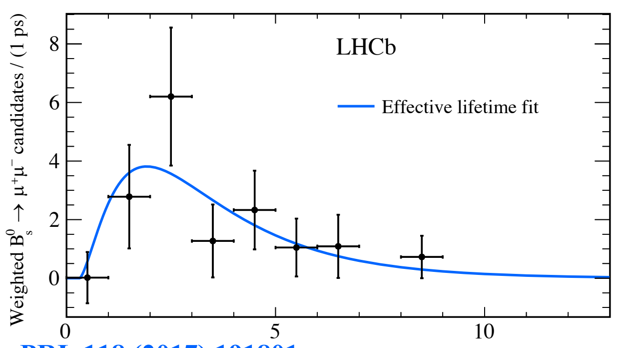
$B_{(s)} \to \mu\mu$

- Occur at loop level, helicity suppressed
- **Very precise SM prediction** [PRL 112 (2014) 101801]
  - $\mathcal{B}(B_s \to \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$
- Combined fit to Run-1 data by CMS and LHCb
  - First observation of $B_s \to \mu\mu$ (6.2σ, SM at 1.2σ)
  - 3.0σ excess of $B^0 \to \mu\mu$ (SM at 2.2σ)
- **New LHCb measurement adds 1.4 fb^{-1} of Run-2**
  - **First observation by single experiment** of $B_s \to \mu\mu$ (7.8σ)
  - $\mathcal{B}(B_s \to \mu\mu) = (3.0 \pm 0.6 \pm 0.3) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu\mu) < 3.4 \times 10^{-10}$ @ 95% CL (1.2σ excess)
  - **First measurement** of B_s effective lifetime
  - $\tau(B_s \to \mu\mu) = 2.04 \pm 0.44 \pm 0.05$ ps
  - Still large uncertainty, but important proof of concept for the future



- Nature 522 (2015) 68
- EPJC 76 (2016) 513



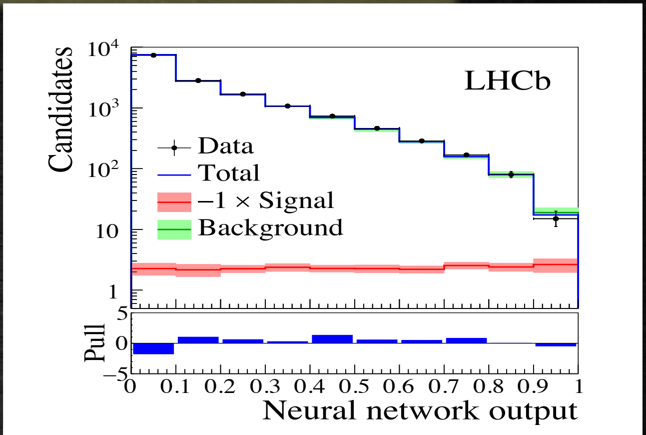


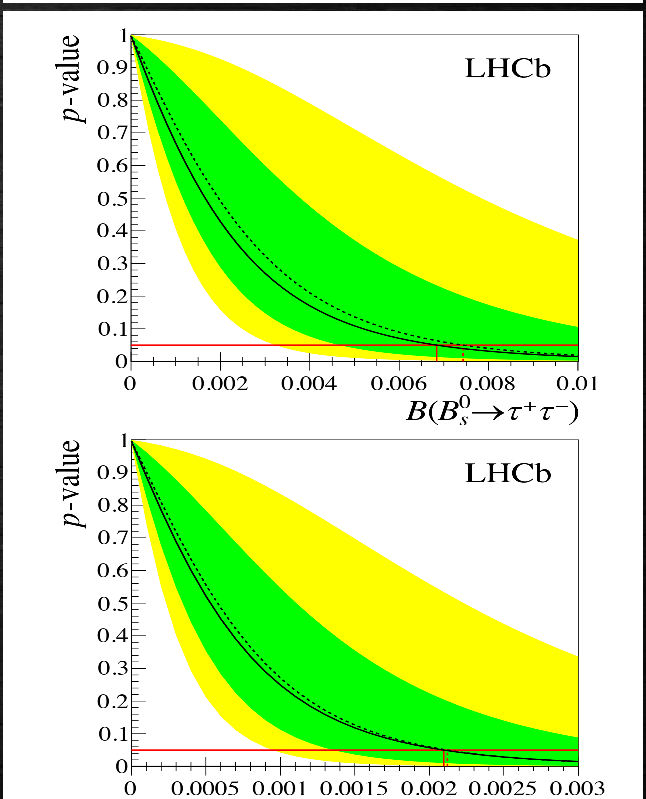
PRL 118 (2017) 191801

$B_{(s)} \to \tau\tau$

- **Less helicity suppressed** than $B_{(s)} \to \mu\mu$
- Very precise SM prediction [PRL 112 (2014) 101801]
  - $\mathcal{B}(B_s \to \tau\tau) = (7.73 \pm 0.49) \times 10^{-7}$
  - $\mathcal{B}(B^0 \to \tau\tau) = (2.22 \pm 0.19) \times 10^{-8}$
- **Hints of LU violation could imply increase of** $\mathcal{B}(B_{(s)} \to \tau\tau)$ by several orders of magnitude

- **Search on Run-1 data**
  - Tau reconstructed using $\tau \to 3\pi\nu$
  - Exploit $a_1(1260) \to \rho(770)[\pi\pi]\pi$ to identify signal
  - **First direct limit:** $\mathcal{B}(B_s \to \tau\tau) < 6.8 \times 10^{-3}$ @ 95% CL
  - **World's best limit:** $\mathcal{B}(B^0 \to \tau\tau) < 2.1 \times 10^{-3}$ @ 95% CL





PRL 118 (2017) 251802

$B_{(s)} \to e\mu$

› **Hints of LU violation could be associated to LF violation** and enhance $\mathcal{B}(B_{(s)} \to e\mu)$ up to 10^{-11} [MPLA 32 (2017) 1730006]

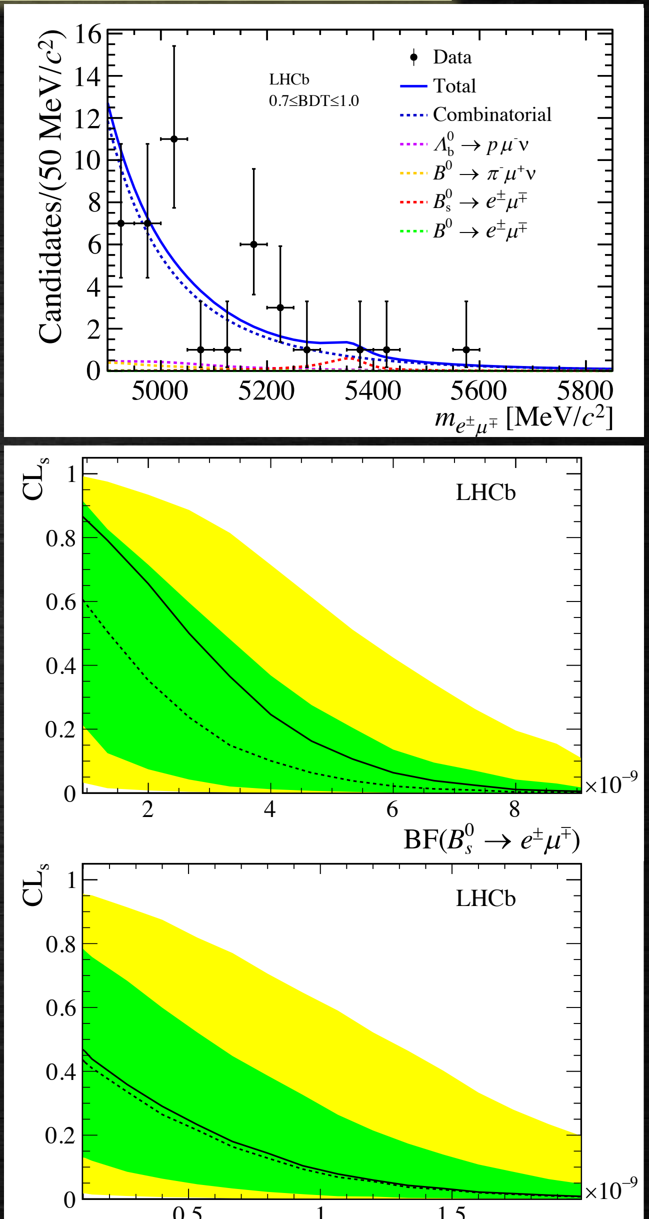
› Search on 1 fb^{-1} of Run-1 data [PRL 111 (2013) 141801]

› **New search on full Run-1 data**

» **World's best limits** (2-3x improvement)

» $\mathcal{B}(B_s \to e\mu) < 6.3 \times 10^{-9}$ @ 95% CL

» $\mathcal{B}(B^0 \to e\mu) < 1.3 \times 10^{-9}$ @ 95% CL



arXiv:1710.04111

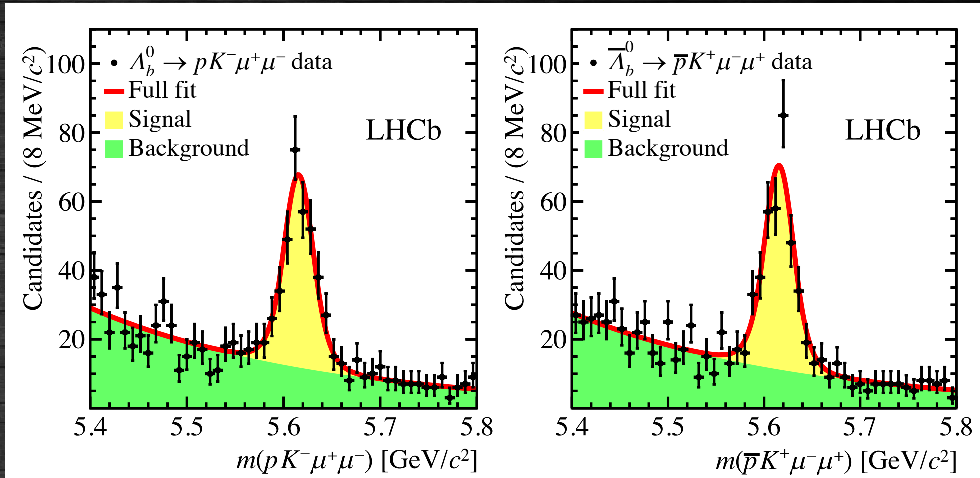
$\Lambda_b \to ph\,\mu\mu$

- Occurs at loop level, b→d CKM suppressed
- **Suppression not necessarily present in BSM**

- **Search on Run-1 data**
  - **First observation** of $\Lambda_b \to pK\mu\mu$
  - $\Delta A_{CP} = (-3.5 \pm 5.0 \pm 0.2)\times10^{-2}$
  - $a_{CP}^{\hat{T}\text{-odd}} = (1.2 \pm 5.0 \pm 0.7)\times10^{-2}$

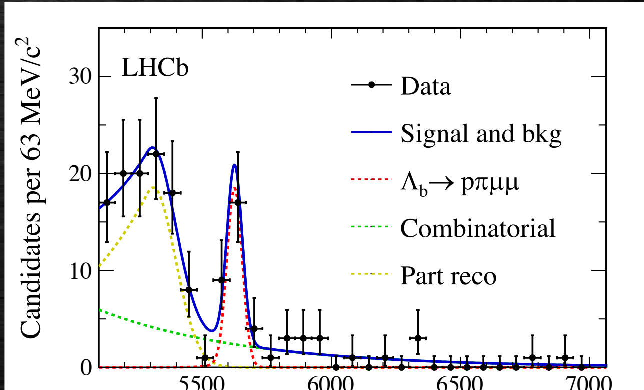
$$C_{\hat{T}} \equiv \vec{p}_{\mu^+} \cdot (\vec{p}_p \times \vec{p}_{K^-})$$
$$A_{\hat{T}} \equiv \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$
$$a_{CP}^{\hat{T}\text{-odd}} \equiv \frac{1}{2}\left(A_{\hat{T}} - \overline{A}_{\hat{T}}\right)$$

charge conjugate



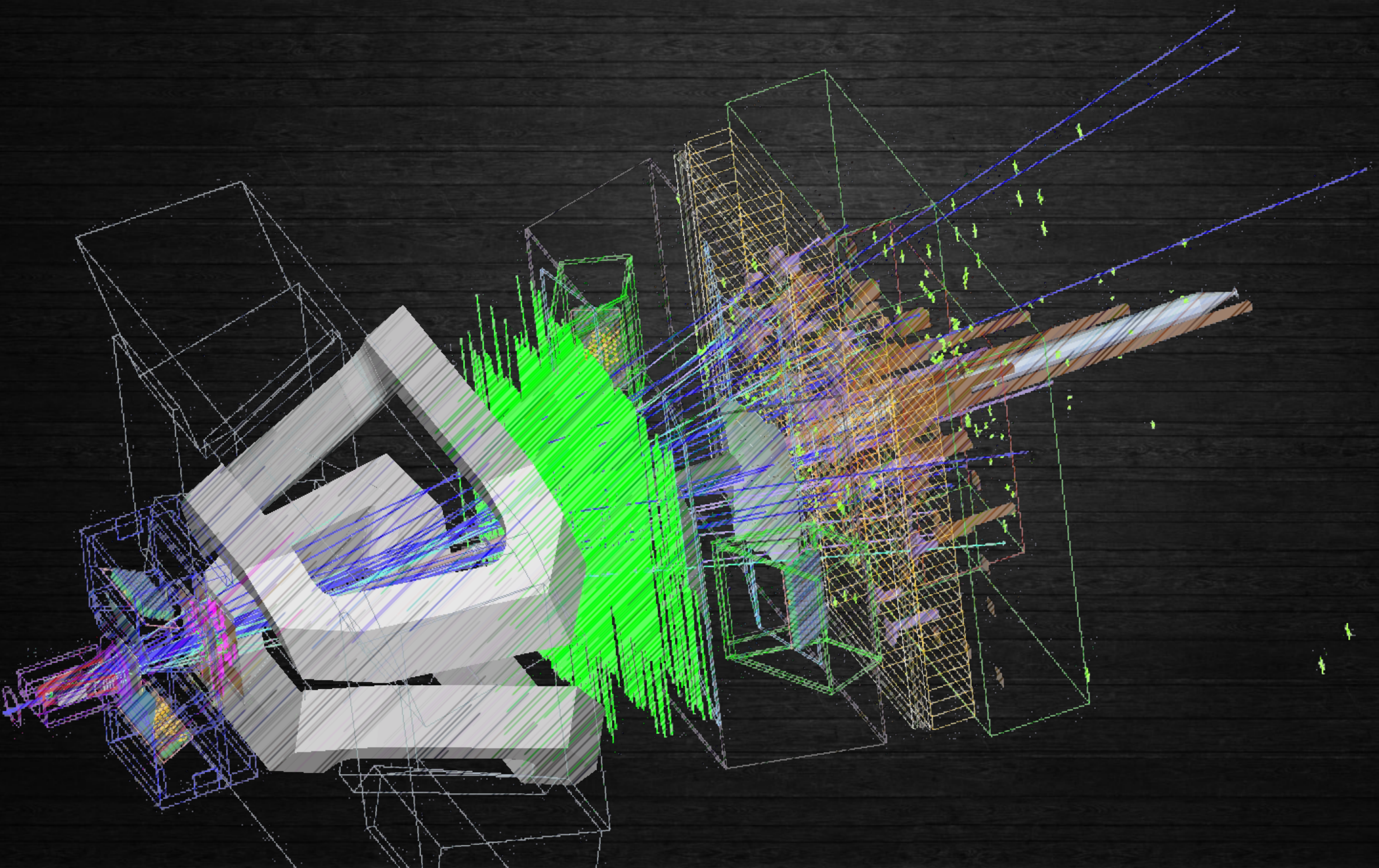
JHEP 06 (2017) 108

  - **First observation of b→d transition in a baryonic decay** at 5.5σ
  - $\mathcal{B}(\Lambda_b \to p\pi\mu\mu) = (6.9 \pm 1.9 \pm 1.1 \pm 1.3)\times10^{-8}$



JHEP 04 (2017) 029

Charm

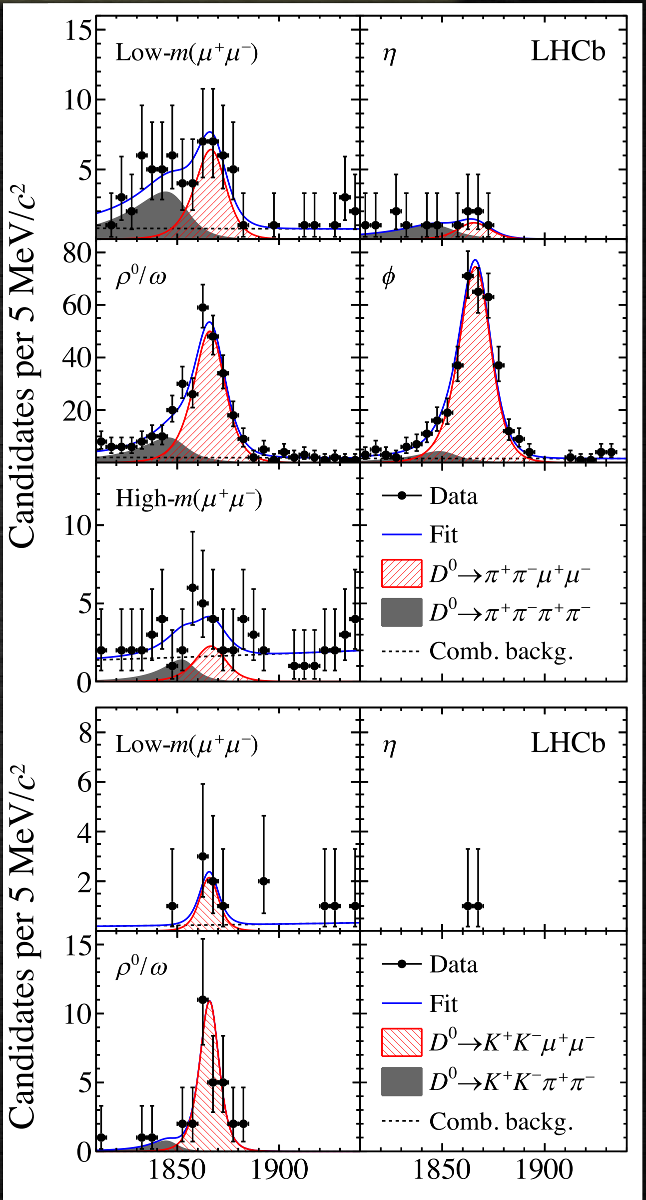


$D^0 \to hh\,\mu\mu$

- c→ull transitions less explored than b→sll
- Short-distance $\mathcal{B}_{SM}(D\to X\mu\mu)$ ~O(10^{-9})
- Long-distance $\mathcal{B}_{SM}(D\to XV[\mu\mu])$ up to O(10^{-6}) [PRD 83 (2011) 114006]
- BSM could enhance $\mathcal{B}(D\to X\mu\mu)$

- **Search on 2 fb^{-1} of Run-1 data**
  - 5 q^2 regions: <525MeV, η, ρ⁰/ω, φ, >1100MeV
  - **First observation** of $D^0\to\pi\pi\mu\mu$ and $D^0\to KK\mu\mu$
  - **Rarest charm decays ever measured to date**
  - $\mathcal{B}(D^0\to\pi\pi\mu\mu) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97)\times10^{-7}$
  - $\mathcal{B}(D^0\to KK\mu\mu) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16)\times10^{-7}$

    ($\mathcal{B}$ integrated over full q^2)

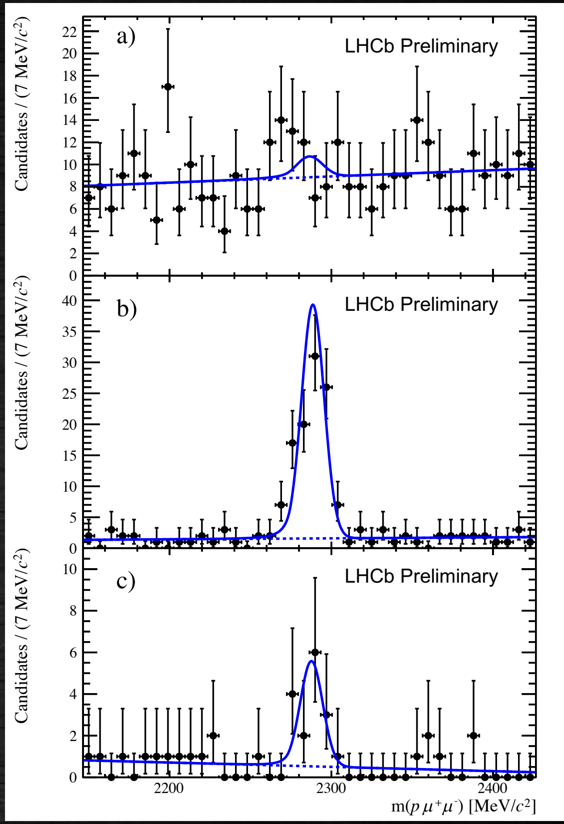


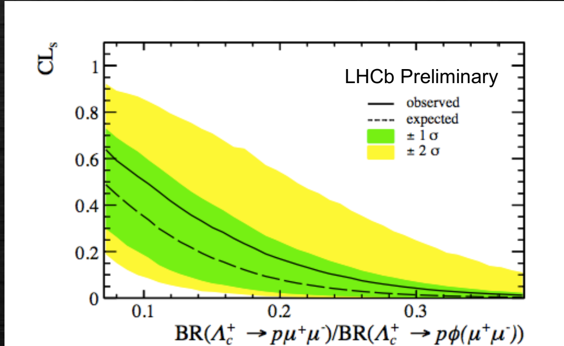
arXiv:1707.08377

$\Lambda_c \to p\,\mu\mu$

- **c→ull transitions less explored than b→sll**
- Short-distance $\mathcal{B}_{SM}$ ~O(10^{-9})
- Long-distance $\mathcal{B}_{SM}$ up to O(10^{-6})
- BSM could enhance $\mathcal{B}(\Lambda_c \to p\mu\mu)$

- **Search on Run-1 data**
  - 3 q^2 regions: a) short-distance, b) ϕ, c) ω
  - **First observation of $\Lambda_c \to p\omega$** at 5σ
  - $\mathcal{B}(\Lambda_c \to p\omega) = (7.6 \pm 2.6 \pm 0.9 \pm 3.1)\times10^{-4}$
  - $\mathcal{B}(\Lambda_c \to p\mu\mu) < 7.68\times10^{-8}$ @ 90% CL

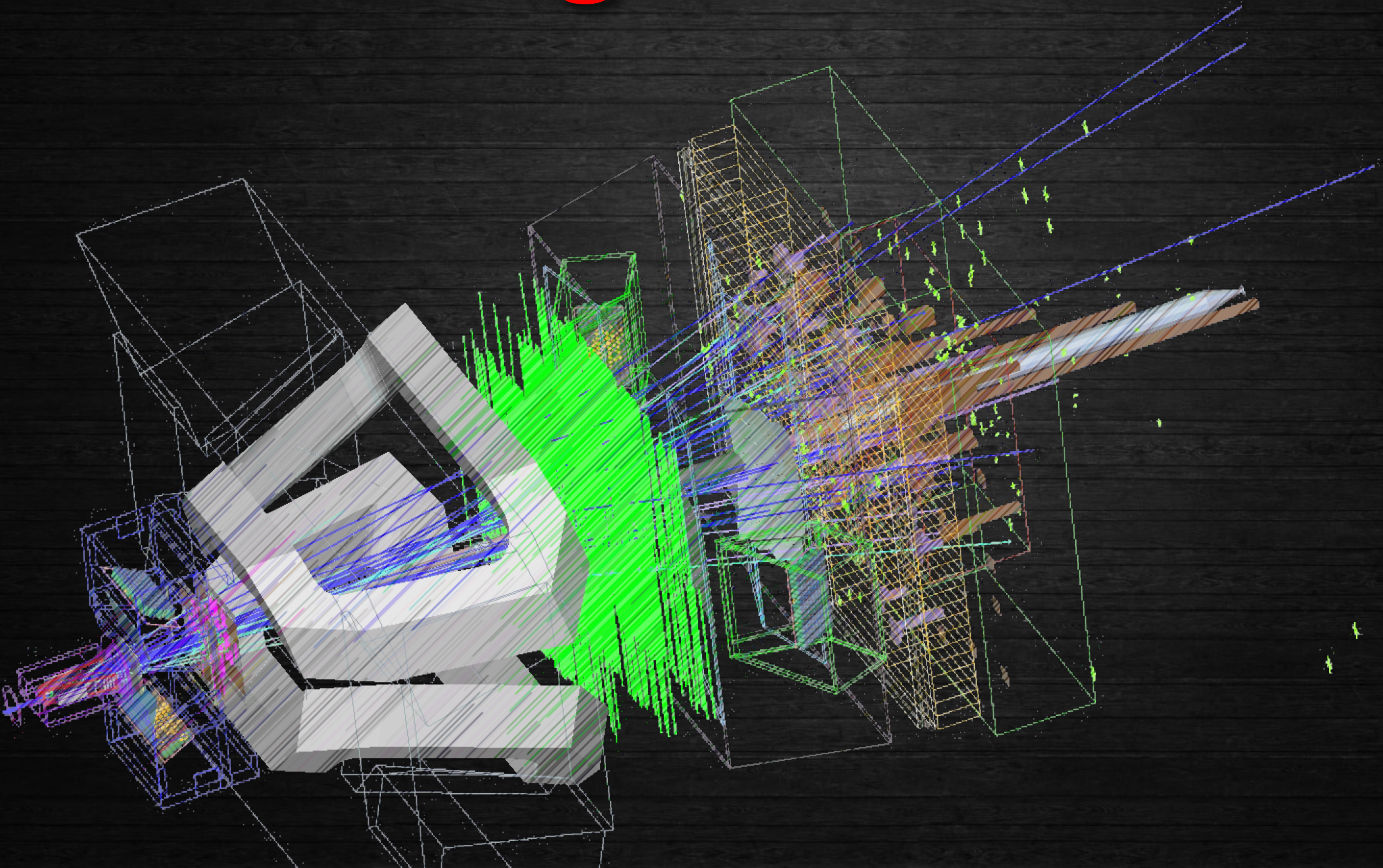




LHCb-PAPER-2017-039

(see also J.Brodzicka's talk)

Strange

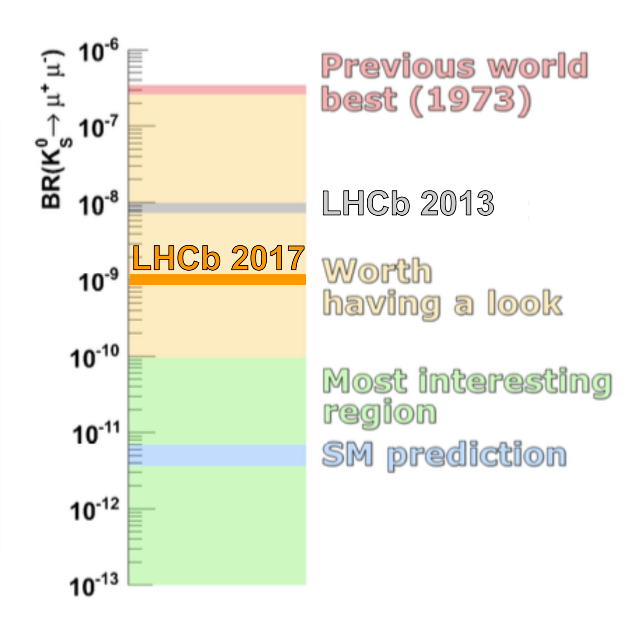


$K_S \to \mu\mu$

› Dominated by long-distance

› $\mathcal{B}_{SM}(K_S\to\mu\mu) = (5.0\pm1.5)\times10^{-12}$ [JHEP 01 (2004) 009]

› **New light scalars could increase $\mathcal{B}(K_S\to\mu\mu)$** by O(10)

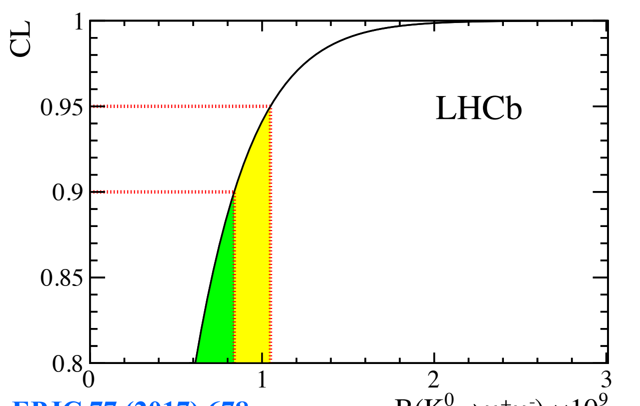


› Search on 1 fb^{-1} of Run-1 data [JHEP 01 (2013) 090]

› **New search on Run-1 data**

» **World's best limits** (10x improvement)

» $\mathcal{B}(K_S\to\mu\mu) < 1\times10^{-9}$ @ 95% CL



EPJC 77 (2017) 678

Summary

› Rare decays are particularly sensitive probes for BSM physics

› LHCb has an extensive programme of studies of rare b-, c- and s-quark decays

› Intriguing set of anomalies in rare decays of b-hadrons observed in the recent years

› If taken together these probably represent the largest "coherent" set of BSM effects in the present data

Outlook

- **Near-term updates** (+½ Run-2 data) **should clarify the experimental situation and can help constrain some of the theoretical issues**
  - **$B^0 \to K^{*0}\mu\mu$ angular analysis**: ~√2 improved precision
  - **R_K** and **$R_{K^{*0}}$** : ~1.8 and ~√2 improved precision

- **Wide range of measurements will be added/updated with full Run-1+Run-2 data to broaden the constraints on BSM physics**
  - **$B^0 \to K^{*0}ee$ angular analysis**: LU tests using angular observables
  - **R_X**: additional final states e.g. ϕ, K_S, K^{*+}, higher K^* resonances, Λ, pK
  - **b→dll**: test if $R_K = R_\pi$ (should give ~500 $B^+ \to \pi^+\mu\mu$, with $R_K = R_\pi$ expect ~50 $B^+ \to \pi^+ee$)
  - **b→ll**: $\Delta\mathcal{B}(B_s \to \mu\mu)/\mathcal{B}(B_s \to \mu\mu)$ ~15%, $B_{(s)} \to ee$
  - **LFV**: $B \to K^{(*)}e\mu$, $B \to K^{(*)}\tau\mu$
  - **CP asymmetry in $D^0 \to hh\mu\mu$**
  - **$K_S \to \pi^0\mu\mu$** [LHCb-PUB-2016-016] and **$K_S \to \pi\pi ee$** [LHCb-PUB-2016-017]

(see G.Cowan's talk for long-term prospects)

› **Near-term u** … **experimental situation and** … **ssues**

» **$B^0 \to K^{*0}\mu\mu$ a** …

» **R_K** and **$R_{K^{*0}}$** : …

› **Wide range** … **ed with full Run-1+Run-2** … **sics**

» **$B^0 \to K^{*0}ee$ a** … s

» **R_X**: additiona … Λ, pK

» **b→dll**: test … $= R_\pi$ expect ~50 $B^+ \to \pi^+ ee$)

» **b→ll**: $\Delta\mathcal{B}(B_s$ …

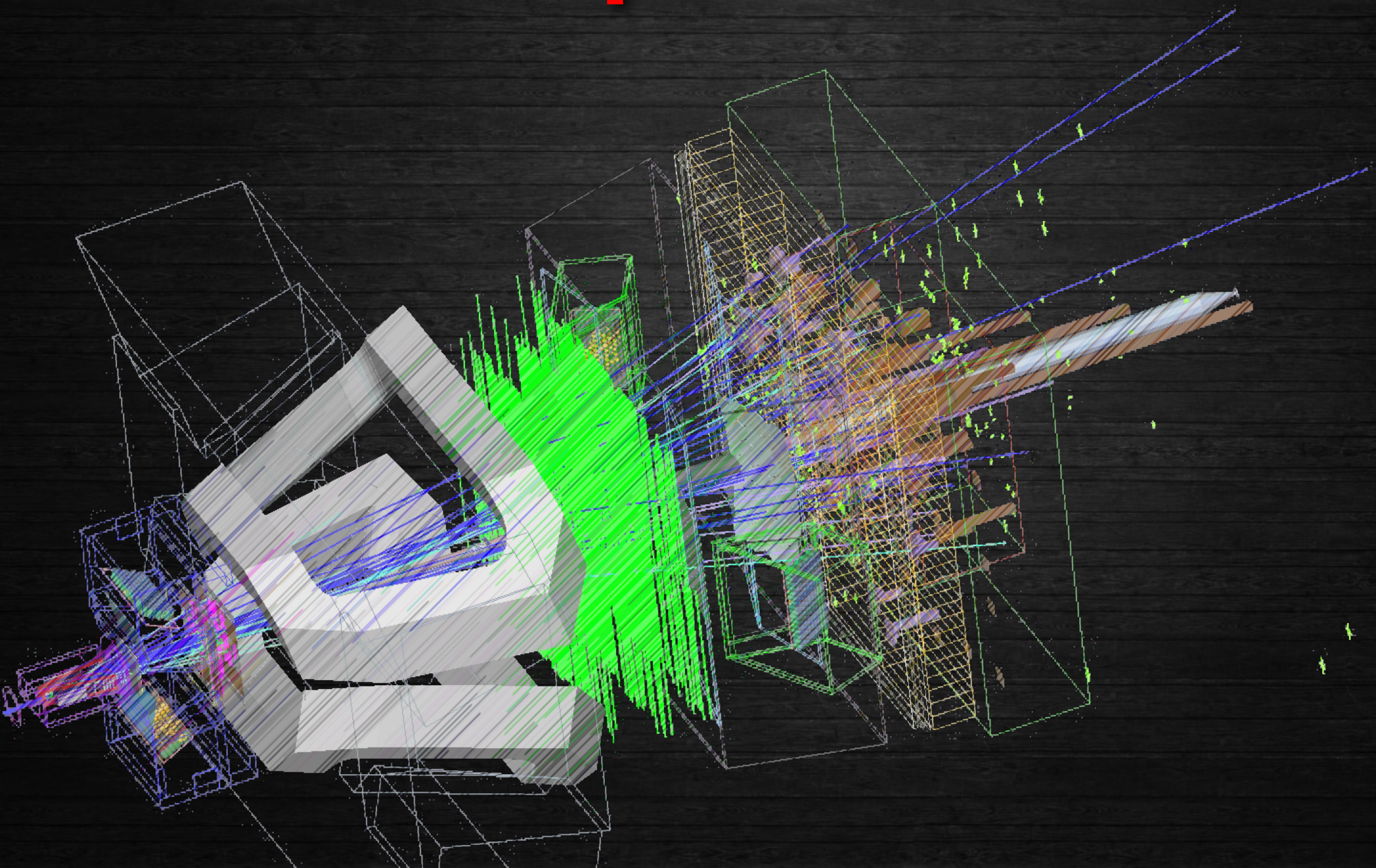
» **LFV**: $B \to K^{(*)}$ …

» **CP asymmet** …

» **$K_S \to \pi^0\mu\mu$** [L … 6-017]

… rm prospects)

Backup



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 $E>\Lambda_{EW}$

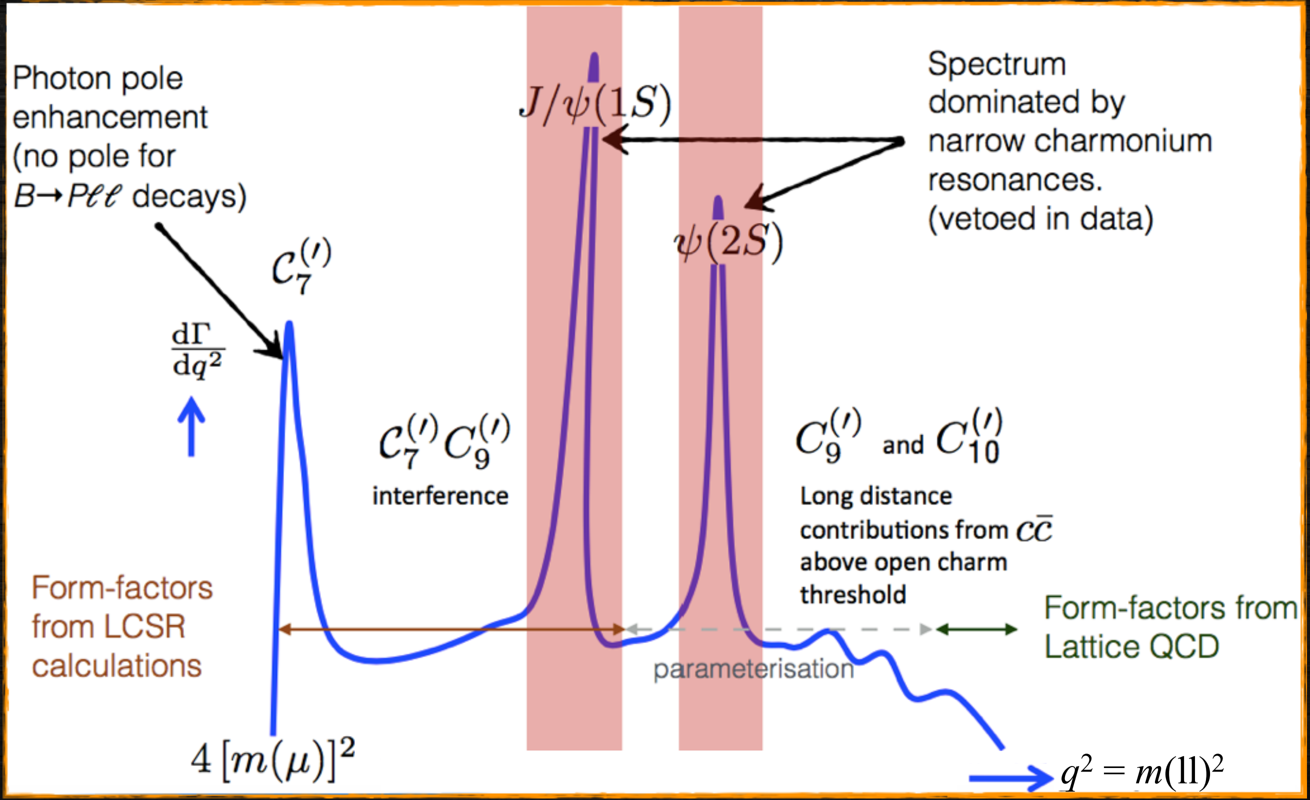
› O_i (**Operators**): non-perturbative QCD, long-distance physics, depends on hadronic form-factors

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

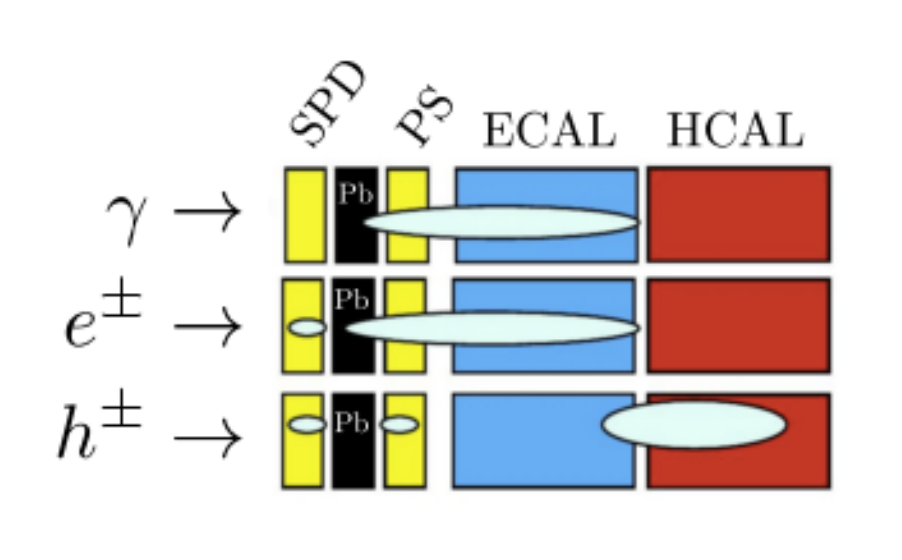
- **BSM physics** can
  - » alter the SM operator contributions (Wilson coefficients)
  - » enter through new operators (right-handed O_i', $O_{S,P}$)

- Different q² regions probe different operators

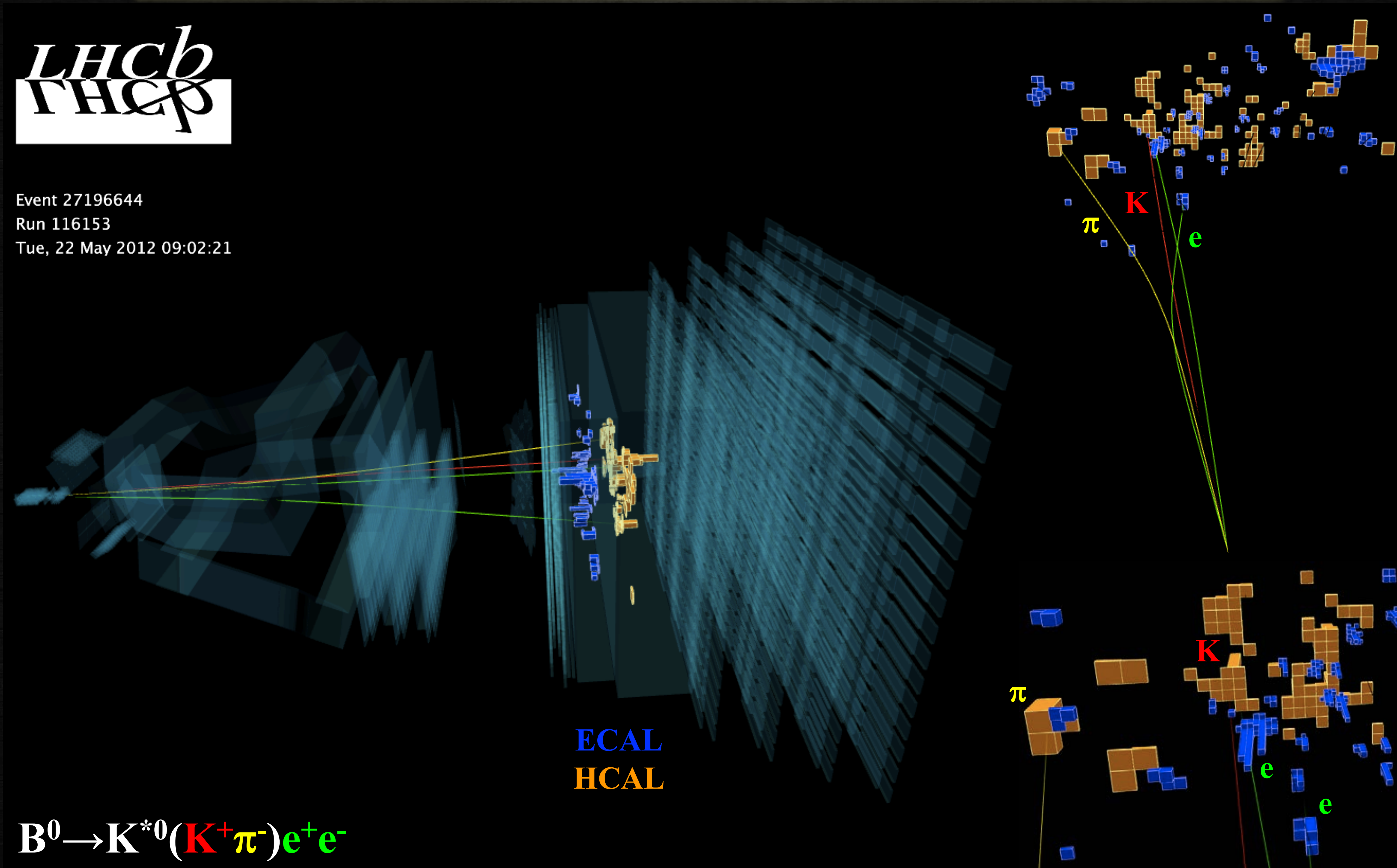


Calorimeter System

- Composed of a Scintillating Pad Detector (SPD), a Preshower (PS), an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL)
- The SPD and the PS consist of a plane of scintillator tiles (2.5 radiation lengths, but to only ~6% hadronic interaction lengths)
- The ECAL has shashlik-type construction, i.e. a stack of alternating slices of lead absorber and scintillator (25 radiation lengths)
- The HCAL is a sampling device made from iron and scintillator tiles being orientated parallel to the beam axis (5.6 interaction lengths)



Event Anatomy



Bremsstrahlung – I

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

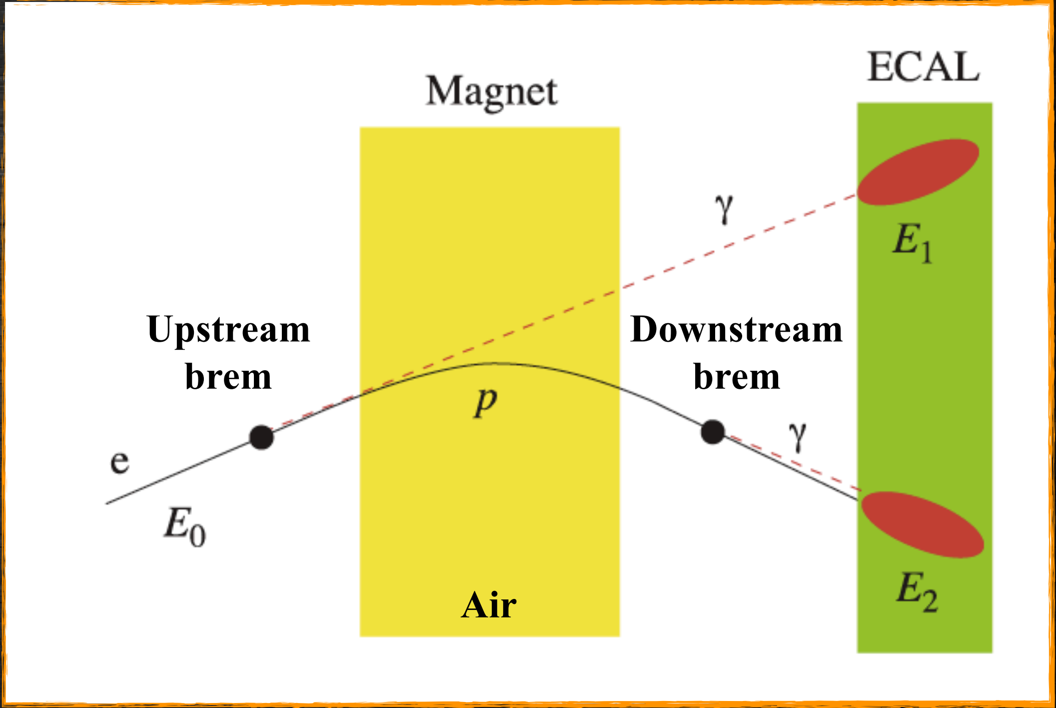
› **Two types of bremsstrahlung**

» **Downstream of the magnet**

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

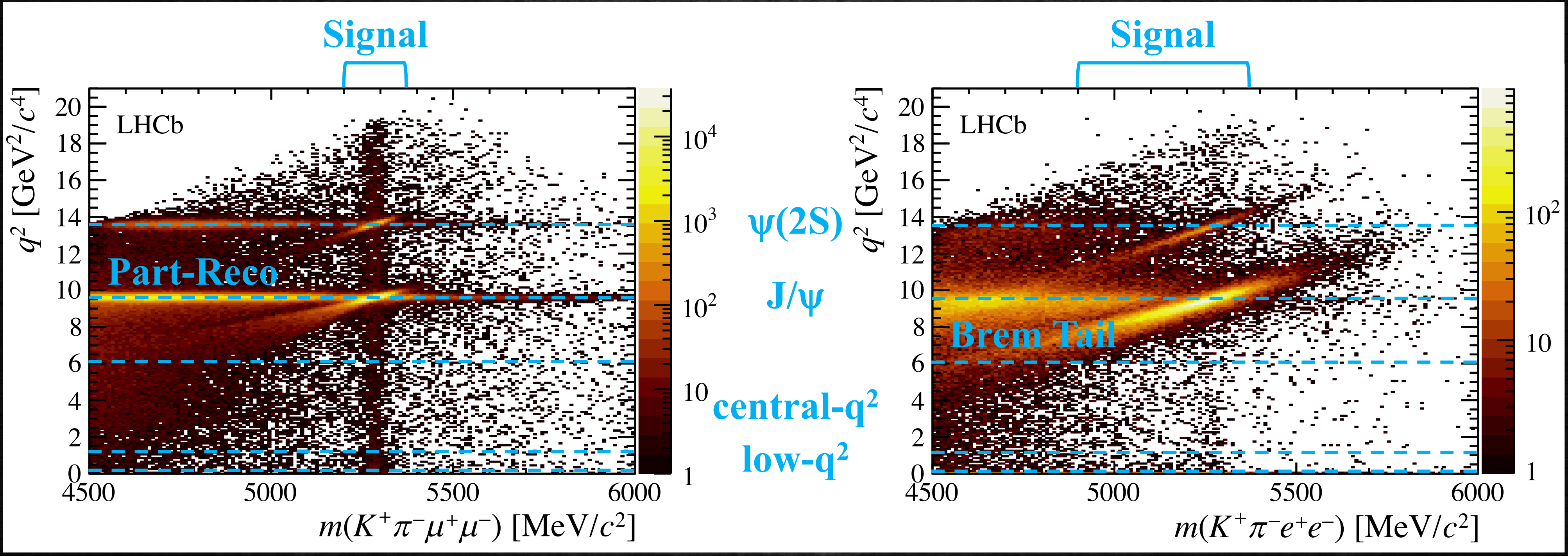
» **Upstream of the magnet**

- 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

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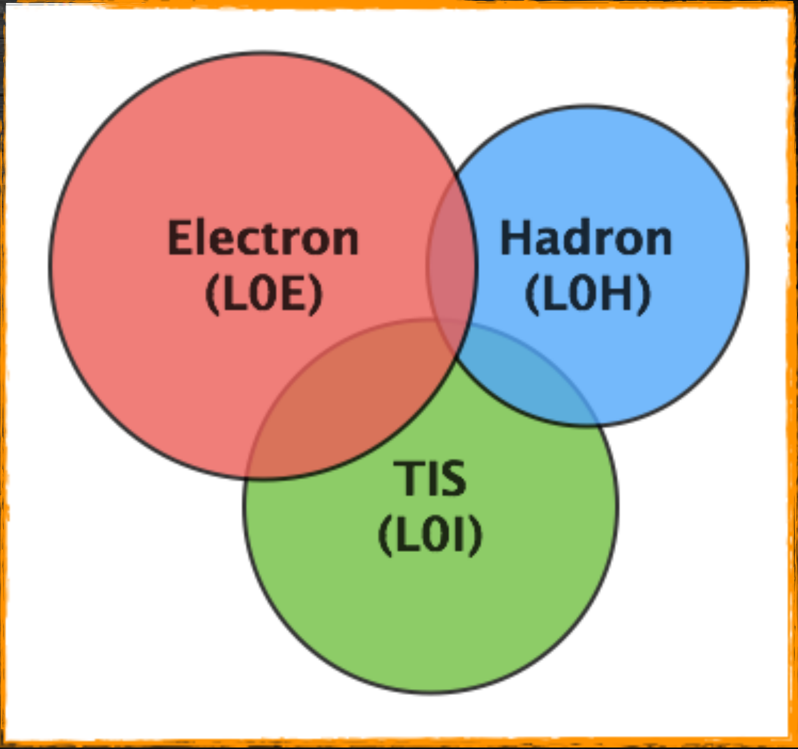
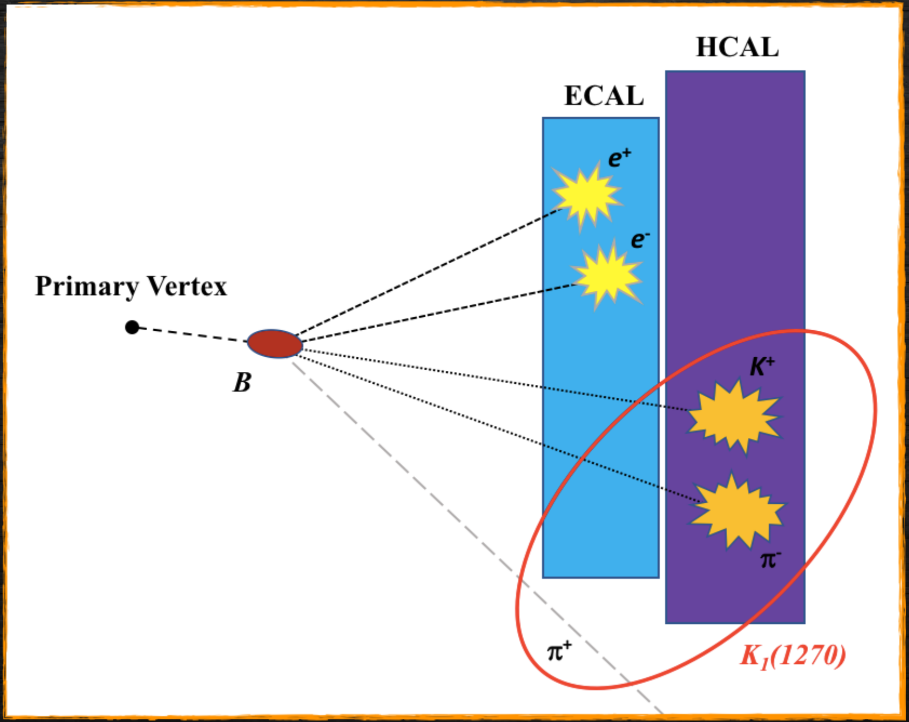
Trigger

- 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



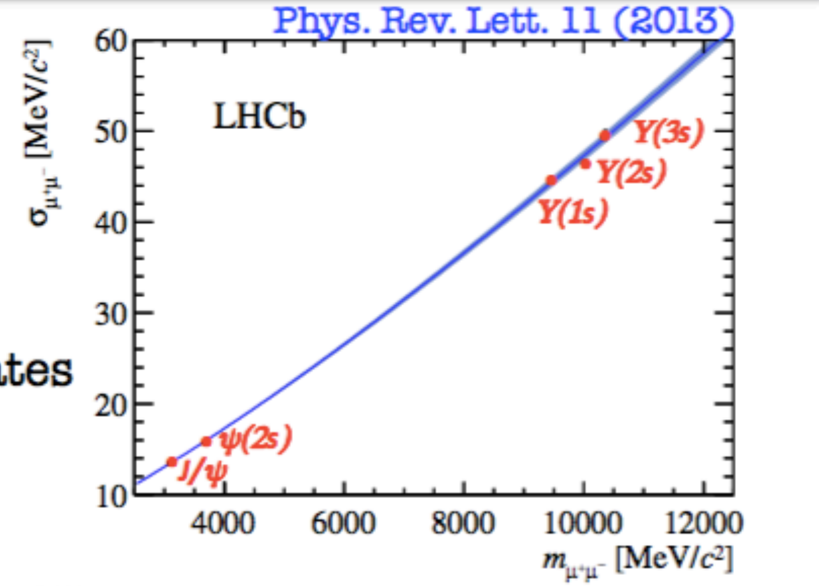
Part-Reco Background

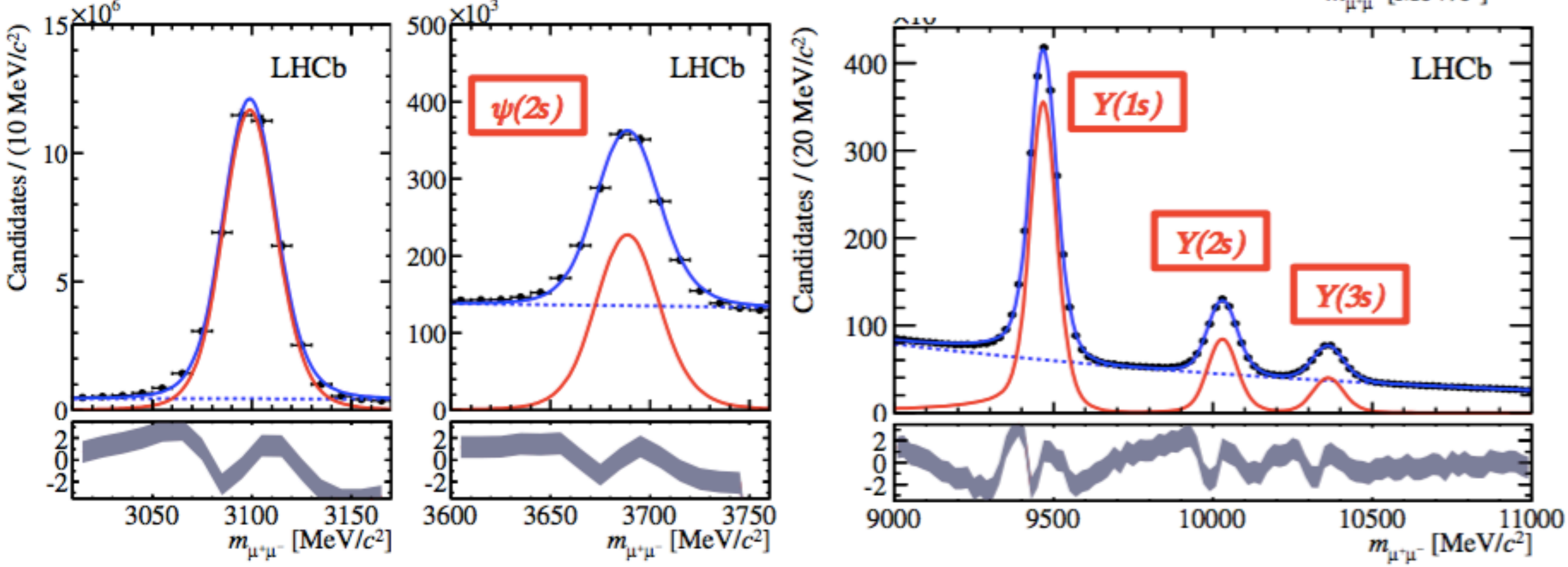
- Partially-reconstructed backgrounds arise from decays involving **higher K resonances** with one or more decay products in addition to a $K\pi$ pair that are not reconstructed
- Large variety of decays, most abundant due to **$B \to K_1(1270)ee$** and **$B \to K_2^*(1430)ee$**
- Modelled with a simulation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



Muon Reconstruction

- **Extremely performant in LHCb**:
  - dedicated muon chambers
  - very efficient tracking system.
- **A muon is a clear trigger signature**:
  ε(L0+HLT)= ~90% for di-muon channels
  ε(L0+HLT)= ~30% for multibody hadronic states
- **Very good di-muon resolution**



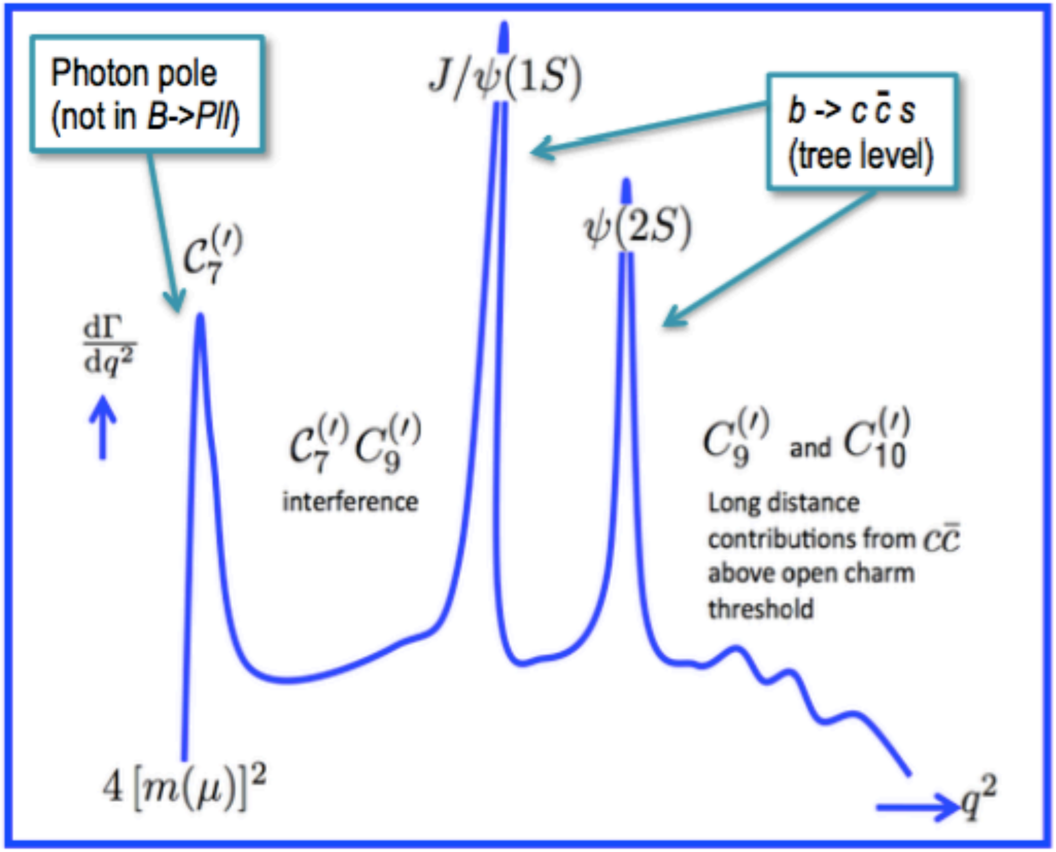


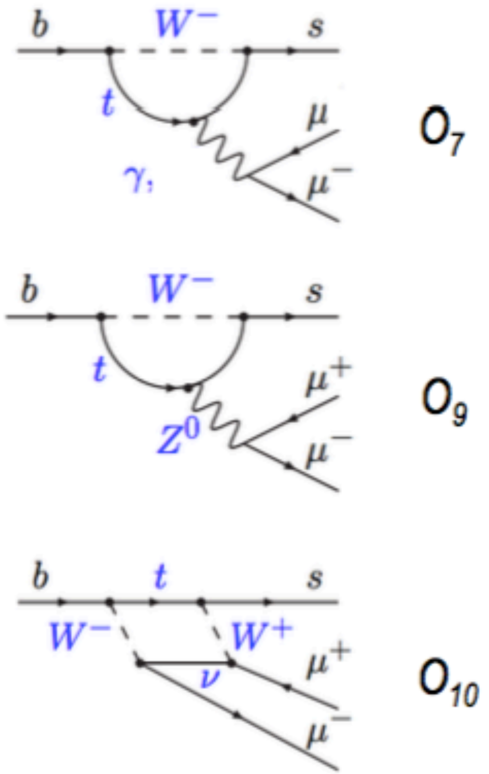
Effective Theory Approach

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

Operators O_i: non-perturbative long-distance effects
Wilson coefficients C_i: perturbative short-distance effects

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





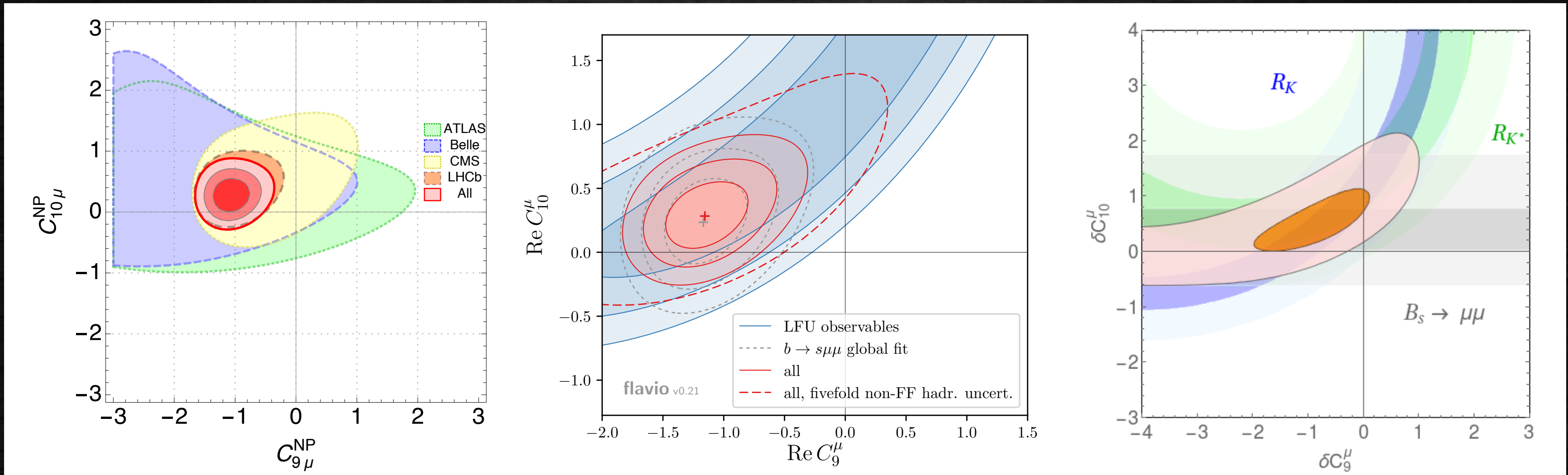
Sensitivity to Wilson Coefficients

- Different observables are complementary in constraining NP
- Leptonic decay uniquely sensitive to scalar operators

Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$B \to X_s\gamma$	X			
$B \to K^*\gamma$	X			
$B \to X_s\ell^+\ell^-$	X	X	X	
$B \to K^{(*)}\ell^+\ell^-$	X	X	X	
$B_s \to \mu^+\mu^-$			X	X

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?

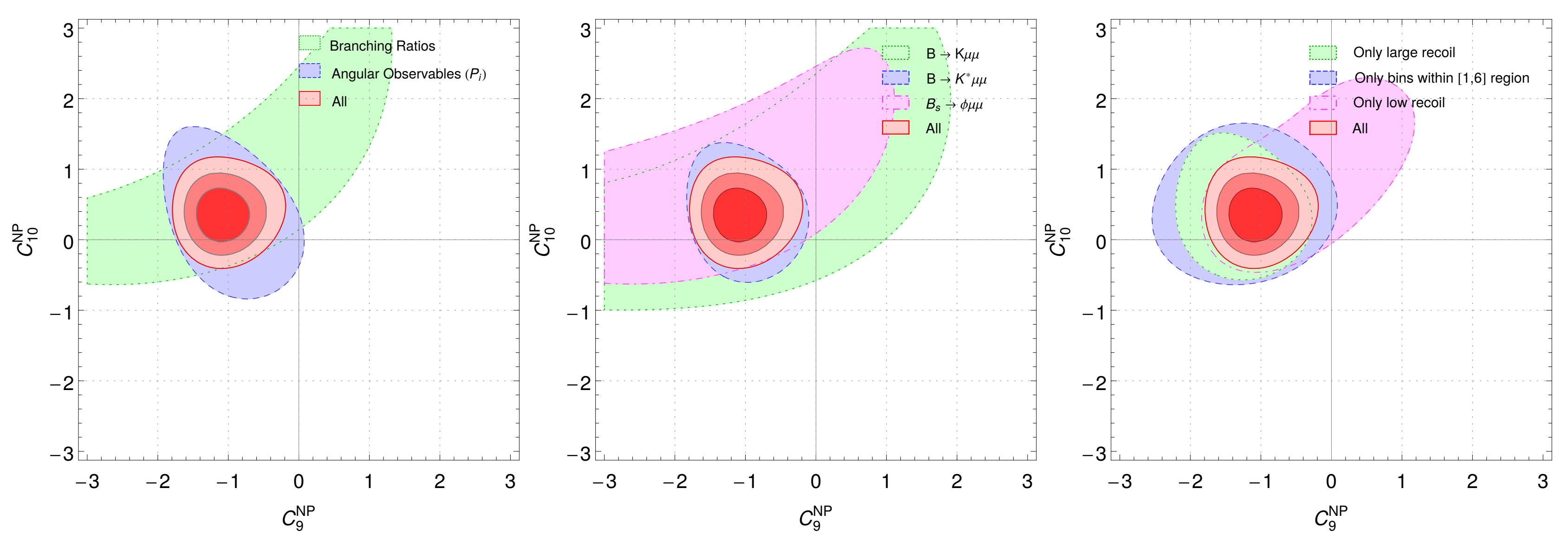
Global Fits – II

› **Good consistency among different fits**

» BFs and Angular Observables

» Different modes

» Different q^2 regions

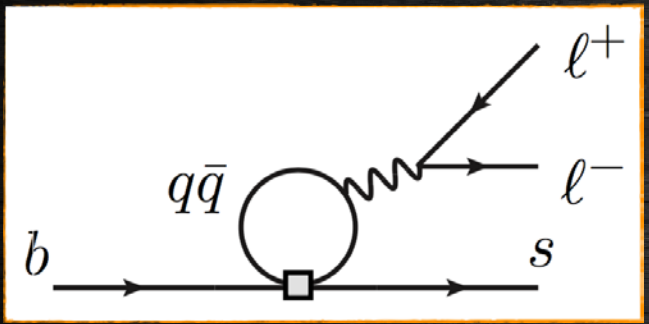


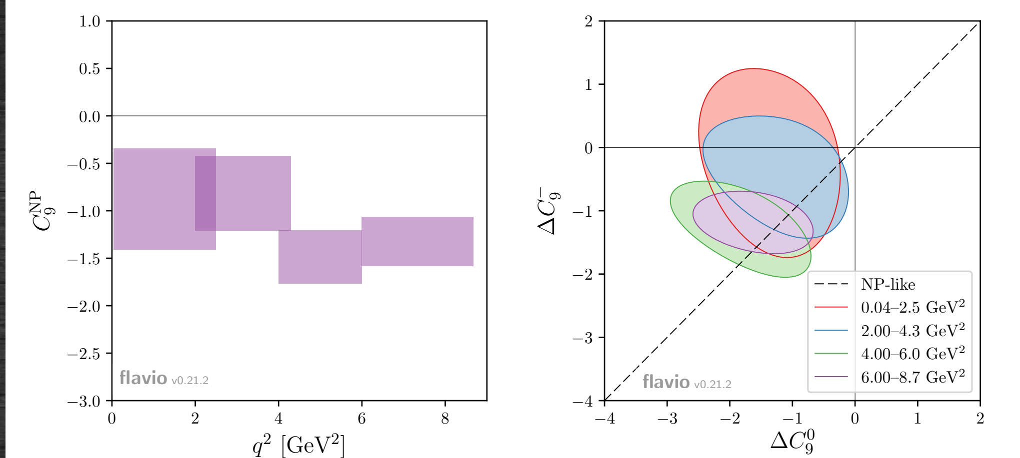
arXiv:1510.04239

› n.b. Different theory issues in each case

Controlling Charm Loops

- Renewed scrutiny of theoretical uncertainties
- The $O_{1,2}$ operator has a component that could **mimic BSM effect** in C_9 through $c\bar{c}$ loop





arXiv:1703.09189

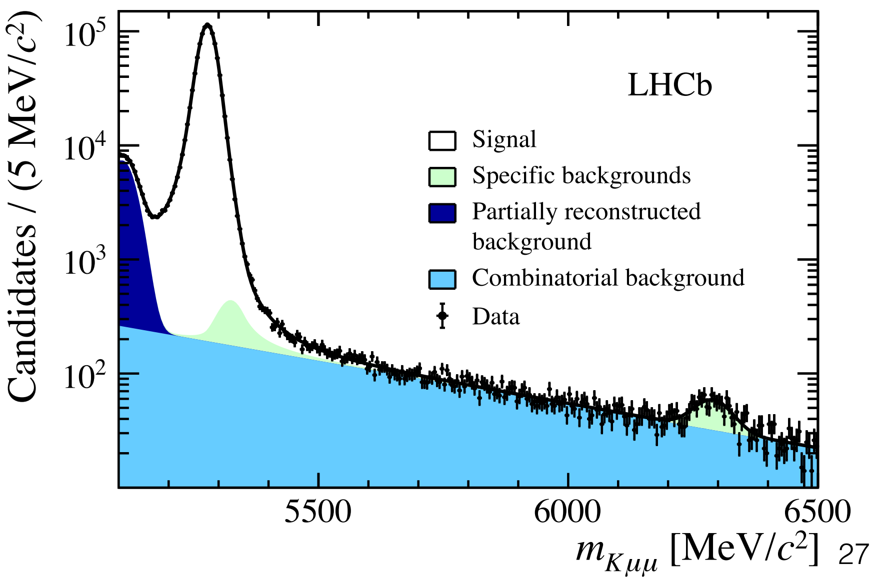
- "The absence of a q^2 and helicity dependence is intriguing, but cannot exclude a hadronic effect as the origin of the apparent discrepancies"

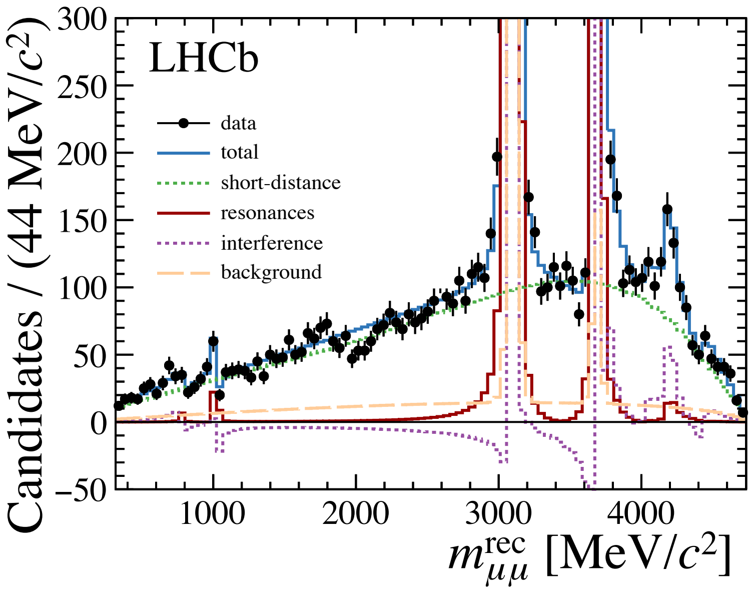
Controlling Charm Loops

Phase difference in $B^+ \to K^+\mu^+\mu^-$ decays

- Fit of to full dimuon mass distribution
  - Sum of relativistic Breit–Wigner amplitudes to describe resonances
  - short-distance contribution in terms of an effective field theory description
  - $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ as normalisation channel
- Magnitudes and relative phases between the resonances and the short-distance contribution allowed to vary in the fit
- Model includes: resonances (ρ, ω, ϕ, J/ψ, $\psi(2S)$) , charmonium states: ($\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$)

[Eur. Phys. J. C (2017) 77: 161]





Controlling Charm Loops

[Eur. Phys. J. C (2017) 77: 161]

Sensitive to C_9 and C_{10}:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} = \frac{G_F^2 \alpha^2 |V_{tb}V_{ts}^*|^2}{128\pi^5} |\boldsymbol{k}| \beta \left\{ \frac{2}{3} |\boldsymbol{k}|^2 \beta^2 \left| \mathcal{C}_{10} f_+(q^2) \right|^2 + \frac{4m_\mu^2 (m_B^2 - m_K^2)^2}{q^2 m_B^2} \left| \mathcal{C}_{10} f_0(q^2) \right|^2 \right.$$
$$\left. + |\boldsymbol{k}|^2 \left[1 - \frac{1}{3}\beta^2 \right] \left| \mathcal{C}_9 f_+(q^2) + 2\mathcal{C}_7 \frac{m_b + m_s}{m_B + m_K} f_T(q^2) \right|^2 \right\}$$

BF of the short-distance component:

$$\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-) = (4.37 \pm 0.15 \pm 0.23) \times 10^{-7}$$

In very good agreement with the old result
[JHEP 06 (2014) 133]

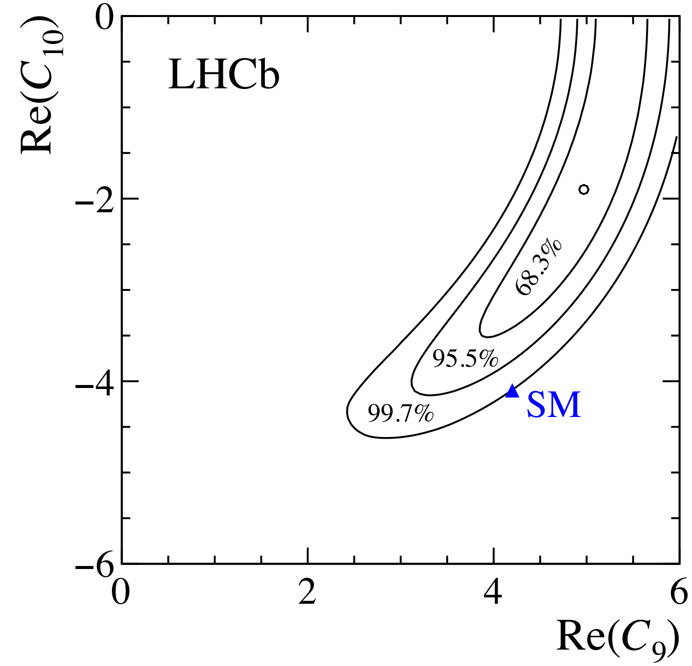
Measurement of the Wilson coefficient:

- $|C_{10}| < |C_{10}^{SM}|$ and $|C_9| > |C_9^{SM}|$ if both free
- $|C_9| < |C_9^{SM}|$ if C_{10} constrained to the SM

Exclusion of $C9 = 0$ hypothesis > 5 σ

Compatible with previous measurement

Working on measurement in $B^0 \to K^{*0}\mu^+\mu^-$



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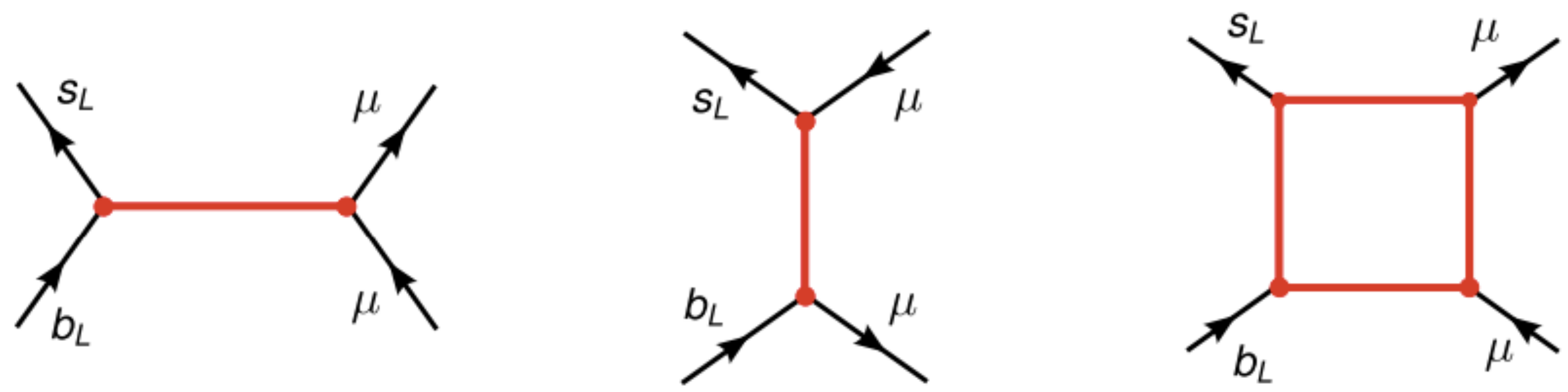
Is it a Z', a LQ or ... ?

› 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