New physics searches using $b \to s\ell\ell$ transitions at LHCb

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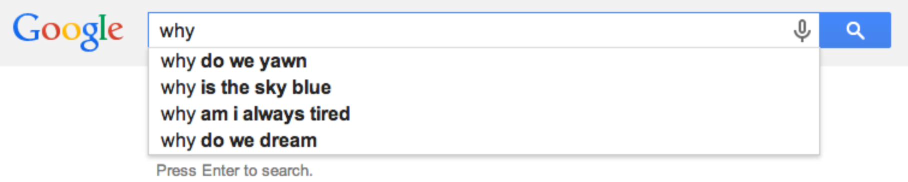
Important questions



- What is the origin of dark matter?
- Why is there a hierarchy of fermion masses?
- Why do elements of the CKM matrix have a large spread?
- What is the origin of CP violation in the universe?

The Standard Model (SM) for all its success has no answers to these

Studying properties of beauty and charm hadrons can shed some light

Higgs and flavour

Two sides of the same coin

- Yukawa couplings ($Y^{U,D}$) of quarks to Higgs field:
  $\mathcal{L}_Y = \bar{u}_{Ri} Y^U_{ij} \phi^{c\dagger} Q_{Lj} + \bar{d}_{Ri} Y^D_{ij} \phi Q_{Lj}$
- $Y^{U,D}$ matrix in 3 quark generations is not necessarily diagonal

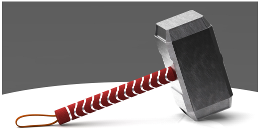
- Transformation of u, d, Q to mass eigenstates:
  - Diagonalises $M^U = V_{u_R} Y^U V^\dagger_{u_L}$ and $M^D = V_{d_R} Y^D V^\dagger_{d_L}$
- W couplings become non-diagonal:
  $W^+_\mu \bar{u}_L \gamma^\mu d_L \rightarrow W^+_\mu \bar{u}_L V^\dagger_{u_L} V_{d_L} \gamma^\mu d_L$ ($V_{CKM} = V^\dagger_{u_L} V_{d_L}$)

- In SM, Z,γ couplings remain diagonal! $\rightarrow$ No tree level Flavour Changing Neutral Currents (FCNC)
  - Z and γ couplings are invariant under transformation. Consequence of s,d,b having same $SU_L(2) \times U_Y(1)$ quantum numbers

Experimental approaches

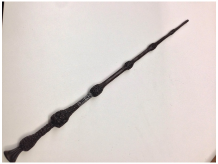
SM could be a low-energy effective theory of a more fundamental theory at higher energy scale with new particles, dynamics/symmetries.

Direct approach



- Rely on high energy collisions to produce new particle(s) on-mass-shell, observed through their decay products

Indirect approach (typical of flavour)



- New particles appear off-mass-shell in heavy flavour processes, leading to deviations from SM expectations

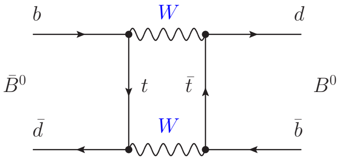
Interplay of direct and indirect measurements

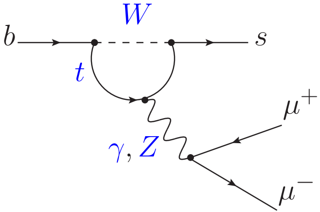
Flavour physics has played central role in the development of the SM

- *c*-quark inferred from measurement showing suppression of $K^0 \to \mu^+\mu^-$ rate compared to $K \to \mu\nu$ (GlM 1970)
  - Discovery of J/ψ in 1974 (SLAC, BNL)
- *t*,*b*-quarks inferred from CP violation in K sector (KM of CKM 1973)
  - Discovery of the Υ in 1977 (Fermilab)
- Limit on top quark mass $m_t > 50\,\text{GeV}$ from B^0 mixing (ARGUS 1987)
  - Discovery of the *t*-quark 1995 (D0, CDF)
- Weak neutral current inferred from neutrino scattering in Gargamelle (1973)
  - Discovery of the Z boson 1983 (UA1,UA2)

New physics probes

Search for deviations from SM predictions from virtual contributions of new heavy particles in loop processes





- Measure CP violating phases and study rare decays of heavy quarks
- Compare to very precise predictions of the SM
  - Uncertainties from QCD is main problem
- Most interesting processes those where SM contribution is suppressed (e.g FCNC)
  - Effects of New Physics (NP) are large
- Discovery potential for NP extends to mass scales >> centre-of-mass energy of collision

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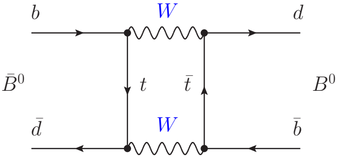

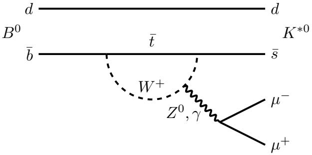

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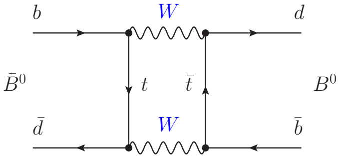

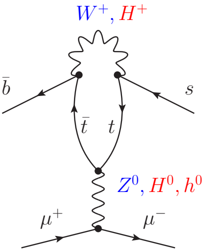

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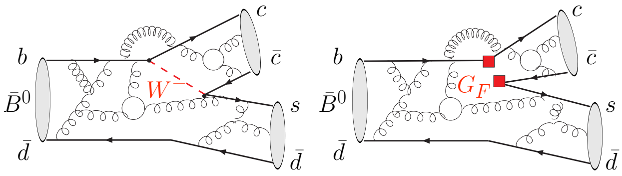
Formalism

- Model independent approach
- "Integrate" out heavy ($m \geq m_W$) field(s) and introduce set of Wilson coefficients C_i, and operators $\mathcal{O}_i$ encoding long and short distance effects

$$\mathcal{H}_{eff} \approx -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{ts(d)} \sum_i C_i^{SM} \mathcal{O}_i^{SM} + \sum_{NP} \frac{c_{NP}}{\Lambda^2_{NP}} \mathcal{O}_{NP}$$

- c.f. Fermi interaction and G_F



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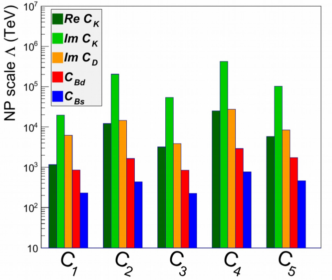
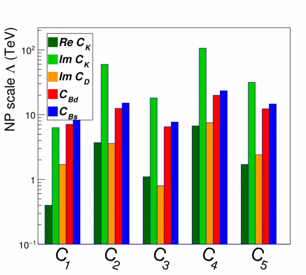
[Silvestrini et al 2016]

Bounds from ΔF=2 processes, generic flavour structure



ΔF=2 processes scale as $1/\Lambda^2$

Bounds from ΔF=2 processes, CKM-like flavour structure



ΔF=2 processes scale as $1/\Lambda^2$

Sensitivity to New Physics

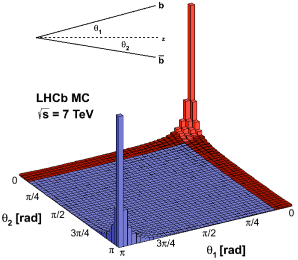
- Different decays probe different operators e.g:

Operator $\mathcal{O}_i$	$B_{s(d)} \to X_{s(d)}\mu^+\mu^-$	$B_{s(d)} \to \mu^+\mu^-$	$B_{s(d)} \to X_{s(d)}\gamma$
$\mathcal{O}_7 \sim m_b(\bar{s}_L\sigma^{\mu\nu}b_R)F_{\mu\nu}$	✓		✓
$\mathcal{O}_9 \sim (\bar{s}_L\gamma^{\mu}b_L)(\bar{\ell}\gamma_{\mu}\ell)$	✓		
$\mathcal{O}_{10} \sim (\bar{s}_L\gamma^{\mu}b_L)(\bar{\ell}\gamma_5\gamma_{\mu}\ell)$	✓	✓	
$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S,P}(\bar{\ell}\ell)_{S,P}$	(✓)	✓	

- In SM $C_{S,P} \propto m_\ell m_b/m_W^2$
- In SM chirality flipped $\mathcal{O}_i$ suppressed by m_s/m_b

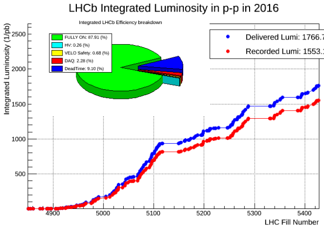
Setting the scene

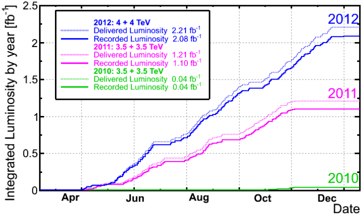
- LHC $\sigma_{b\bar{b}} = 460\,\mu$b @ $\sqrt{s} = 13$ TeV (scale $\sim$ linear with $\sqrt{s}$)
- $\sigma_{b\bar{b}}$ in LHCb acceptance $\sim 100\,\mu$b
  - c.f $\sigma_{b\bar{b}} = 0.001\,\mu$b @ B-factories



>300 publications in total

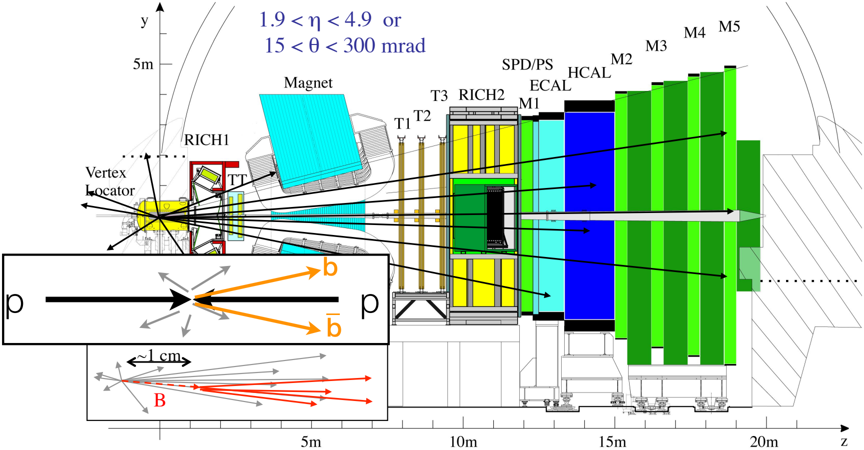
Run 2: 2fb^{-1} (current), Run 1: 3fb^{-1}





$L_{inst}^{Max} = 4 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ (double the design value)

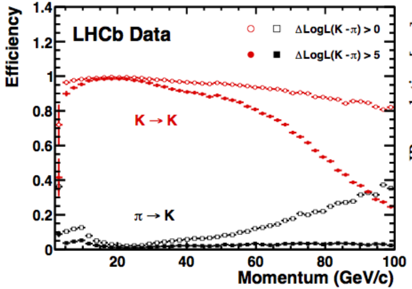
The LHCb detector

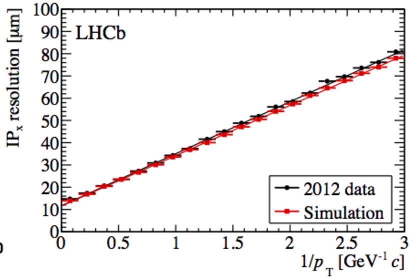


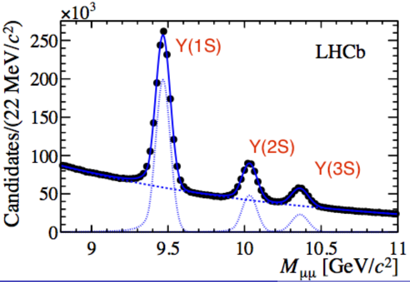
- *B*-lifetime means displaced secondary vertex

Detector performance

[Int.J.Mod.Phys.A30(2015)1530022]





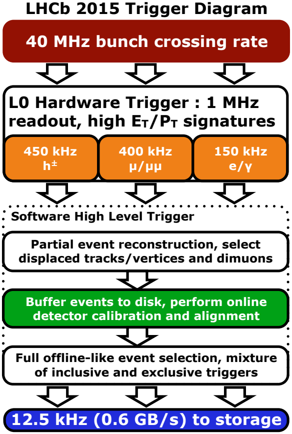


- **Tracking** $\delta p/p = 0.4 - 0.6\%$
- **Muon** $\epsilon_{\mu}^{id} = 98\%$ for 1% mis-id
- Mass resolution $J/\psi \to \mu\mu$
  - LHCb: 13 MeV
  - CMS: 28 MeV [arXiv:1011.4193]
  - ATLAS: 46 MeV [arXiv:1104.3038]

The LHCb trigger in Run 2

The challenge

- Only 1 in 200 pp inelastic events contain a *b*-quark
- Looking for *B*-hadron decays with $BF \sim 10^{-6} - 10^{-9}$



Major development for Run 2:

- Buffer all events after HLT1 to perform calibrations and alignment
  - Determine calibration and alignment constants per fill (minutes)
  - Global offline-like reconstruction using these constants
  - Major step towards realising upgrade trigger strategy (see later)

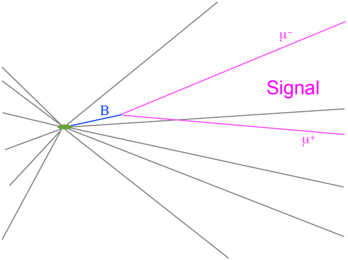
  → More selective triggers e.g offline like particle ID in the trigger!

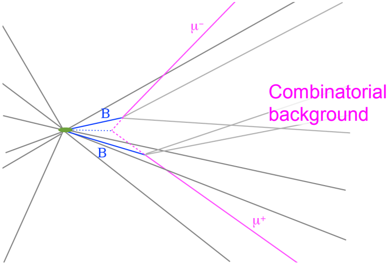
  → Physics measurement with data straight out of HLT2
- Output rate of HLT2 ~~5kHz~~ 12.5kHz

Experimental aspects

Selection:

- Reduce combinatorial background using Multivariate classifiers, (typically Boosted Decision Tree)
  - Using kinematic and topological information
  - Variable choice based on minimising correlation with mass
- Reduce "peaking" backgrounds using particle-ID information
  - Exclusive decays with final state hadron(s) mis-Id
  - Estimate by mixture of MC and data-driven studies





Experimental aspects

Normalisation:

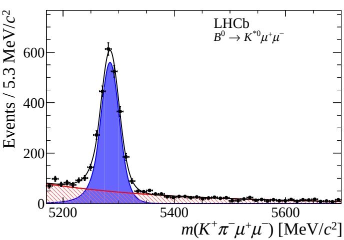
- Make use of proxy-decay (same topology) of known $\mathcal{B}$ to normalize against

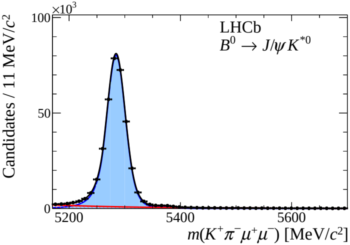
$$\mathcal{B}(sig) = \frac{N_{sig}\epsilon_{sig}}{N_{prx}\epsilon_{prx}}\mathcal{B}(prx)$$

  - Reduces experimental uncertainties

Acceptance correction:

- Efficiency parametrised depending on type of measurement of $\mathcal{B}$
  - Differential with respect to di-muon mass squared (q^2) or angular distribution of decay products of the b-Hadron
- Efficiency (ϵ) obtained from MC corrected from data





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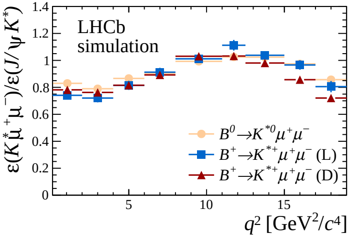
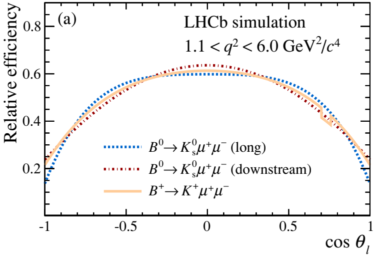




Cracks appearing in the SM?

Cracks appearing in the SM?

1. **Measurements of decay rates of $B \to K^{(*)}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$ and $\Lambda_b \to \Lambda\mu^+\mu^-$**

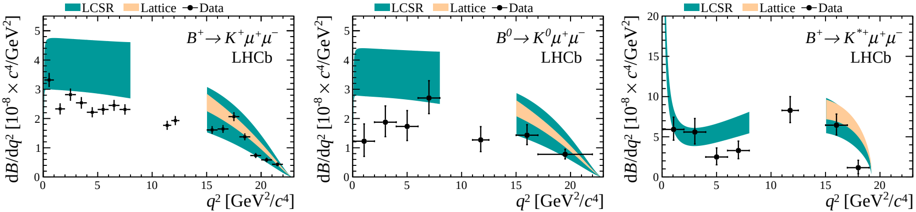
2. **Measurement of the ratio of branching fractions $\frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to \mu^+\mu^-)}$**

3. **Measurements of the angular distributions of $B \to K^{(*)}\mu^+\mu^-$ decays**

All four measurements can be consistently explained through New Physics

1. Differential branching fractions

- Large LHCb datasets allows for precision measurements

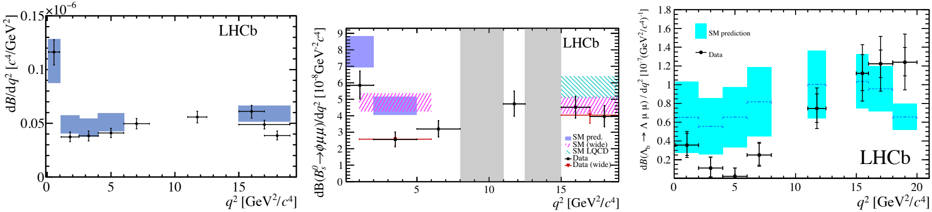


- For $B^+ \to K^+\mu^+\mu^-$, compatible at 2.6σ level with SM

$B^+ \to K^+\mu^+\mu^-$, $B^{\mathbf{0}} \to K^{\mathbf{0}}\mu^+\mu^-$,$B^+ \to K^{*+}\mu^+\mu^-$: [JHEP06(2014)133]
LCSR: Bobeth et al [JHEP07(2011)067]
Lattice: Bouchard et al [1310.3207] missing 2-loop corrections to $C_{\mathbf{9}}^{eff}$,
Horgan et al [PRL112,212003(2014)]

1. Differential branching fractions cont'd

$B^0 \to K^{*0}\mu^+\mu^-$ [1606.04731], $B_s \to \phi\mu^+\mu^-$ [JHEP06(2015)115], $\Lambda_b \to \Lambda\mu^+\mu^-$ [JHEP06(2015)115]



SM: Bharucha et al[1503.05534], Detmold et al [PRD87(2013)074502], LQCD: Horgan et al [PRL112,212003(2014)]

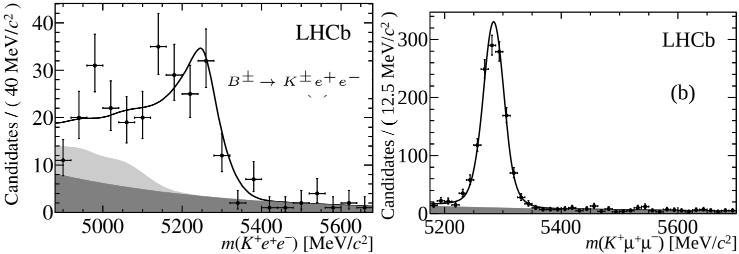
- For $B_s \to \phi\mu^+\mu^-$, bin $1.1 < q^2 < 6.0\text{GeV}^2$ is 3.3σ from SM
- All branching fraction measurements potentially point to new physics in C_9 (e.g new vector Z')

2. Ratios of decay rates

Experimental challenge in: $B \to Ke^+e^-$

- Reduced mass resolution and q^2 migration
- Modelling of part reco backgrounds

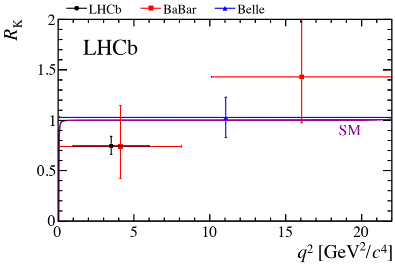
Left: $B \to Ke^+e^-$, Right: $B \to K\mu^+\mu^-$



- Correct for bremsstrahlung by looking for compatible photons in calorimeter
- Correct for q^2 migration from simulation using PHOTOS to model Final State Radiation

2. Ratios of decay rates cont'd

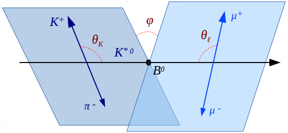
- Measurement of: $R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$ [PRL113(2014)151601]
  - Precise theory prediction due to cancellation of hadronic form factor uncertainties
- Expected to be 1.000 in SM (Higgs contribution m_ℓ suppressed)
- Z' models with enhanced couplings to muons e.g [Altmannshofer et al 1403.1269]
  $\rightarrow$ Destructive interference with SM can lead to $R_K < 1$



- Measure for $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$
  $\rightarrow R_K = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.035(\mathrm{syst})$
- R_K consistent at $\sim 2.6\sigma$

- Consistent with decay rate measurements assuming Z' does not couple to electrons!

3. Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$



- Differential decay rate of $B^0 \to K^{*0}\mu^+\mu^-$ and $\bar{B}^0\bar{K}^{*0}\mu^+\mu^-$:

$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega}) \quad \text{and}$$

$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega}) \ ,$$

- I_i: bilinear combinations of 6 P-wave and 2 S-wave helicity amplitudes (since K^{*0} can be found in $J = 1$ and $J = 0$)
- Reparametrise distribution in terms of:

$$S_i = (I_i + \bar{I}_i) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right) \quad \text{and}$$

$$A_i = (I_i - \bar{I}_i) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right) .$$

- Determine various S_i or A_i by a 3+1D angular $m_{K\pi}$ distribution in bins of q^2

Angular terms

i	I_i	f_i
$1s$	$\frac{3}{4}\left[\lvert\mathcal{A}_\parallel^{\rm L}\rvert^2+\lvert\mathcal{A}_\perp^{\rm L}\rvert^2+\lvert\mathcal{A}_\parallel^{\rm R}\rvert^2+\lvert\mathcal{A}_\perp^{\rm R}\rvert^2\right]$	$\sin^2\theta_K$
$1c$	$\lvert\mathcal{A}_0^{\rm L}\rvert^2+\lvert\mathcal{A}_0^{\rm R}\rvert^2$	$\cos^2\theta_K$
$2s$	$\frac{1}{4}\left[\lvert\mathcal{A}_\parallel^{\rm L}\rvert^2+\lvert\mathcal{A}_\perp^{\rm L}\rvert^2+\lvert\mathcal{A}_\parallel^{\rm R}\rvert^2+\lvert\mathcal{A}_\perp^{\rm R}\rvert^2\right]$	$\sin^2\theta_K\cos 2\theta_l$
$2c$	$-\lvert\mathcal{A}_0^{\rm L}\rvert^2-\lvert\mathcal{A}_0^{\rm R}\rvert^2$	$\cos^2\theta_K\cos 2\theta_l$
3	$\frac{1}{2}\left[\lvert\mathcal{A}_\perp^{\rm L}\rvert^2-\lvert\mathcal{A}_\parallel^{\rm L}\rvert^2+\lvert\mathcal{A}_\perp^{\rm R}\rvert^2-\lvert\mathcal{A}_\parallel^{\rm R}\rvert^2\right]$	$\sin^2\theta_K\sin^2\theta_l\cos 2\phi$
4	$\sqrt{\frac{1}{2}}{\rm Re}(\mathcal{A}_0^{\rm L}\mathcal{A}_\parallel^{\rm L*}+\mathcal{A}_0^{\rm R}\mathcal{A}_\parallel^{\rm R*})$	$\sin 2\theta_K\sin 2\theta_l\cos\phi$
5	$\sqrt{2}{\rm Re}(\mathcal{A}_0^{\rm L}\mathcal{A}_\perp^{\rm L*}-\mathcal{A}_0^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin 2\theta_K\sin\theta_l\cos\phi$
$6s$	$2{\rm Re}(\mathcal{A}_\parallel^{\rm L}\mathcal{A}_\perp^{\rm L*}-\mathcal{A}_\parallel^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin^2\theta_K\cos\theta_l$
7	$\sqrt{2}{\rm Im}(\mathcal{A}_0^{\rm L}\mathcal{A}_\parallel^{\rm L*}-\mathcal{A}_0^{\rm R}\mathcal{A}_\parallel^{\rm R*})$	$\sin 2\theta_K\sin\theta_l\sin\phi$
8	$\sqrt{\frac{1}{2}}{\rm Im}(\mathcal{A}_0^{\rm L}\mathcal{A}_\perp^{\rm L*}+\mathcal{A}_0^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin 2\theta_K\sin 2\theta_l\sin\phi$
9	${\rm Im}(\mathcal{A}_\parallel^{\rm L*}\mathcal{A}_\perp^{\rm L}+\mathcal{A}_\parallel^{\rm R*}\mathcal{A}_\perp^{\rm R})$	$\sin^2\theta_K\sin^2\theta_l\sin 2\phi$

10	$\frac{1}{3}\left[\lvert\mathcal{A}_{\rm S}^{\rm L}\rvert^2+\lvert\mathcal{A}_{\rm S}^{\rm R}\rvert^2\right]$	1
11	$\sqrt{\frac{4}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_0^{\rm L*}+\mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_0^{\rm R*})$	$\cos\theta_K$
12	$-\frac{1}{3}\left[\lvert\mathcal{A}_{\rm S}^{\rm L}\rvert^2+\lvert\mathcal{A}_{\rm S}^{\rm R}\rvert^2\right]$	$\cos 2\theta_l$
13	$-\sqrt{\frac{4}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_0^{\rm L*}+\mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_0^{\rm R*})$	$\cos\theta_K\cos 2\theta_l$
14	$\sqrt{\frac{2}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\parallel^{\rm L*}+\mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\parallel^{\rm R*})$	$\sin\theta_K\sin 2\theta_l\cos\phi$
15	$\sqrt{\frac{8}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\perp^{\rm L*}-\mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin\theta_K\sin\theta_l\cos\phi$
16	$\sqrt{\frac{8}{3}}{\rm Im}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\parallel^{\rm L*}-\mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin\theta_K\sin\theta_l\sin\phi$
17	$\sqrt{\frac{2}{3}}{\rm Im}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\perp^{\rm L*}+\mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin\theta_K\sin 2\theta_l\sin\phi$

Amplitudes I

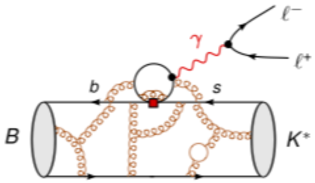
[JHEP 0901(2009)019] Altmannshofer et al.

$$A_\perp^{L(R)} = N\sqrt{2\lambda}\left\{\left[(\mathbf{C_9^{eff}} + \mathbf{C_9'^{eff}}) \mp (\mathbf{C_{10}^{eff}} + \mathbf{C_{10}'^{eff}})\right]\frac{\mathbf{V(q^2)}}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} + \mathbf{C_7'^{eff}})\mathbf{T_1(q^2)}\right\}$$

$$A_\parallel^{L(R)} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9'^{eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}'^{eff}})\right]\frac{\mathbf{A_1(q^2)}}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} - \mathbf{C_7'^{eff}})\mathbf{T_2(q^2)}\right\}$$

$$A_0^{L(R)} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9'^{eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}'^{eff}})\right]\left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})\mathbf{A_1(q^2)} - \lambda\frac{\mathbf{A_2(q^2)}}{m_B + m_{K^*}}\right]\right.$$
$$\left. + 2m_b(\mathbf{C_7^{eff}} - \mathbf{C_7'^{eff}})\left[(m_B^2 + 3m_{K^*} - q^2)\mathbf{T_2(q^2)} - \frac{\lambda}{m_B^2 - m_{K^*}^2}\mathbf{T_3(q^2)}\right]\right\}$$

- $\mathbf{C}_i^{\rm eff}$: Wilson coefficients (including 4-quark operator contributions)
- $\mathbf{A}_i$, $\mathbf{T}_i$ and $\mathbf{V}_i$: 7 $B \to K^*$ form factors



Amplitudes II

- At leading order and for large dimuon masses squared (q^2) below $\sim 6\text{GeV}^2/c^4$, form factors reduce to $\xi_\perp$,$\xi_\parallel$:

$$A_\perp^{L,R} = \sqrt{2}Nm_B(1-\hat{s})\left[(\mathcal{C}_9^{\text{eff}} + \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}'_{10}) + \frac{2\hat{m}_b}{\hat{s}}(\mathcal{C}_7^{\text{eff}} + \mathcal{C}_7^{\text{eff}\prime})\right]\xi_\perp(E_{K^*})$$

$$A_\parallel^{L,R} = -\sqrt{2}Nm_B(1-\hat{s})\left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}'_{10}) + \frac{2\hat{m}_b}{\hat{s}}(\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime})\right]\xi_\perp(E_{K^*})$$

$$A_0^{L,R} = -\frac{Nm_B(1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}}\left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}'_{10}) + 2\hat{m}_b(\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime})\right]\xi_\parallel(E_{K^*})$$

- Can build form factor independent observables using ratios of bilinear amplitude combinations [JHEP 1301(2013)048] Descotes-Genon et al. e.g:

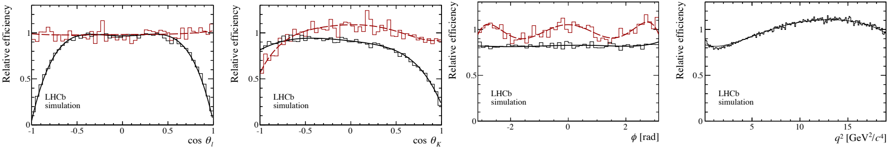
$$P'_5 \sim \frac{Re(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{(|A_0^L|^2+|A_0^R|^2)(|A_\perp^L|^2+|A_\perp^R|^2+|A_\parallel^L|^2+|A_\parallel^R|^2)}}$$

Acceptance correction

- Trigger, reconstruction and selection efficiency distorts the angular and q^2 distribution of $B^0 \to K^{*0}\mu^+\mu^-$
- Acceptance correction parametrised using 4D Legendre polynomials
- Use moment analysis in $B^0 \to K^{*0}\mu^+\mu^-$ MC to obtain coefficients c_{klmn}
- Cross-check acceptance in $B^0 \to J/\psi K^{*0}$

$$\varepsilon(\cos\theta_\ell, \cos\theta_K, \phi, q^2) = \sum_{klmn} c_{klmn} P_k(\cos\theta_\ell) P_l(\cos\theta_K) P_m(\phi) P_n(q^2)$$

1D projections



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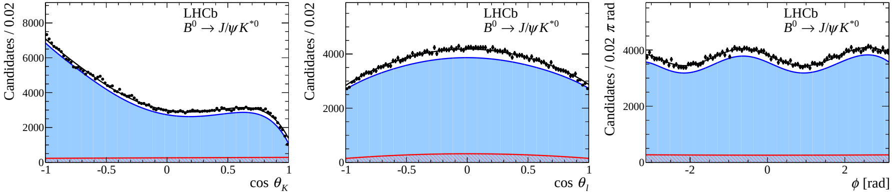
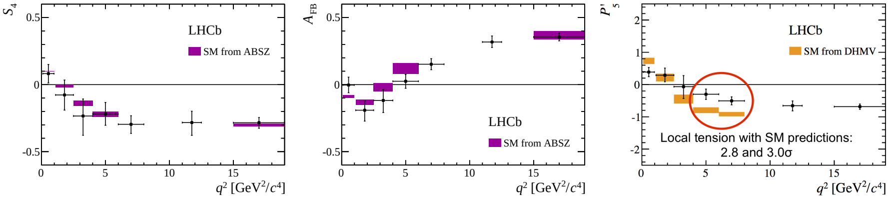


Angular analysis results

- LHCb has performed the first full angular analysis of the decay through a maximum likelihood fit to the data
  $\rightarrow$ Measurement of the full set of CP-averaged and CP-asymmetric angular terms and their correlations

  $\rightarrow$ Also determine the "less form-factor dependent" observables $P_i^{(\prime)}$

[JHEP02(2016)104]

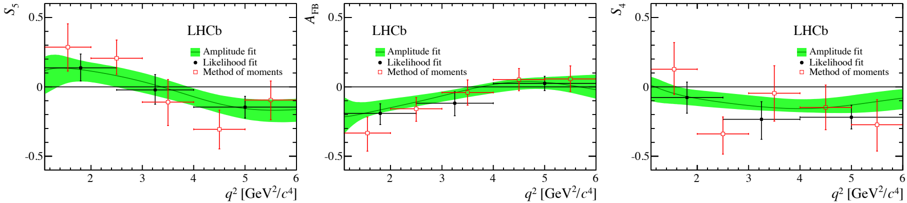


- Also measure all observables using a principal moment analysis of the angular distribution
  - Robust estimator even for small datasets $\rightarrow$ finer q^2 binning
  - Statistically less precise than result of maximum likelihood fit

Zero crossing points

- Determine zero crossing points of S_4, S_5 and $A_{\rm FB}$ by parametrising the angular distribution in terms of q^2 dependent decay amplitudes
- Choose a q^2 ansatz to model the six complex amplitudes:
  $A^{L,R}_{0,\perp,\|} = \alpha_i + \beta_i q^2 + \gamma_i/q^2$ Egede,Patel,KP [JHEP06(2015)084]

[JHEP02(2016)104]



The zero crossing points measured are:

$q_0^2(S_5) \in [2.49, 3.95]{\rm GeV}^2/c^4$ at 68% C.L.

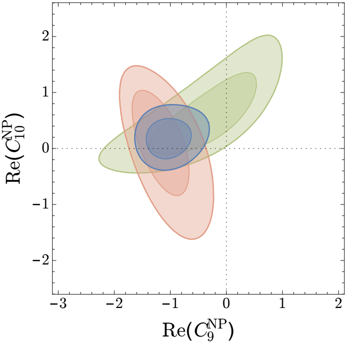
$q_0^2(A_{\rm FB}) \in [3.40, 4.87]{\rm GeV}^2/c^4$ at 68% C.L.

$q_0^2(S_4) < 2.65{\rm GeV}^2/c^4$ at 95% C.L.

Can we form a consistent picture?

Interpretations

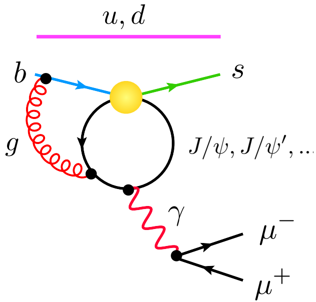
- Several attempts to interpret all our $b \to s\ell^+\ell^- \to$ Two views



Altmannshofer,Straub[1503.06199]

- Modified vector coupling $C_9^{NP} \neq 0$ at $\sim 4.5\sigma$

  $\to$ New vector Z', leptoquarks, vector-like confinement...
  Buttazzo et al [1604.03940], Bauer et al [PRL116,141802(2016)], Crivellin et al [PRL114,151801(2015)], Altmannshofer et al [PRD89(2014)095033]...

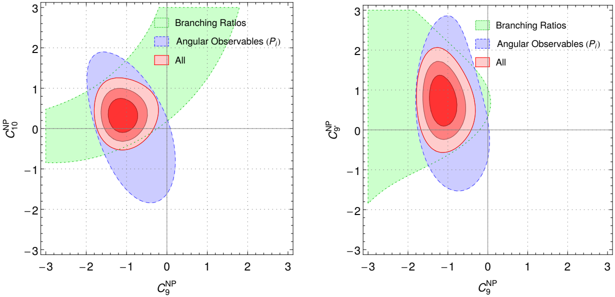


- Potential problem with our understanding of the contribution from $c\bar{c}$ producing dimuon pair
  Lyon,Zwicky [1406.0566], Altmannshofer,Straub[1503.06199], Ciuchini et al [1512.07157]... (more details by Enrico and Jorge)

  $\to$ Mimics vector-like new physics effects

Hint of new physics?

- Global fits to the data, e.g. Matias et al. [1510.04239] including $b \to K^*\gamma$, $b \to s\gamma$, $B \to \mu^+\mu^-$



angular observables, branching fractions, combination

- 3σ contours shown. Tension at the level of $\sim 4.5\sigma$ to the SM. Good description of the data. other theory groups see consistent tensions
- Concrete model: Z' with mass:
  $\sim$ 35 TeV for $\mathcal{O}(1)$ couplings (tree)
  $\sim$ 7 TeV for CKM-like couplings (tree)
  Straub et al [1308.1501]
- Including $b \to see$ data and assuming SM like electron couplings: Tension with SM at 5σ level! yes yes ok... i know you dont believe this... certainly interesting!

New physics concrete model (example)

Single massive vector particle Z' Crivellin et al [PRL114,151801(2015)]

- Explain all $b \to s\ell\ell$ anomalies (including non-universality) and CMS's $h \to \mu\tau$ excess (yeah ok...)

CERN-PH-TH-2015-001
ULB-TH/14-26

Explaining $h \to \mu^{\pm}\tau^{\mp}$, $B \to K^*\mu^+\mu^-$ and $B \to K\mu^+\mu^-/B \to Ke^+e^-$ in a two-Higgs-doublet model with gauged $L_\mu - L_\tau$

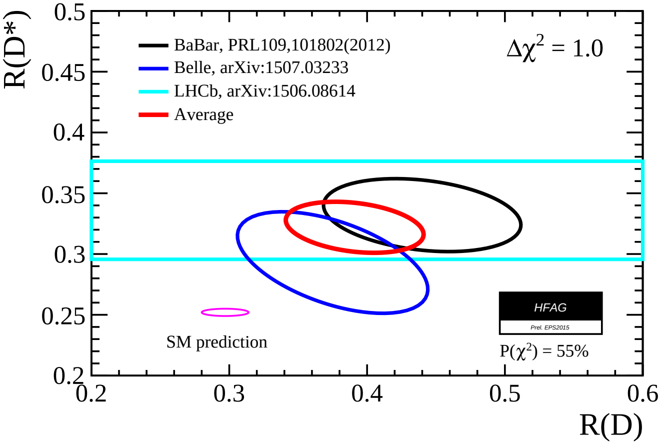
Andreas Crivellin,[1] Giancarlo D'Ambrosio,[1,2] and Julian Heeck[3]

[1]*CERN Theory Division, CH–1211 Geneva 23, Switzerland*
[2]*INFN-Sezione di Napoli, Via Cintia, 80126 Napoli, Italy*
[3]*Service de Physique Théorique, Université Libre de Bruxelles, Boulevard du Triomphe, CP225, 1050 Brussels, Belgium*

The LHC observed so far three deviations from the Standard Model (SM) predictions in flavour observables: LHCb reported anomalies in $B \to K^*\mu^+\mu^-$ and $R(K) = B \to K\mu^+\mu^-/B \to Ke^+e^-$ while CMS found an excess in $h \to \mu\tau$. We show, for the first time, how these deviations from the SM can be explained within a single well-motivated model: a two-Higgs-doublet model with gauged $L_\mu - L_\tau$ symmetry. We find that, despite the constraints from $\tau \to \mu\mu\mu$ and B_s–$\overline{B}_s$ mixing, one can explain $h \to \mu\tau$, $B \to K^*\mu^+\mu^-$ and $R(K)$ simultaneously, obtaining interesting correlations among the observables.

One more thing: $\bar{B}^0 \to D^{*+}\tau\bar{\nu}$ vs $\bar{B}^0 \to D^{*+}\mu\bar{\nu}$

- Test of lepton universality at tree level: $\frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau\bar{\nu})}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu\bar{\nu})}$



- Combination of BaBar, Belle and LHCb: $\sim 4\sigma$ from SM
- Dominant systematic uncertainty: MC template statistics

New physics concrete model (another example)

Leptoquark model Bauer et al [1511.01900]

- Non-universality tensions including muon (g-2) simultaneously explained through introduction of leptoquark sector

MITP/15-100
November 9, 2015

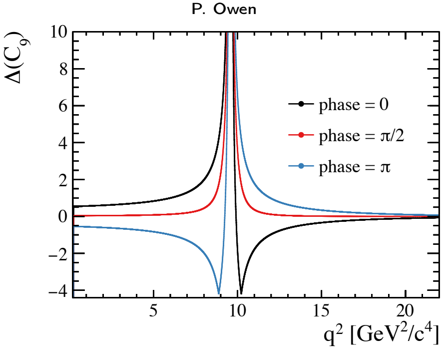
One Leptoquark to Rule Them All:
A Minimal Explanation for $R_{D^{(*)}}$, R_K and $(g-2)_\mu$

Martin Bauer[a] and Matthias Neubert[b,c]
[a] *Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany*
[b] *PRISMA Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany*
[c] *Department of Physics & LEPP, Cornell University, Ithaca, NY 14853, U.S.A.*

We show that by adding a single new scalar particle to the Standard Model, a TeV-scale leptoquark with the quantum numbers of a right-handed down quark, one can explain in a natural way three of the most striking anomalies of particle physics: the violation of lepton universality in $\bar{B} \to \bar{K}\ell^+\ell^-$ decays, the enhanced $\bar{B} \to D^{(*)}\tau\bar{\nu}$ decay rates, and the anomalous magnetic moment of the muon. Constraints from other precision measurements in the flavor sector can be satisfied without fine-tuning. Our model predicts enhanced $\bar{B} \to \bar{K}^{(*)}\nu\bar{\nu}$ decay rates and a new-physics contribution to $B_s - \bar{B}_s$ mixing close to the current central fit value.

QCD effect

- Dependence of observables on vector couplings always enters through $C_9^{eff} = C_9 + Y(q^2)$
  - $\rightarrow Y(q^2)$ summarises contributions from $bs\bar{c}c$ operators
  - $\rightarrow$ Interference between $B \rightarrow K^{(*)}\mu^+\mu^-$ and the tail of $B \rightarrow J/\psi(\mu^+\mu^-)K^{(*)}$

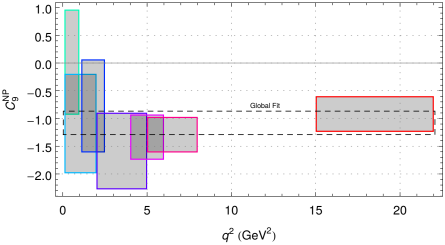


- At low q^2 main culprit is the J/ψ
  - $\rightarrow$ Corrections to C_9^{eff} (ΔC_9) all the way down to $q^2 = 0$
  - $\rightarrow$ **Effect strongly dependent on relative phase with penguin**

QCD effect cont'd

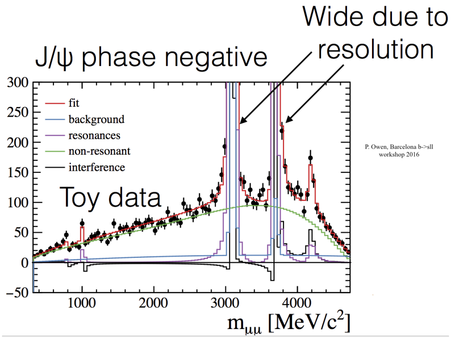
- If C_9 is related to a problem in our understanding of QCD then it should exhibit a q^2 dependence.
- It should be largest closest to the J/ψ.
- More data will help resolve apparent q^2 dependence of C_9

- **Note: Even if it is not new physics, it would be something new in QCD to understand!**
- We plan dedicated measurements to dissentangle we are working on it ok?...



Measuring phase differences

- Measure relative phase between narrow resonances and penguin amplitudes
  $\rightarrow$ Model resonances as relativistic BWs multiplied by relative scale and phase Lyon et al. [1406.0566], Hiller et al. [1606.00775]
  $\rightarrow$ Use this model to replace $Y(q^2)$ in $C_9^{eff} = Y(q^2) + C_9$
  $\rightarrow$ $B \rightarrow K$ form factors constrained to LCSR+Lattice predictions
  $\rightarrow$ Fit for phases and C_9 and C_{10}



- Fit dimuon spectrum in $B^+ \rightarrow K^+\mu^+\mu^-$
  $\rightarrow$ Expect precision of phase ~ 0.1 rad (ambiguities over sign of phase)[Owen Barcelona workshop 2016]
- In final stages of review

Conclusions

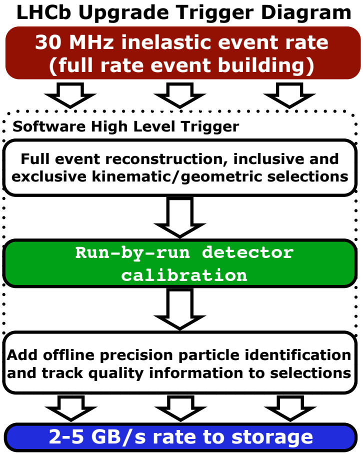
- Intriguing set of measurements of electroweak penguin decays at LHCb
- Combination of measurements results in tensions with the SM at level $\sim 4.5\sigma$
  - Can be explained through extensions to the SM
  - Can be attributed to large unexpected experimental or theory effects
  - More tests underway
- Run2 quadrupules our dataset $\rightarrow$ major benefit as all measurements statistically limited and theory precision is better than experimental
- Larger yields means we can start comparing $b \rightarrow s\ell\ell$ with $b \rightarrow d\ell\ell$ at test Minimal Flavour Violation hypothesis of potential new physics

As LHC pushes energy scale of new physics $\gg$1TeV, Minimal Flavour Violation constraints get lifted $\rightarrow$ Increase chances to see NP in flavour

Backup

Upgrade Trigger

The problem: saturation of L0 Hadronic trigger rate on hadronic decays at $> 4 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$



LHCb upgrade

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\,A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	$\sim 10\,\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–12° [19, 20]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

The LHCb upgrade

- If cracks in the SM persist in Run 2, the LHCb upgrade will allow for precision measurements of the flavour structure of New Physics
- Otherwise, LHCb upgrade will probe NP at multi-TeV energy scale
- General purpose forward experiment: Complementary non-flavour programme to ATLAS and CMS

Run 1 (2010-2012)	2012-2015	Run 2 (2015-2018)	2018-2021	Run 3 (2021-2023)	2023-2025	Run 4 (2025-2028)	2028-2030	Run 5 (2030+)
$3fb^{-1}$	Shutdown	$\sim 5fb^{-1}$	Shutdown	$\sim 23fb^{-1}$	Shutdown	$\sim 46fb^{-1}$	Shutdown	$\sim 100fb^{-1}$
LHCb			LHCb upgrade				LHCb upgrade++	

2017-2024 Belle-II ($50ab^{-1}$)

The problem:

- Current conditions: up to $L_{inst} = 4 \times 10^{32} cm^{-2} s^{-1}$, $\mu \sim 1.7$
- 2020 conditions: $L_{inst} = 2 \times 10^{33} cm^{-2} s^{-1}$, $\mu \sim 5$

Higher luminosities:

- More interactions per crossing, more vertices, higher track multiplicities, more ghost tracks...

The LHCb upgrade cont'd

The solution:

- More flexible trigger, reading out full detector at 40 MHz and HLT output between 20 and 100 kHz

LHCb UK

→ VELO upgrade:

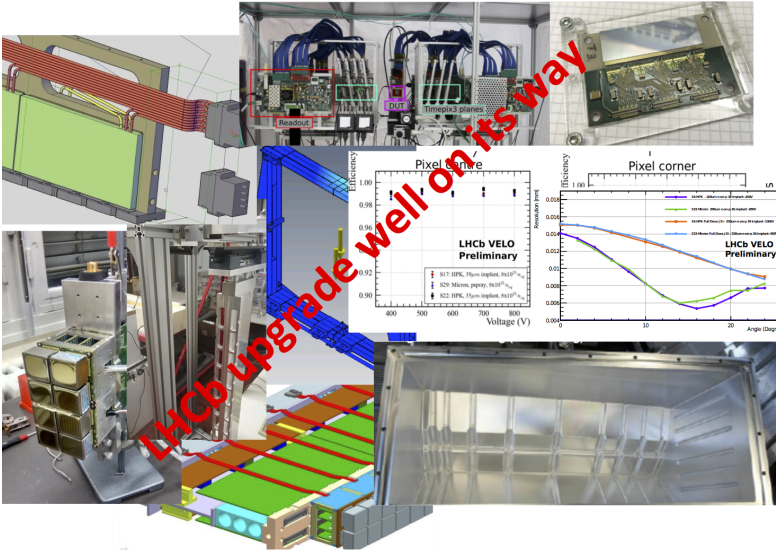
- ▷ Silicon microstrips → Pixel sensors
- ▷ 40MHz readout
- ▷ Closer to the beam (8mm→5mm)
- ▷ Microchannel cooling and RF foil

→ RICH upgrade:

- ▷ Replace HPDs with MaPMTs in RICH1,2
- ▷ 40MHz readout
- ▷ Upgrade photodetector assembly in RICH1,2
- ▷ Complete redesign of RICH1 mechanical structure to reoptimise optics and easier access

→ Major upgrades to tracking as well

[LHCb-TDR-013], [LHCb-TDR-014], [LHCb-TDR-015],[LHCb-TDR-016]



Phase 1 upgrade of LHCb firmly established

→ Momentum building for developing a detector for Run4,5...

→ Theatre of Dreams Beyond the LHCb Phase 1 upgrade: 6-7 April Manchester [link]