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

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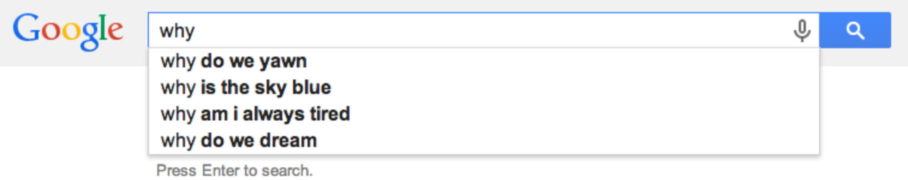
Overview

- A brief introduction to heavy flavour
- Electro-Weak penguin processes
- How and what do we measure
- LHCb results and implications
- Outlook

Important questions


why

why do we yawn

why is the sky blue

why am i always tired

why do we dream

- 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 top-quarks, beauty and charm hadrons can shed some light

Higgs and flavour

Two sides of the same coin

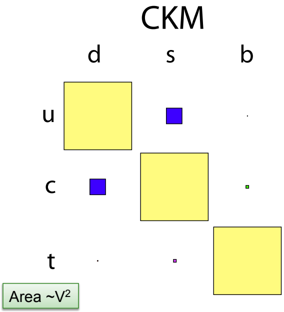
- Yukawa couplings ($Y^{U,D}$) of quarks to Higgs field:
  $\mathcal{L}_Y = \bar{u}_{Ri} Y^U_{ij} \phi^{c\dagger} Q_{Lj} + \bar{d}_{Ri} Y^D_{ij} \phi Q_{Lj}$
- $Y^{U,D}$ matrix in 3 quark generations is not necessarily diagonal

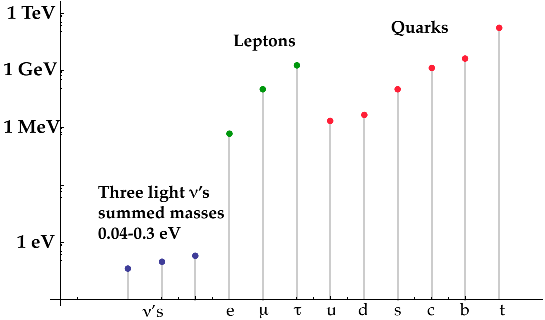
- Transformation of u, d, Q to mass eigenstates:
  - Diagonalises $M^U = V_{u_R} Y^U V^\dagger_{u_L}$ and $M^D = V_{d_R} Y^D V^\dagger_{d_L}$
- W couplings become non-diagonal:
  $W^+_\mu \bar{u}_L \gamma^\mu d_L \rightarrow W^+_\mu \bar{u}_L V^\dagger_{u_L} V_{d_L} \gamma^\mu d_L$ ($V_{CKM} = V^\dagger_{u_L}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

- In SM, Z,γ couplings remain diagonal! → 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

CKM and masses

CKM matrix is a cornerstone of our understanding of particle physics



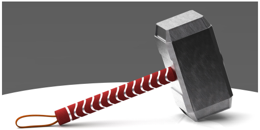


- One complex phase accounts for CPV in SM ($\mathcal{O}(10^{10})$ too small)
- Do not understand relative sizes of the values ($|V_{ub}| = \mathcal{O}(10^{-3})|V_{tb}|$)
- Pattern of masses similarly puzzling ($m_u = \mathcal{O}(10^{-3})m_t$)

Experimental approaches

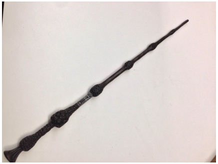
SM could be a low-energy effective theory of a more fundamental theory at higher energy scale with new particles, dynamics/symmetries.

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

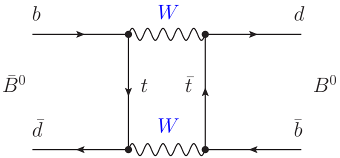
Interplay of direct and indirect measurements

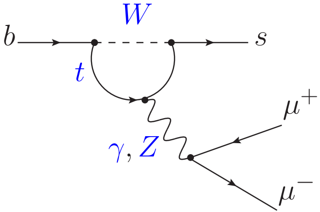
Flavour physics has played central role in the development of the SM

- *c*-quark inferred from measurement showing suppression of $K^0 \rightarrow \mu^+\mu^-$ rate compared to $K \rightarrow \mu\nu$ (GlM 1970)
  - ▷ Discovery of J/ψ in 1974 (SLAC, BNL)
- *t*,*b*-quarks inferred from CP violation in K sector (KM of CKM 1973)
- 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

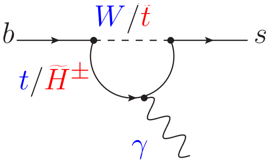
Heavy flavour production

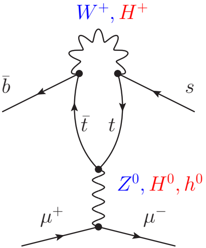
Experiment	Belle/BaBar	TeVatron	LHC
Process	$e^+e^- \to \Upsilon(4s) \to B\bar{B}$	$p\bar{p} \to b\bar{b}X(\sqrt{s} = 2\,\text{TeV})$	$pp \to b\bar{b}X(\sqrt{s} = 8\,\text{TeV}\ )$
σ_{tot}	$1 \times 10^{-3}\,\mu$b	$\sim 100\,\mu$b	$\sim 320\,\mu$b
Lumi/exp.	$\sim 500\,\text{fb}^{-1}$	$\sim$10 fb^{-1}	5-25 fb^{-1}
pile-up	0	1.7	0.5-20
B content	$B^+B^-(50\%)$, $B^0\bar{B}^0(50\%)$	$B^0(40\%)$, $B^+(40\%)$, $B_s^0(10\%)$, b-baryon (10%), $B_c(< 1\%)$	
B boost	small	large, decay vertices are displaced	
B_{tag}^{Q}	$\mathcal{O}(10\%)$	$\mathcal{O}(1\%)$	
$B^0\bar{B}^0$ mixing	coherent	incoherent→flavour tagging dilution	

- Prolific charm production at hadron machines ($\sigma_{c\bar{c}} \sim 20 \times \sigma_{b\bar{b}}$ @LHC)

Electroweak penguin processes

- $b \to s$ FCNC transitions are suppresed in SM
- Only occur via loop or box processes
- First $b \to s$ transition observed in $B^0 \to K^{*0}\gamma$ decays by CLEO in 1993
  - Expected $\mathcal{B} = (2-4) \times 10^{-5}$
  - Measured $(4.5 \pm 1.7) \times 10^{-5}$ → stringent constraints on parameter space of new physics
  - Current average $(4.34 \pm 0.15) \times 10^{-5}$





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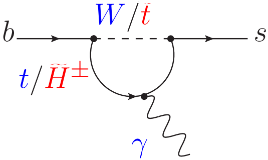
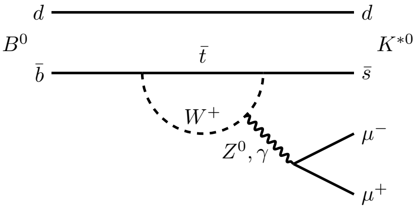


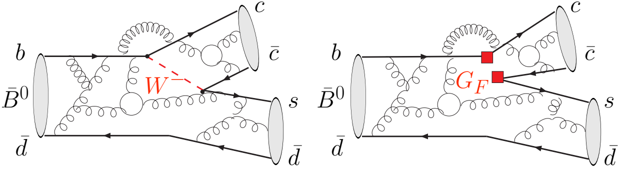


Theoretical Formalism

- 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

$$\mathcal{H}_{eff} \approx -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{ts(d)} \sum_{i=1}^{10,S,P,T} (C_i^{SM} + \Delta C_i^{NP}) \mathcal{O}_i$$

- c.f. Fermi interaction and G_F



- New physics enters at the Λ_{NP} scale

Sensitivity to New Physics

- $b \to s(d)\mu^+\mu^-$ transitions probe a range of operators

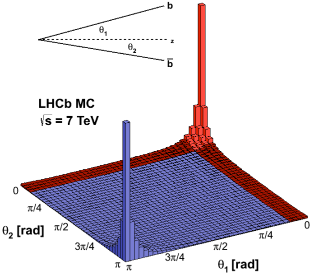
Operator $\mathcal{O}_i$	$B_{s(d)} \to X_{s(d)}\mu^+\mu^-$	$B_{s(d)} \to \mu^+\mu^-$	$B_{s(d)} \to X_{s(d)}\gamma$
$\mathcal{O}_7 \sim m_b(\bar{s}_L\sigma^{\mu\nu}b_R)F_{\mu\nu}$	✓		✓
$\mathcal{O}_9 \sim (\bar{s}_L\gamma^{\mu}b_L)(\bar{\ell}\gamma_{\mu}\ell)$	✓		
$\mathcal{O}_{10} \sim (\bar{s}_L\gamma^{\mu}b_L)(\bar{\ell}\gamma_5\gamma_{\mu}\ell)$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

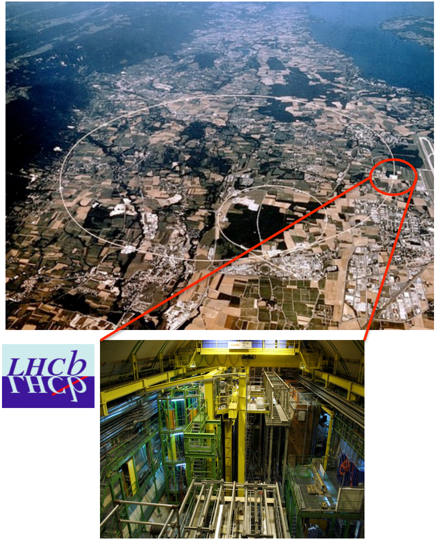
- In SM $C_{S,P} \propto m_\ell m_b/m_W^2$
- In SM chirality flipped $\mathcal{O}_i$ suppressed by m_s/m_b

Setting the scene

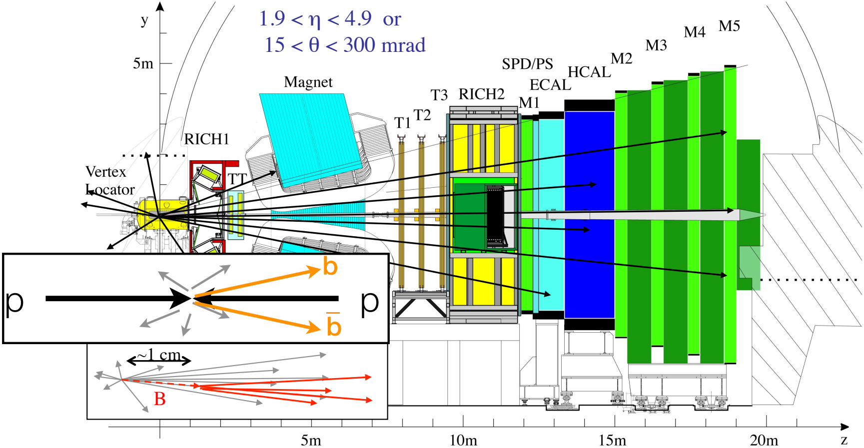
- LHC $\sigma_{b\bar{b}} = 280\,\mu\text{b}$ @ $\sqrt{s} = 7$ TeV (scale $\sim$ linear with $\sqrt{s}$)

- $\sigma_{b\bar{b}}$ in LHCb acceptance $\sim 76\,\mu\text{b}$
  - c.f $\sigma_{b\bar{b}} = 0.001\,\mu\text{b}$ @ B-factories



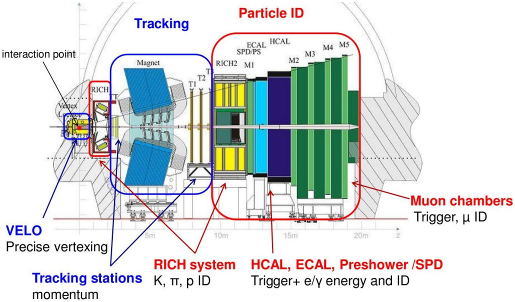


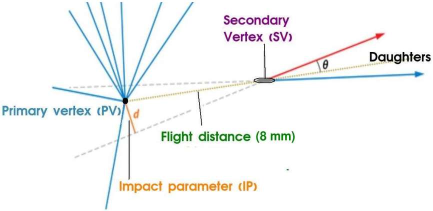
The LHCb detector



- B-lifetime means displaced secondary vertex
- Operate at inst. luminosity 10-50 times lower than central detectors

Detector performance





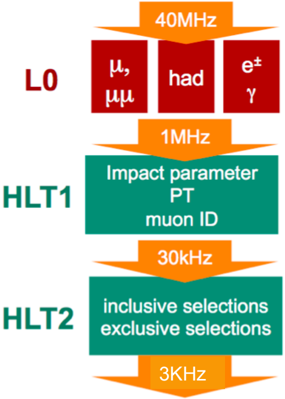
- **VeLo** $\sigma_{IP}^{trk} \sim 20\,\mu\text{m}$ for $p_T^{trk} > 2\,\text{GeV}$
- **Tracking** $\delta p/p = 0.4 - 0.6\%$
- **RICH** $\epsilon_K^{id} = 95\%$ for 5% mis-id
- **Muon** $\epsilon_\mu^{id} = 98\%$ for 1% mis-id

- 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-I

The challenge

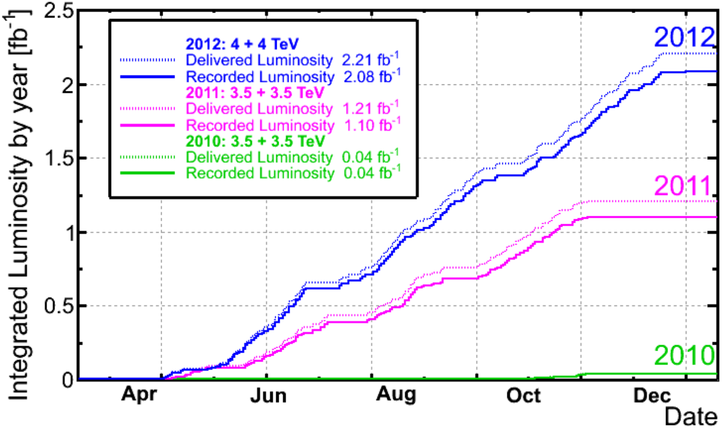
- Only 1 in 200 pp inelastic events contain a *b*-quark
- Looking for *B*-hadron decays with $BR \sim 10^{-6} - 10^{-9}$



- L0 (Hardware): high p_T signals in calorimeter and muon systems
- HLT1 (Software): Partial reco/selection on one or two displaced tracks/muon ID
- HLT2 (Software): Global reco (close to offline), mostly for inclusive signatures using MVA

	Charm	Hadronic *B*	Leptonic *B*
Efficiency	$\sim 10\%$	$\sim 40\%$	$\sim 75 - 90\%$

LHCb dataset

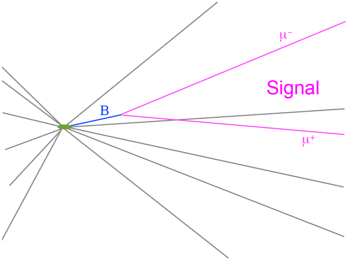


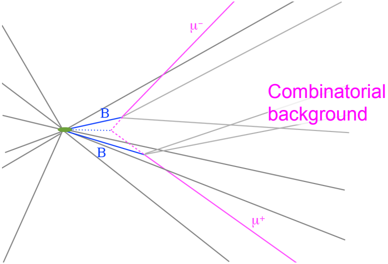
- Total of $3\,\mathrm{fb}^{-1}$ at instantaneous luminosities of up to $4 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (double the design value!)
- Inclusion of Run-II data will quadruple current dataset

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:

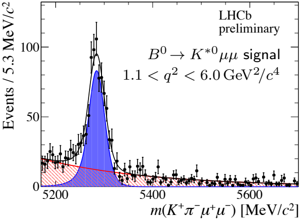
- Make use of proxy-decay (same topology) of known $\mathcal{B}$ to normalize against

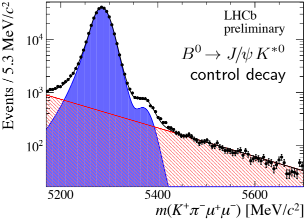
$$\mathcal{B}(sig) = \frac{N_{sig}\epsilon_{sig}}{N_{prx}\epsilon_{prx}}\mathcal{B}(prx)$$

  - ▷ 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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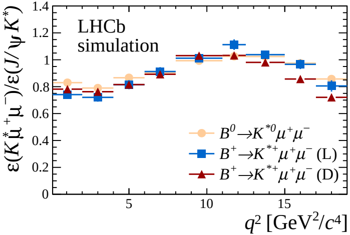

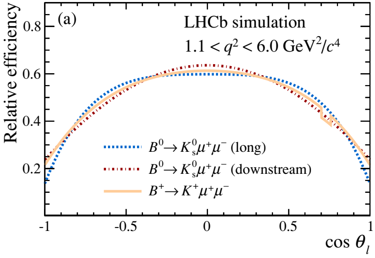

An intriguing set of results

1. Measurements of decay rates of $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$
   $\to$ Large theory uncertainties. But lattice calculations provide precision at large dimuon masses squared (q^2)

2. Measurements of ratios of decay rates of $B \to K^{(*)}\ell^+\ell^-$
   $\to$ Cancellations of hadronic form-factor uncertainties in predictions

3. Angular analyses of $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$
   $\to$ Can access observables with reduced dependence on theory uncertainties

[1]

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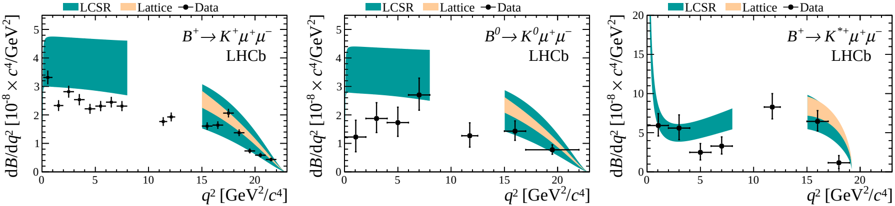
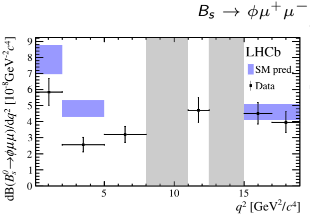
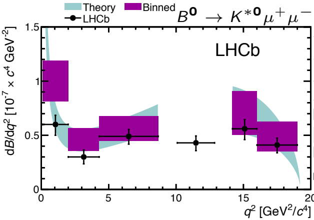
[1] No time to discuss CP and Isospin asymmetry measurements, latest $\Lambda_b \to \Lambda\mu\mu$, $B \to K^* e^+ e^-$, $B_s \to \phi\mu\mu$ $B^{+,0} \to K^{+,0}\mu^+\mu^-$ angular analyses, $B \to \pi\pi\mu\mu$ BFs

1. Decay rate measurements

- Large LHCb datasets allows for precision measurements
- Results hint towards lower rates than predicted
  $\rightarrow$ Could be explained with new physics in C_9 e.g Z'



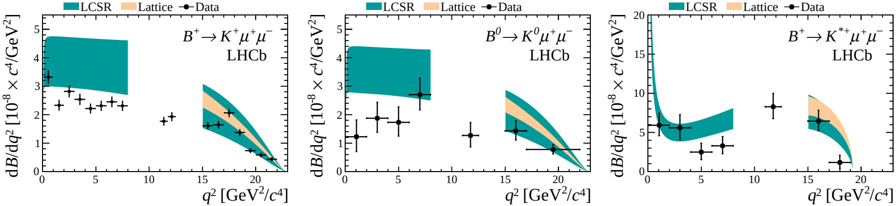


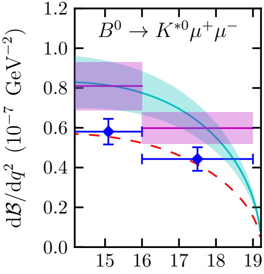


$B^0 \rightarrow K^{*0}\mu^+\mu^-$: [JHEP08(2013)131]
$B_s \rightarrow \phi\mu^+\mu^-$: [JHEP07(2013)084]
$B^+ \rightarrow K^+\mu^+\mu^-$, $B^0 \rightarrow K^0\mu^+\mu^-$,
$B^+ \rightarrow K^{*+}\mu^+\mu^-$: [JHEP06(2014)133]
LCSR: Bobeth et al. [1111.2558],
[JHEP07(2011)067]
Lattice: Bouchard et al. [1310.3207]
missing 2-loop corrections to C_9^{eff}

1. Decay rate measurements

- Large LHCb datasets allows for precision measurements
- Precision from lattice also confirms this





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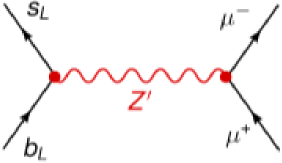
Lattice: Horgan et al.
[PRL112,212003(2014)]

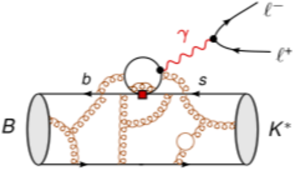
First interpretation

Optimistic



- Vector-like contribution could come from new tree level contribution from a Z' with mass of $\mathcal{O}(10)$ TeV.

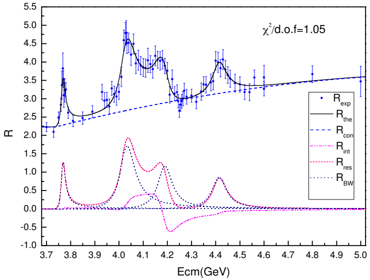
Pessimistic



- Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon.

BES-II R-ratio interlude

$$R(q^2) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

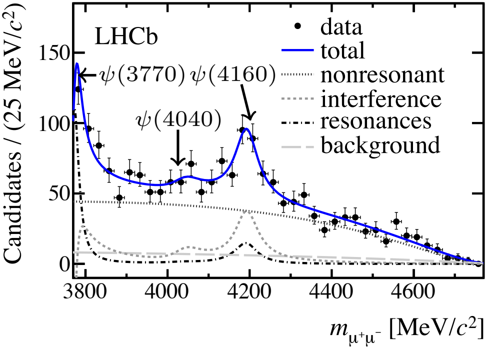


Resonance	Mass [MeV/c^2]	Width [MeV]
$\psi(3770)$	3773.2 ± 0.3	27.2 ± 1.0
$\psi(4040)$	4039.6 ± 4.3	84.5 ± 12.3
$\psi(4160)$	4191.7 ± 6.5	71.8 ± 12.3
$\psi(4415)$	4415.1 ± 7.9	71.5 ± 19.0

- Charmonium resonances 1^{--} above open charm (DD) threshold from BES
- Fits account for interference between states
- Watch out. PDG information is misleading!

What can $c\bar{c}$ say about this?

- For the first time $c\bar{c}$ resonances observed in high q^2 region of $B^+ \to K^+\mu^+\mu^-$ using full RunI data [PRL 111,112003 (2013)]

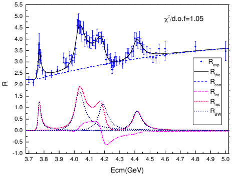


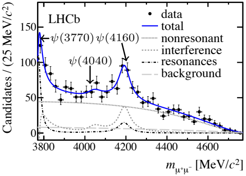
- Resonant contribution (including interference) at high q^2 amounts to $\sim 20\%$ of the $B^+ \to K^+\mu^+\mu^-$ rate in that region [PRL 111,112003 (2013)]
- $\mathcal{B}(B^+ \to K^+\psi_{4160}(\mu^+\mu^-)) = 3.9^{+0.7}_{-0.6} \times 10^{-9}$!
- Sensitive due to interference with large non-resonant component!
- How does this fit in with QCD treatment of high q^2?

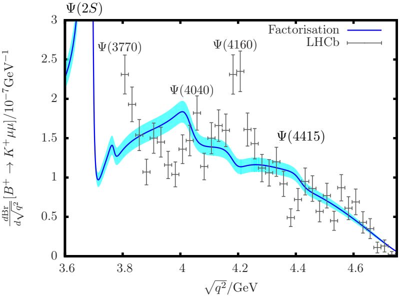
The repulsive charm

- Assuming factorisation of the hadronic and dimuon systems, can predict resonant contribution by simultaneously fitting $e^+e^- \rightarrow$hadron data from BESII and $B^+ \rightarrow K^+\mu^+\mu^-$ from LHCb [Lyon, Zwicky 1406.0566]

$$R(q^2) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$







- Require 350% correction on factorisation assumption to describe LHCb data

  Require large fudge factor (→ $C_{1,2}$ terms in C_9^{eff})

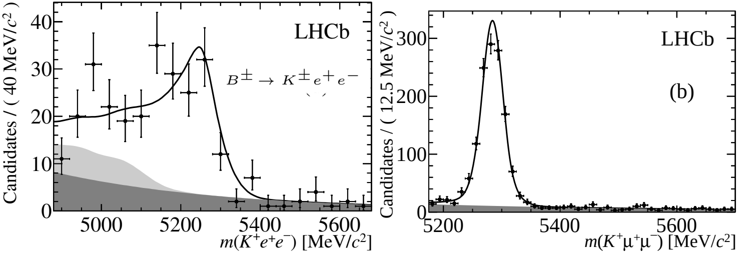
  → Could in priniple affect measurements below the J/ψ and "mimic" new physics in C_9
- R_K measurement however independent of this

$B^+ \to K^+e^+e^-$

Experimental challenge:

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

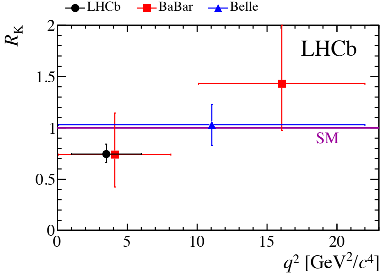
Left: $B \to Ke^+e^-$, Right: $B \to K\mu^+\mu^-$



- Correct for bremsstrahlung by looking for compatible photons in calorimeter
- Correct for q^2 migration from simulation
- Determine part-reco from combination of data and MC

2. Ratios of decay rates

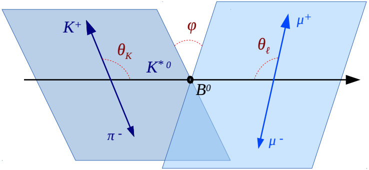
- Recent measurement of: $R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$ [1406.6482 accepted by PRL]
  - Precise theory prediction due to cancellation of hadronic form factor uncertainties
- Expected to be 1.000 in SM (Higgs contribution m_ℓ suppressed)
- Z' models with 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

$B^0 \to K^{*0}\mu^+\mu^-$



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

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

- Assuming only P-wave $K\pi$ system (see later)
- Ignoring scalar contributions and lepton masses:
- S_i terms depend on K^* spin amplitudes $A_0^{L,R}$,$A_\parallel^{L,R}$,$A_\perp^{L,R}$

Angular terms

$$
\begin{aligned}
J_{1s} &= \frac{(2+\beta_\ell^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2\right] + \frac{4m_\ell^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R^*} + A_\parallel^L A_\parallel^{R^*}\right)\,,\\
J_{1c} &= |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\ell^2}{q^2}\left[|A_t|^2 + 2\mathrm{Re}(A_0^L A_0^{R^*})\right] + \beta_\ell^2\,|A_S|^2\,,\\
J_{2s} &= \frac{\beta_\ell^2}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2\right], \qquad J_{2c} = -\beta_\ell^2\left[|A_0^L|^2 + |A_0^R|^2\right]\,,\\
J_3 &= \frac{1}{2}\beta_\ell^2\left[|A_\perp^L|^2 - |A_\parallel^L|^2 + |A_\perp^R|^2 - |A_\parallel^R|^2\right], \qquad J_4 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Re}(A_0^L A_\parallel^{L^*} + A_0^R A_\parallel^{R^*})\right],\\
J_5 &= \sqrt{2}\beta_\ell\left[\mathrm{Re}(A_0^L A_\perp^{L^*} - A_0^R A_\perp^{R^*}) - \frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_\parallel^L A_S^* + A_\parallel^{R^*} A_S)\right],\\
J_{6s} &= 2\beta_\ell\left[\mathrm{Re}(A_\parallel^L A_\perp^{L^*} - A_\parallel^R A_\perp^{R^*})\right]\,, \qquad J_{6c} = 4\beta_\ell\frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_0^L A_S^* + A_0^{R^*} A_S)\,,\\
J_7 &= \sqrt{2}\beta_\ell\left[\mathrm{Im}(A_0^L A_\parallel^{L^*} - A_0^R A_\parallel^{R^*}) + \frac{m_\ell}{\sqrt{q^2}}\mathrm{Im}(A_\perp^L A_S^* - A_\perp^{R^*} A_S))\right],\\
J_8 &= \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Im}(A_0^L A_\perp^{L^*} + A_0^R A_\perp^{R^*})\right]\,, \qquad J_9 = \beta_\ell^2\left[\mathrm{Im}(A_\parallel^{L^*} A_\perp^L + A_\parallel^{R^*} A_\perp^R)\right]\,, \quad (3)
\end{aligned}
$$

Amplitudes I

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

$$\begin{aligned}
A_\perp^{L(R)} &= N\sqrt{2\lambda}\left\{\left[(\mathbf{C_9^{eff}} + \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} + \mathbf{C_{10}^{\prime eff}})\right]\frac{\mathbf{V(q^2)}}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} + \mathbf{C_7^{\prime eff}})\mathbf{T_1(q^2)}\right\} \\
A_\parallel^{L(R)} &= -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}})\right]\frac{\mathbf{A_1(q^2)}}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} - \mathbf{C_7^{\prime eff}})\mathbf{T_2(q^2)}\right\} \\
A_0^{L(R)} &= -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}})\right]\left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})\mathbf{A_1(q^2)} - \lambda\frac{\mathbf{A_2(q^2)}}{m_B + m_{K^*}}\right]\right. \\
&\qquad \left. + 2m_b(\mathbf{C_7^{eff}} - \mathbf{C_7^{\prime eff}})\left[(m_B^2 + 3m_{K^*} - q^2)\mathbf{T_2(q^2)} - \frac{\lambda}{m_B^2 - m_{K^*}^2}\mathbf{T_3(q^2)}\right]\right\} \\
A_t &= \frac{N}{\sqrt{q^2}}\sqrt{\lambda}\left\{2(\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}}) + \frac{q^2}{m_\mu}(\mathbf{C_P^{eff}} - \mathbf{C_P^{\prime eff}})\right\}\mathbf{A_0(q^2)} \\
A_S &= -2N\sqrt{\lambda}(\mathbf{C_S} - \mathbf{C_S})\mathbf{A_0(q^2)}
\end{aligned}$$

- $\mathbf{C_i^{eff}}$ are the Wilson coefficients (including 4-quark operator contributions)
- $\mathbf{A_i}$, $\mathbf{T_i}$ and $\mathbf{V_i}$, are form factors typically treated as nuisance parameters

Amplitudes II

- At leading order and for large $E_{K^*} >> \Lambda_{QCD}$ (large recoil), form factors reduce to $\xi_\perp$,$\xi_\parallel$:

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

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

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

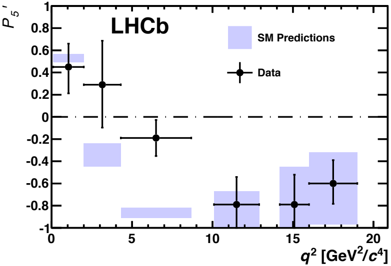
- Can build form factor independent observables using ratios of bilinear amplitude combinations [JHEP 1301(2013)048] Descotes-Genon et al. e.g:

$$P_5^\prime \sim \frac{Re(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{(|A_0^L|^2 + |A_0^R|^2)(|A_\perp^L|^2 + |A_\perp^R|^2 + |A_\parallel^L|^2 + |A_\parallel^R|^2)}}$$

Experimental aspects of 1 fb^{-1} result

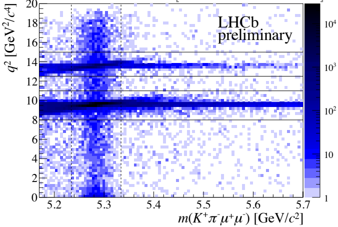
- Previous analysis [JHEP 08(2013)131] extracted all observables from separate fits to the data (by transforming the angular distribution)
  - Cannot trivially correlate experimental uncertainties
- Low stats meant:
  - Large bins in q^2 degrading sensitivity to NP
  - S-wave contribution to $K\pi$ system ignored and systematic uncertainty added
- Acceptance correction assumed to factorise in the 3 angles

- $P'_{4,5,6,8} \propto (S_{4,5,7,8})/\sqrt{F_L(1-F_L)}$
- $1\,\mathrm{fb}^{-1}$ of 2011 data
- 3.7σ tension in P'_5
- 0.5% probability to see a deviation assuming 24 independent measurements

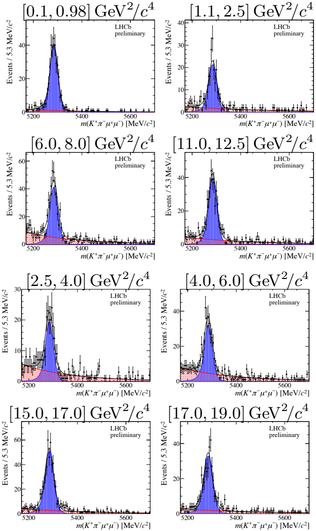


Latest $B^0 \to K^{*0}\mu^+\mu^-$ analysis

[LHCb-CONF-2015-002]



- Observe ∼2400 signal candidates.
- Finer q^2 binning that 1 fb^{-1} result
- $m_{K\pi\mu\mu}$ lineshape obtained from control channel and corrected for q^2 dependence from simulation



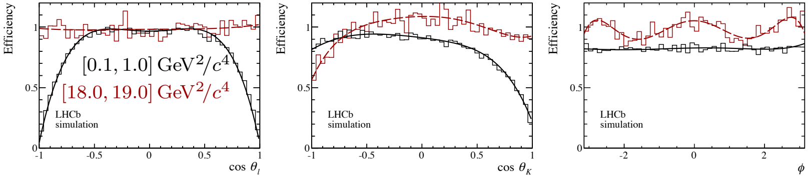
Improvements since last round

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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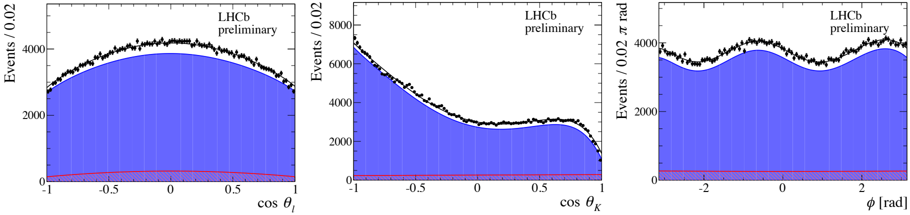


Improvements since last round

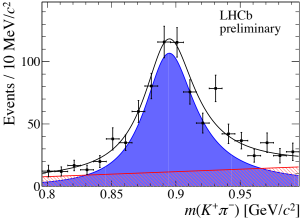
S-wave in $K\pi$ system

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Big|_{\mathrm{S+P}} = (1-F_{\mathrm{S}})\,\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Big|_{\mathrm{P}} + \frac{3}{16\pi}F_{\mathrm{S}}\sin^2\theta_\ell + \text{S-P interference}$$

- $K\pi$ system not from K^{*0} also exists in spin-0 configuration (S-wave) introducing two additional decay amplitudes and 6 additional observables
- S-wave fraction F_s scales P-wave observables
- Precise determination required

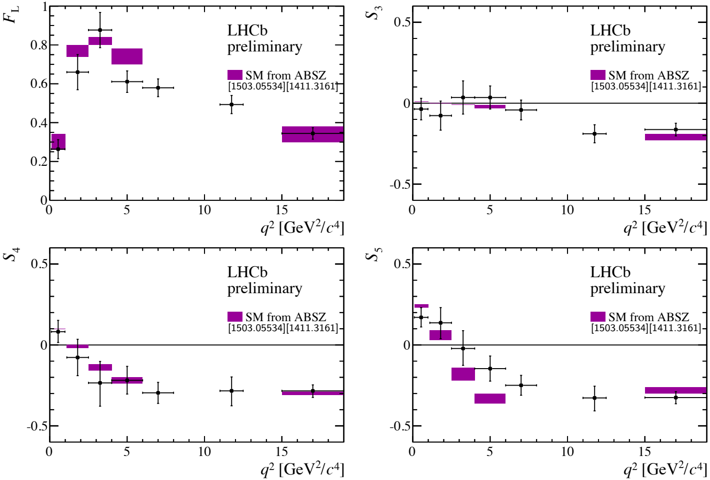
  → Perform simultaneous fit to $m_{K\pi}$

- S-wave described by LASS model and P-wave with relativistic BW
  - Isobar for S-wave used as x-check



Results

- Unbinned maximum likelihood fit to 3 decay angles, $m_{K\pi\mu\mu}$ in q^2 bins, simultaneously fitting to $m_{K\pi}$ (4D+1D) to extract 8 CP-averaged observables and correlations!
- Measurement is statistically dominated



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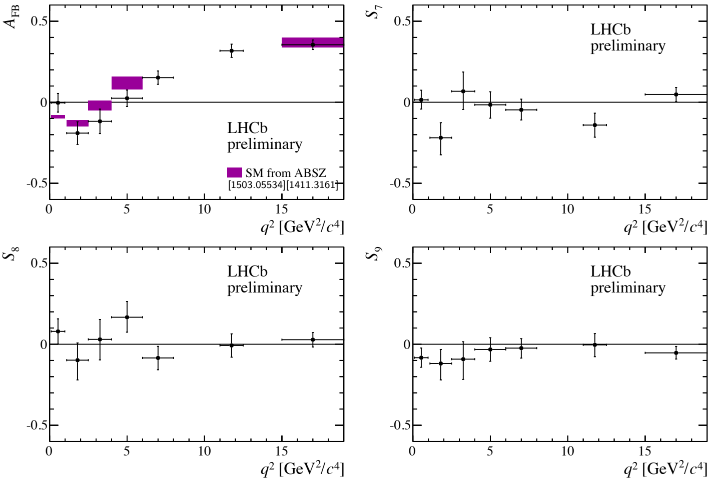

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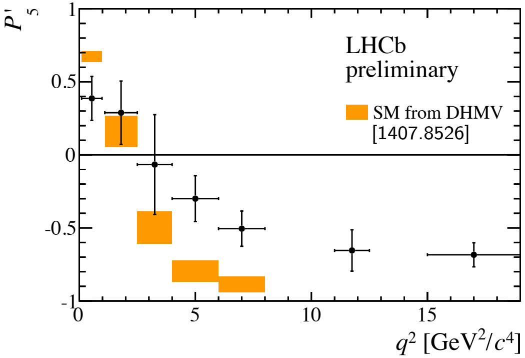
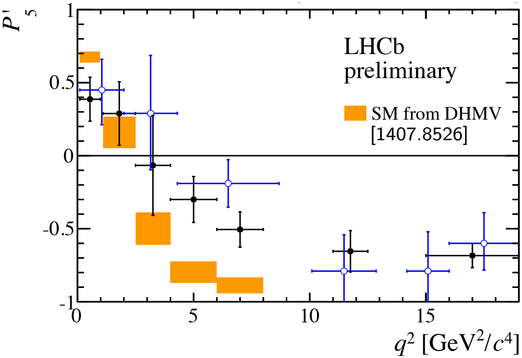


- Tension in P'_5 presists
- Level of disagreement: 2.9σ in [4,6] and [6,8] q^2 bins
- Naive combination 3.7σ (not a typo...)
- Compatible with 1 fb^{-1} measurement

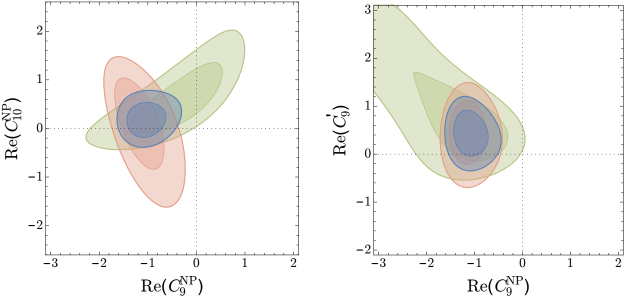
Results



- Tension in P_5' presists
- Level of disagreement: 2.9σ in [4,6] and [6,8] q^2 bins
- Naive combination 3.7σ (not a typo...)
- Compatible with 1 fb^{-1} measurement

Hint of new physics?

- Latest global fits to the data, e.g. Altmannshofer et al. [arXiv:1503.06199] including $b \to K^*\gamma$, $b \to s\gamma$, $B \to \mu^+\mu^-$



angular observables, branching fractions, combination

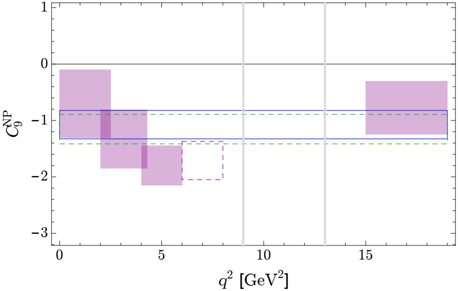
- Data favours a new vector current ($C_9^{\mathrm{NP}} \neq 0$).
- Numerous other theory papers: Descotes-Genon et al [1307.5683], Beaujean et al [1310.2478], Gauld et al [1308.1959], Hurth et al [1312.5267], Straub et al [1308.1501], Horgan et al [1310.3887],Altmannshofer et al [1403.1269], Biancofiore et al [1403.2944]...
- Consistent with Z' of mass:
  $\sim$ 35 TeV for $\mathcal{O}(1)$ couplings (tree)
  $\sim$ 7 TeV for CKM-like couplings (tree)
  Straub et al [1308.1501]
- Difficult to accomodate within MSSM

Hint of new physics?

Could it be a QCD effect?

- If C_9^{NP} 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.
- Our data can help clarify the situation

- **Note: Even if it is not new physics, it would be something new in QCD to understand!**
- We plan dedicated measurements to dissentangle



So what is next

Full exploitation of available data:

- Have two additional ways of analysing the angular distribution of $B^0 \to K^{*0}\mu^+\mu^-$
- Directly fitting for q^2 dependent helicity amplitudes, maximising sensitivity (only possible $1.1 < q^2 < 6\text{GeV}^2$) KP,Egede,Patel [JHEP06(2015)084]
- Moment analysis to extract angular observables allowing finer q^2 binning in a robust way Serra,Chrzasz,v.Dyk[PRD91, 114012 (2015)]
- Rewrite angular distribution to obtain 8 CP-asymmetric observables
- Analyse higher $K\pi$ states
- $d\mathcal{B}/dq^2$ measurement will also include a measurement of the S-wave in $K\pi$ system

New and updates of all analyses to $3\,\text{fb}^{-1}$

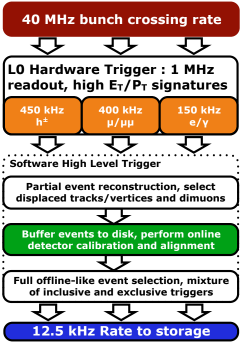
- Measurement of R_{K^*}, R_ϕ
- $B^+ \to \pi^+\mu^+\mu^-$, $\Lambda_b \to pK\mu^+\mu^-$, angular analysis of $B \to Ke^+e^-$
- Measure phase difference between $B \to K^{(*)}\mu^+\mu^-$ and $B \to J/\psi K^{(*)}$ amplitudes to understand potential QCD effects

Run-II

RunII data means quadrupling current dataset

- Experimental precision will start catching up with theory in most measurements
- Large datasets open up precision era in $b \to d$ transitions (suppressed by $|V_{td}|^2/|V_{ts}|^2 \sim 25$ in SM) and tests of MFV
- Look for final states with τ's (also with Run-I data)
    - Lepton non-universality could point to LFV effects enhancing $B \to X_s \tau \mu$ e.g Glashow et al. [arXiv:1411.0565]
- Perform inclusive measurements (?)

LHCb 2015 Trigger Diagram



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$ | 400 kHz $\mu/\mu\mu$ | 150 kHz e/γ

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

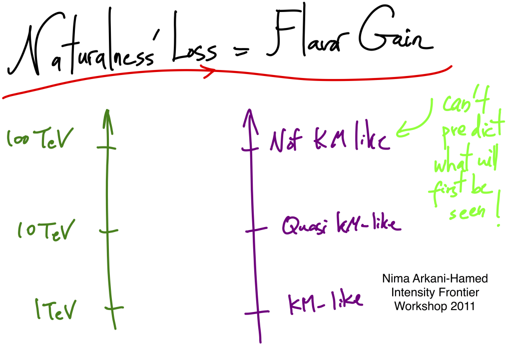
Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz Rate to storage

Flavour measurements are critical

- NP at $\Lambda_{NP} \sim 1\,\text{TeV}$ motivated to tame fine tuning in Higgs sector
- NP at $\Lambda_{NP} \sim 1\,\text{TeV}$ refuted by flavour measurements (pre LHC) $\rightarrow$CKM-like NP couplings (MFV)
- As LHC pushes Λ_{NP} to $>> 1\,\text{TeV}$ lift MFV constraints
  - increase chances to see NP in flavour



Nima Arkani-Hamed
Intensity Frontier
Workshop 2011

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