New physics searches through suppressed EW penguin processes at LHCb

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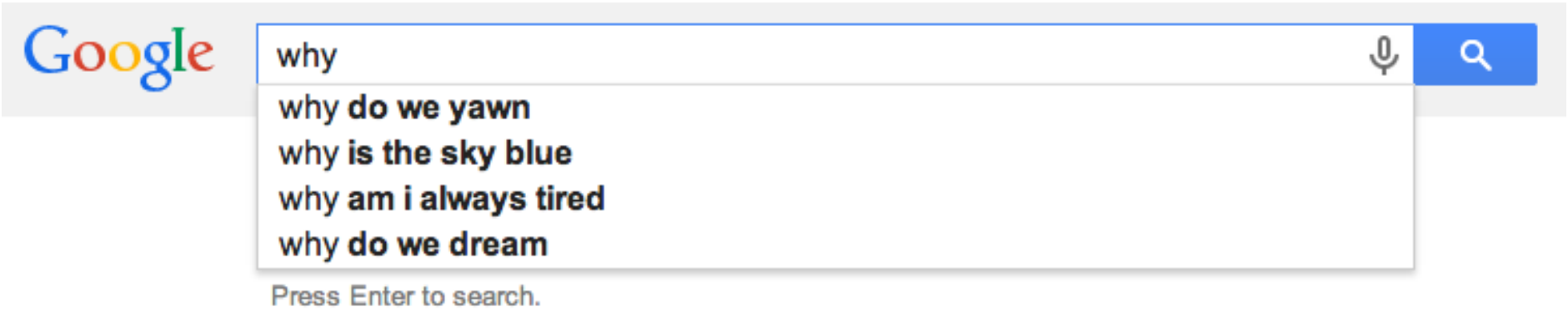
Overview

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

Important questions



- 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

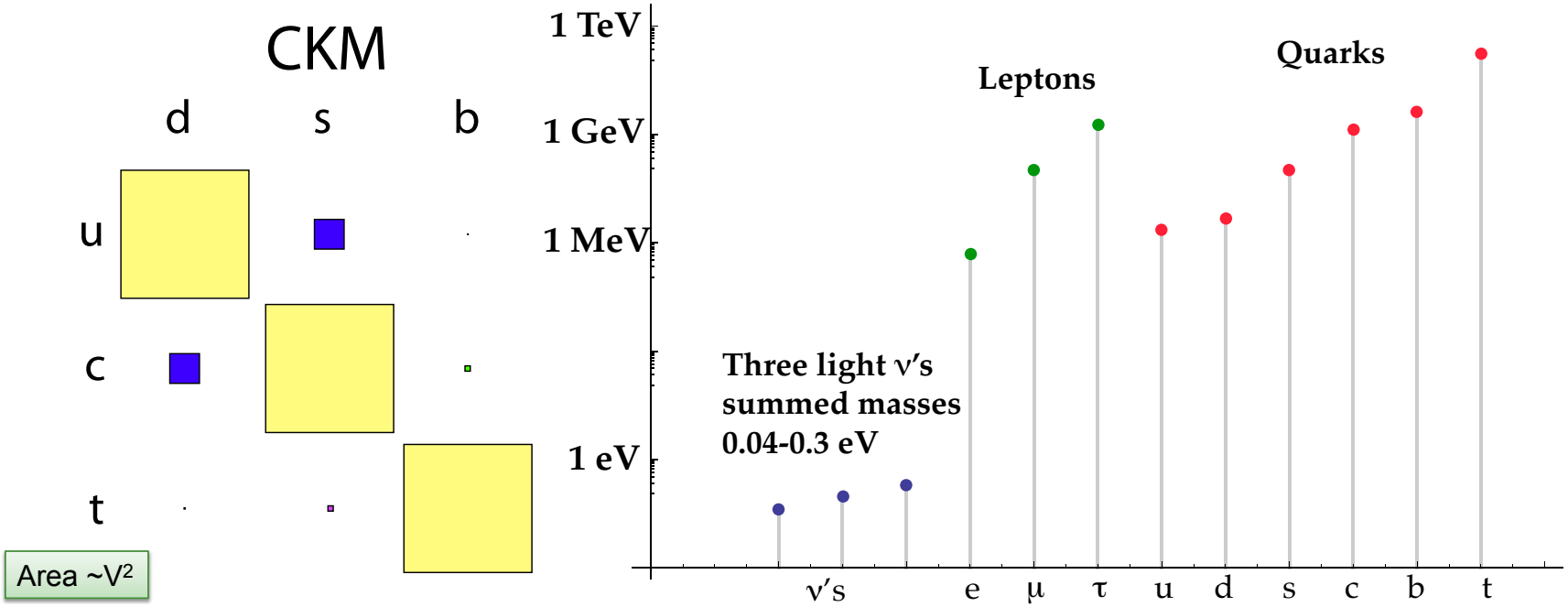
- Yukawa couplings ($Y^{U,D}$) of quarks to Higgs field:
  $\mathcal{L}_Y = \bar{u}_{Ri} Y^U_{ij} \phi^{c\dagger} Q_{Lj} + \bar{d}_{Ri} Y^D_{ij} \phi Q_{Lj}$
- $Y^{U,D}$ matrix in 3 quark generations is not necessarily diagonal

- 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:
  $W^+_\mu \bar{u}_L \gamma^\mu d_L \to W^+_\mu \bar{u}_L V^\dagger_{u_L} V_{d_L} \gamma^\mu d_L$ ($V_{CKM} = V^\dagger_{u_L} V_{d_L}$)

- In SM, Z,γ couplings remain diagonal! $\to$ 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 ($m_u = \mathcal{O}(10^{-3})m_t$)

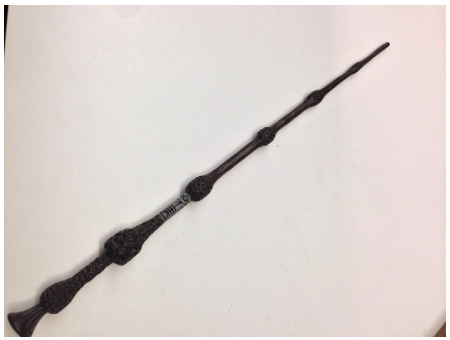
Experimental approaches

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

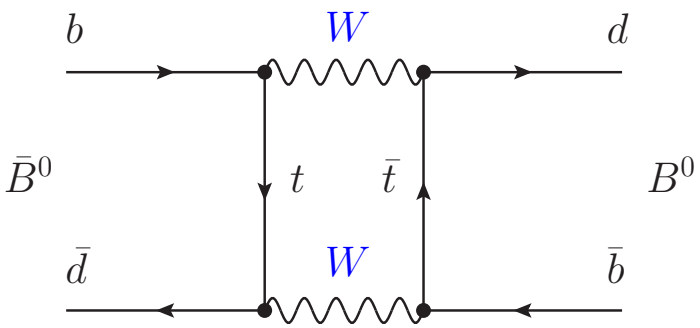
Interplay of direct and indirect measurements

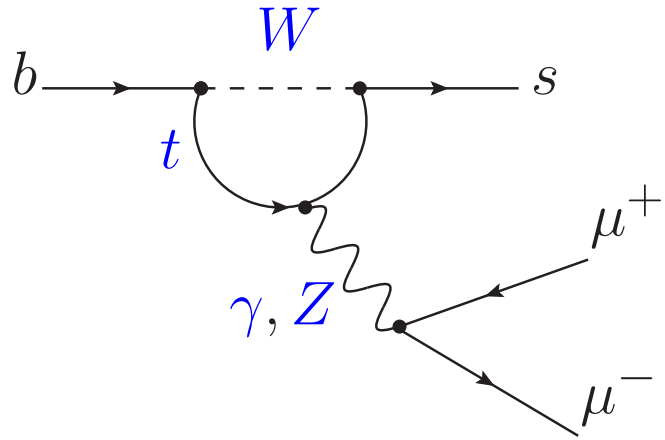
Flavour physics has played central role in the development of the SM

- c-quark inferred from measurement showing suppression of $K^0 \to \mu^+\mu^-$ rate compared to $K \to \mu\nu$ (GIM 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

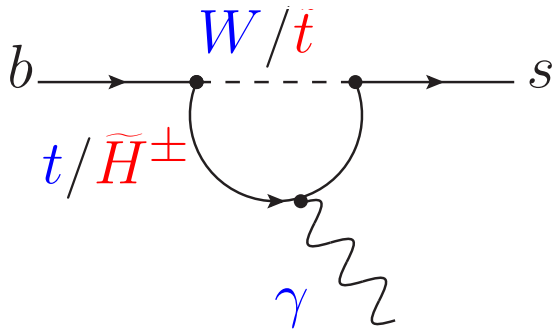
Heavy flavour production

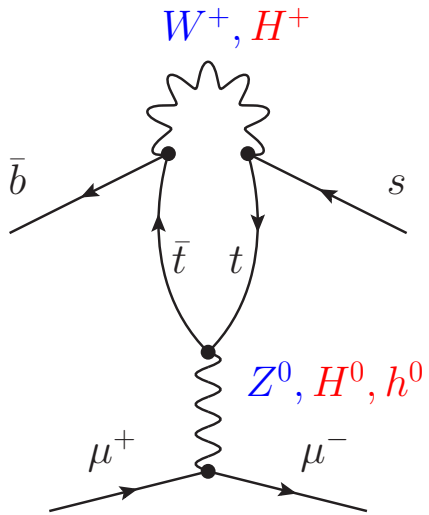
Experiment	Belle/BaBar	TeVatron	LHC
Process	$e^+e^- \to \Upsilon(4s) \to B\bar{B}$	$p\bar{p} \to b\bar{b}X(\sqrt{s} = 2\,\text{TeV})$	$pp \to b\bar{b}X(\sqrt{s} = 8\,\text{TeV}\ )$
σ_{tot}	$1 \times 10^{-3}\,\mu$b	$\sim 100\,\mu$b	$\sim 320\,\mu$b
Lumi/exp.	$\sim 500\,\text{fb}^{-1}$	$\sim$10 fb^{-1}	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$\to$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 $(4.5 \pm 1.7) \times 10^{-5} \to$ stringent constraints on parameter space of new physics
  - Current average $(4.34 \pm 0.15) \times 10^{-5}$



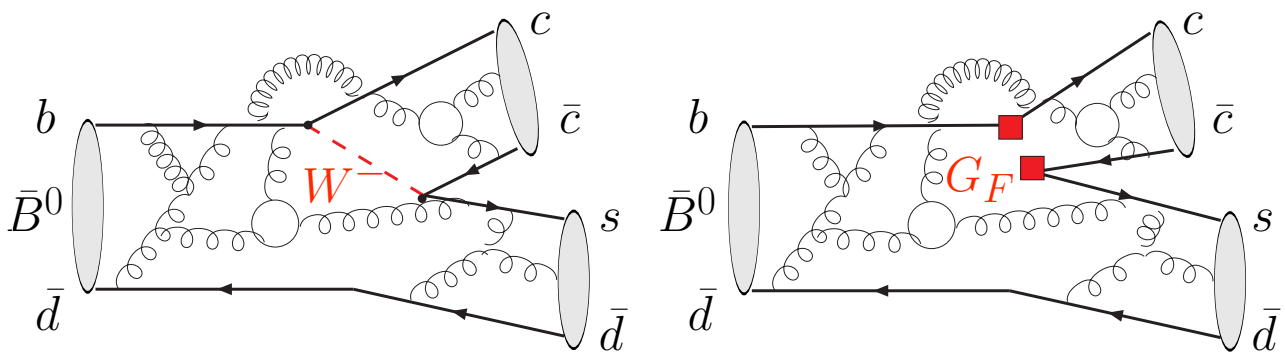


Theoretical Formalism

- 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

Todays focus

- Measurements in $B^0_{s,d} \to \mu^+\mu^-$, $B \to K^{(*)}\mu^+\mu^-$

- Measurements of:
  - Branching fractions
  - Isospin asymmetries
  - Angular distributions (angular analysis)

If time permits:

- Angular analysis of $B^+ \to K^+\mu^+\mu^-$ [1403.8045]

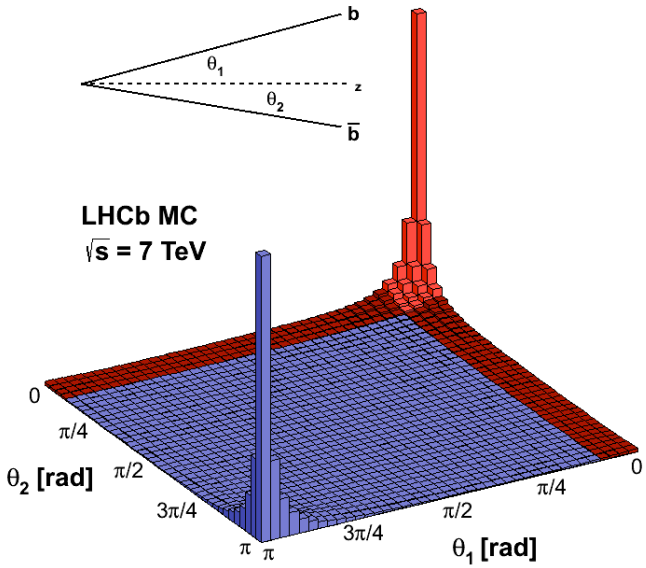
Will not discuss:

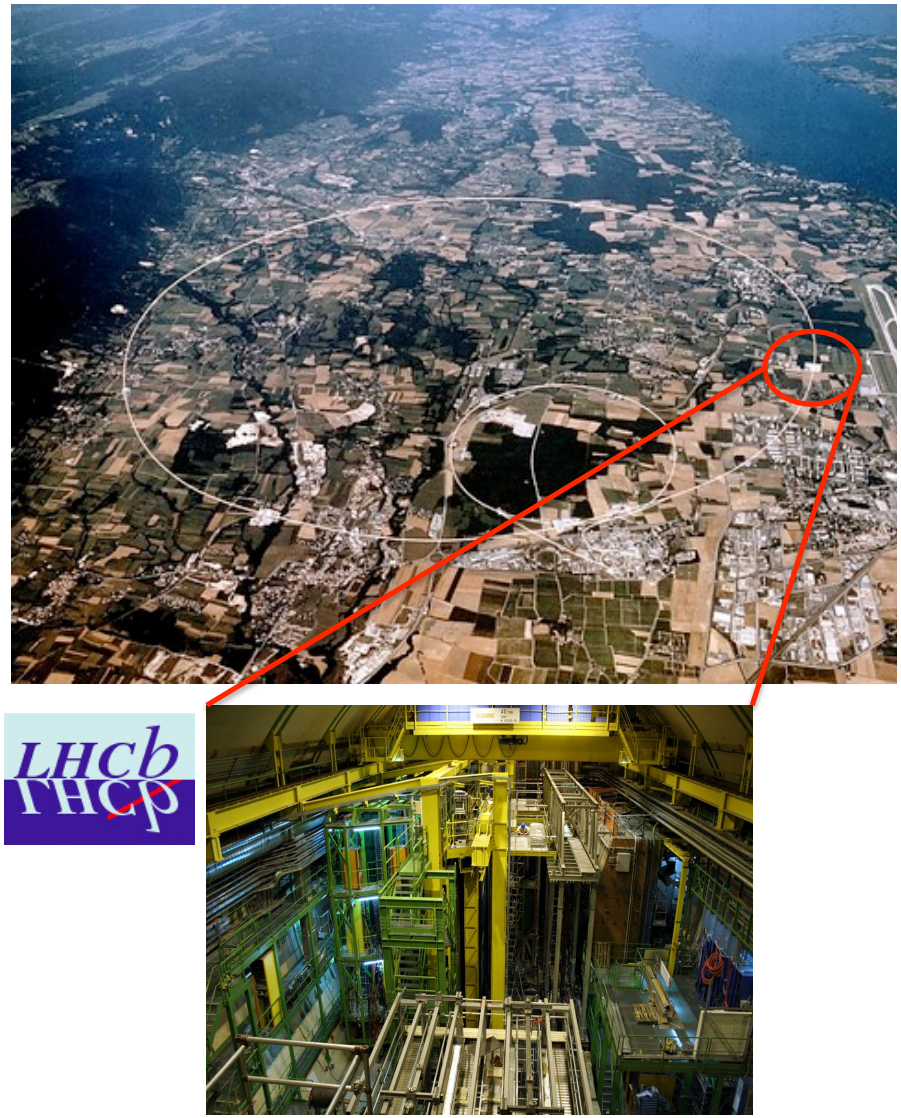
- Measurement of photon polarisation in $B^+ \to K^+\pi^+\pi^-\gamma$ [PRL 112, 161801 (2014)]

Setting the scene

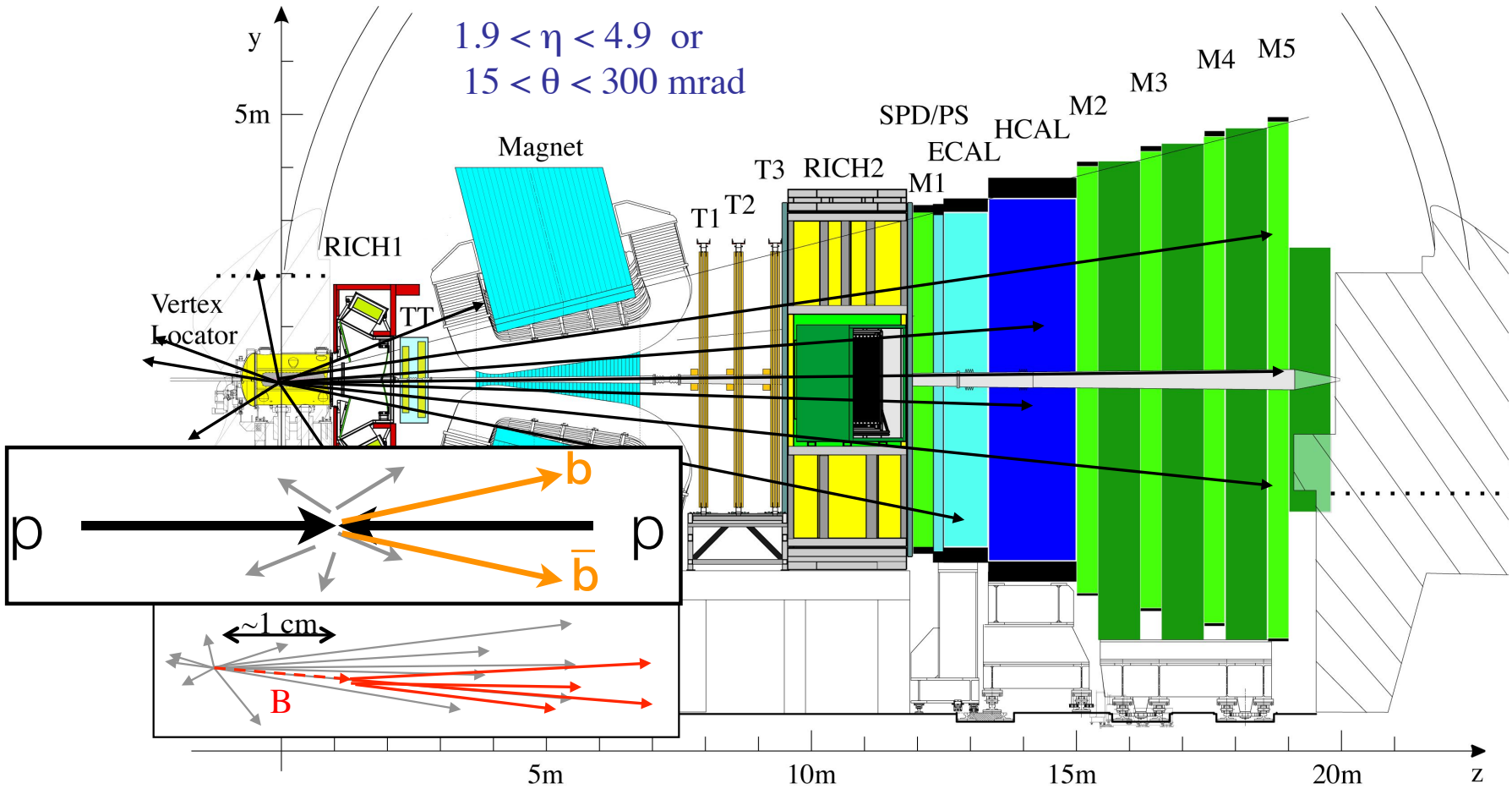
- LHC $\sigma_{b\bar{b}} = 280\,\mu$b @ $\sqrt{s} = 7$ TeV (scale $\sim$ linear with $\sqrt{s}$)

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



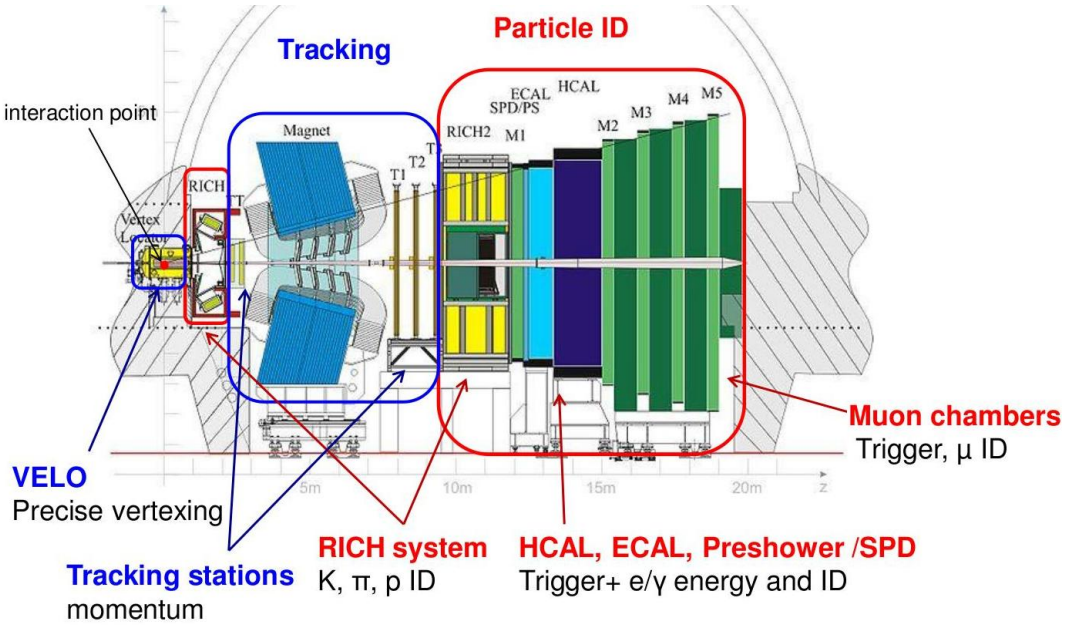


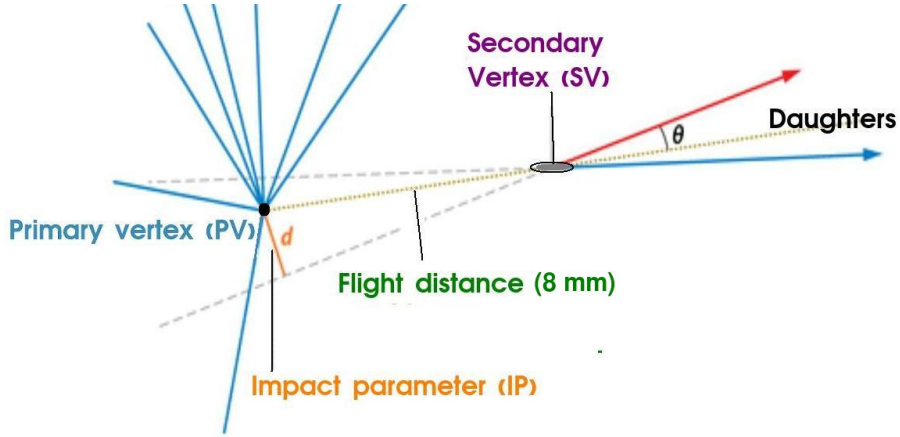
The LHCb detector



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

Detector performance





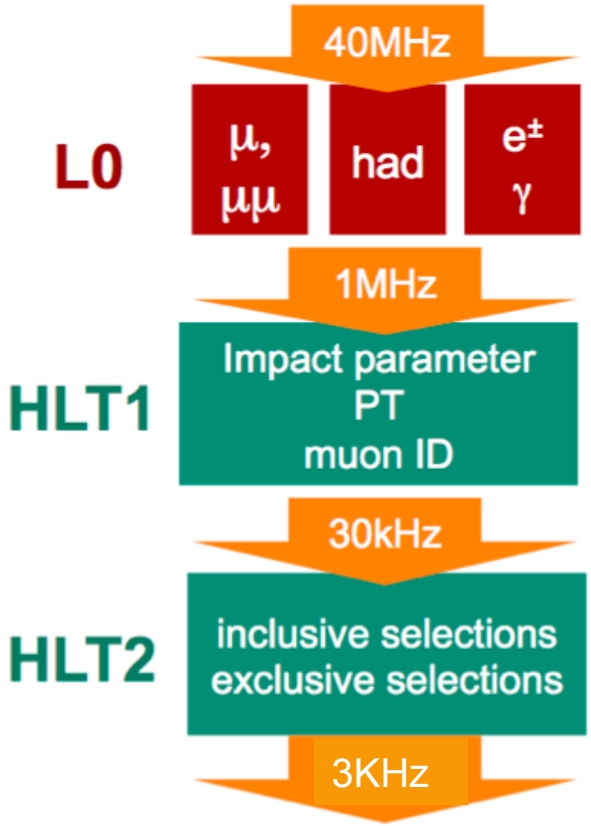
- **VeLo** $\sigma_{IP}^{trk} \sim 20\,\mu$m for $p_T^{trk} > 2$ GeV
- **Tracking** $\delta p/p = 0.4 - 0.6\%$
- **RICH** $\epsilon_K^{id} = 95\%$ for 5% mis-id
- **Muon** $\epsilon_\mu^{id} = 98\%$ for 1% mis-id

- 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

The challenge

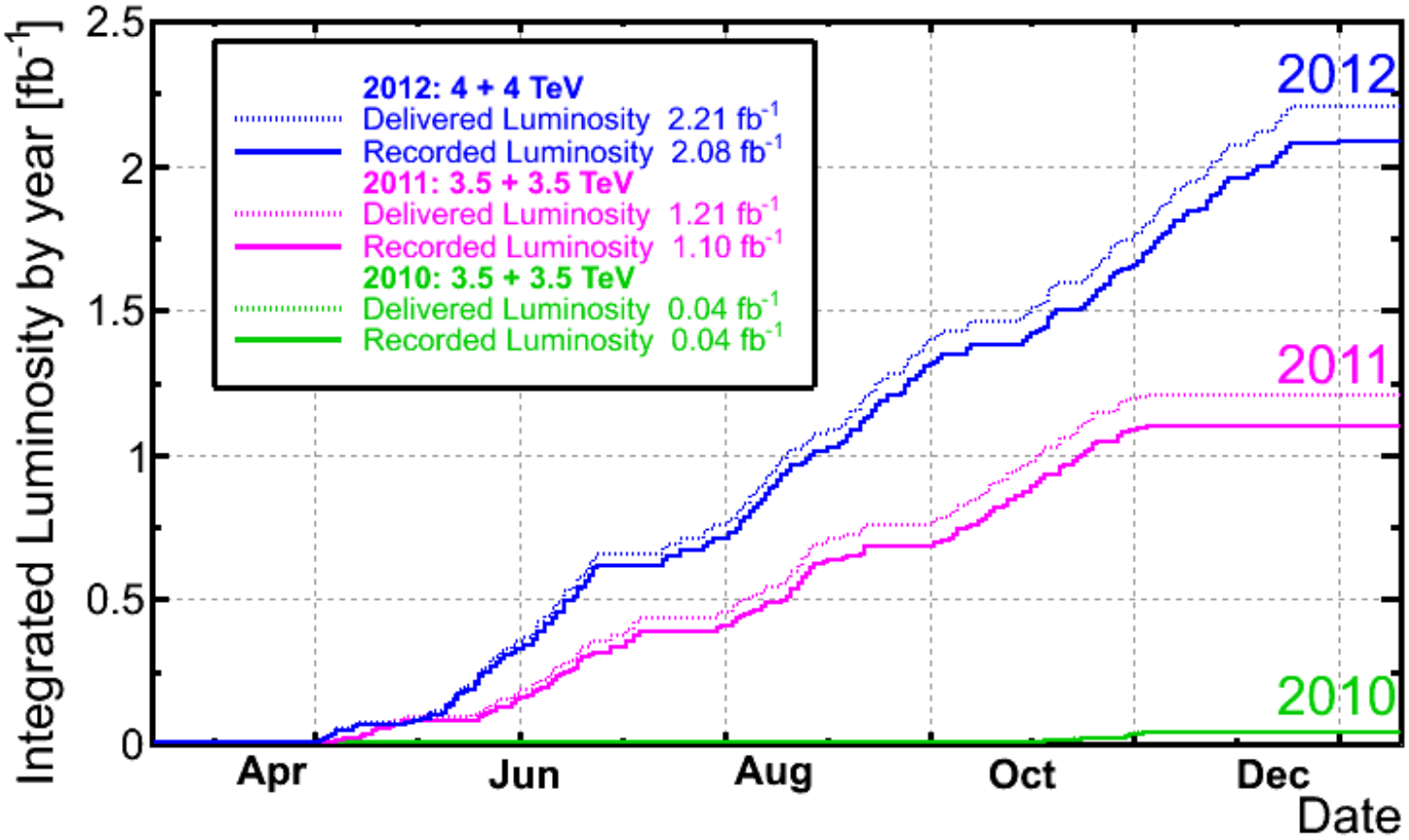
- Only 1 in 200 pp inelastic events contain a b-quark
- Looking for B-hadron decays with $BR \sim 10^{-6} - 10^{-9}$



- 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

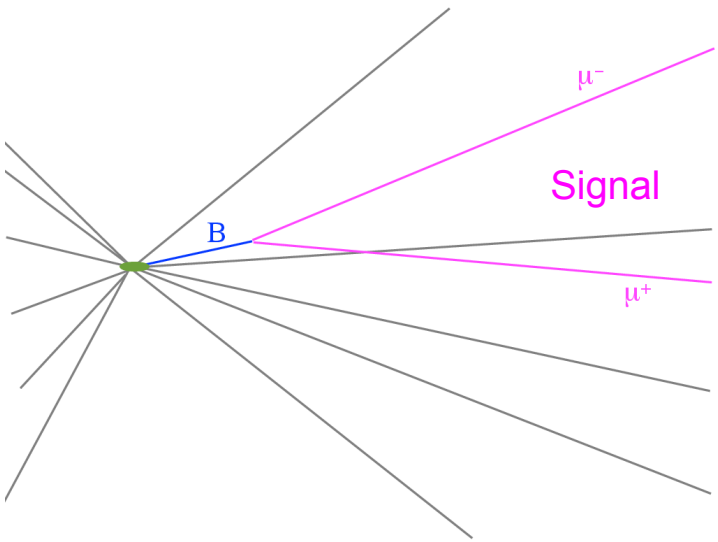


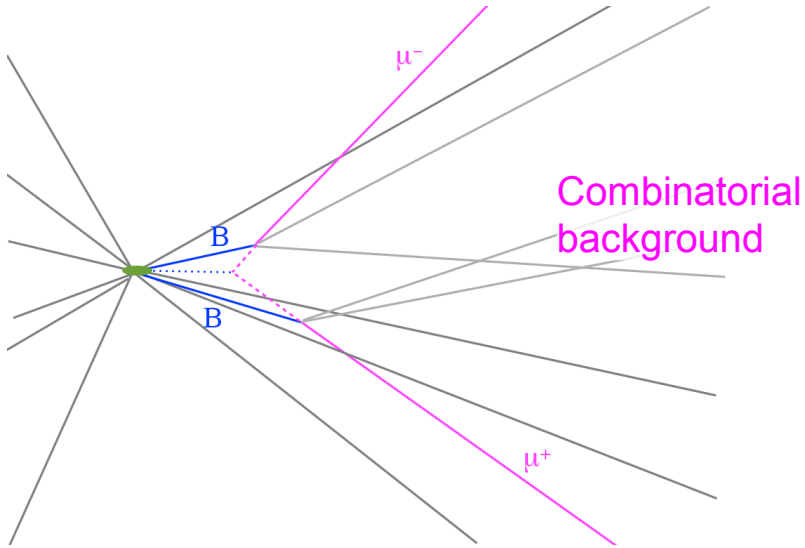
- Total of $3\,\text{fb}^{-1}$ at instantaneous luminosities of up to $4 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ (double the design value!)

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:

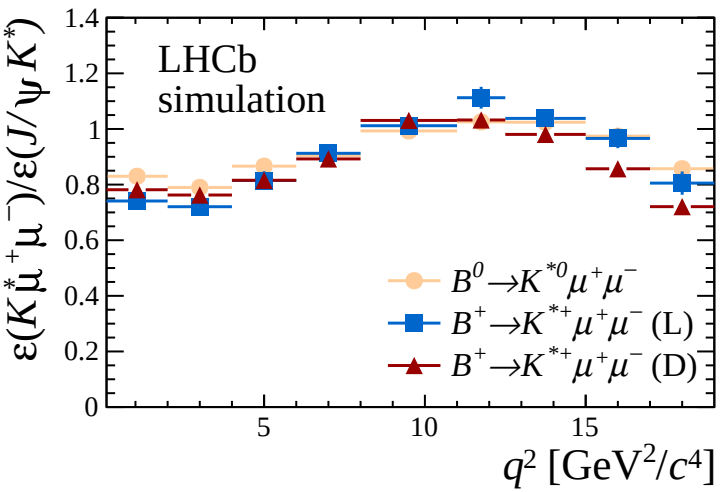
- Make use of proxy-decay (same topology) of known $\mathcal{B}$ to normalize against

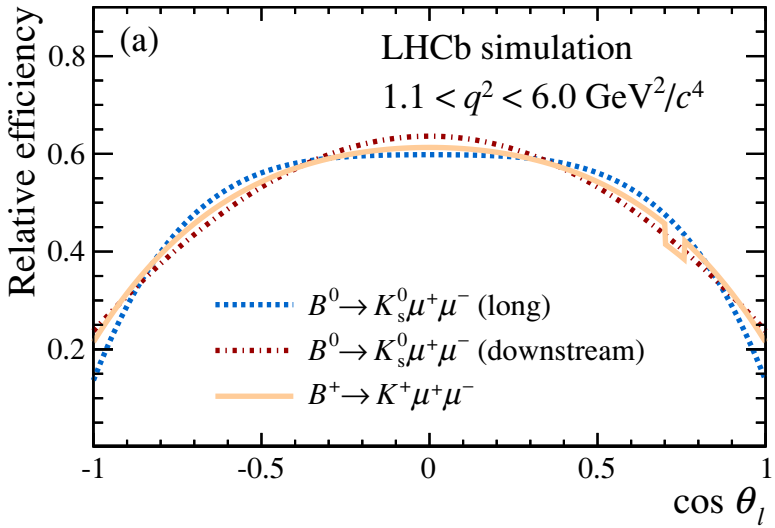
$$\mathcal{B}(sig) = \frac{N_{sig}\epsilon_{sig}}{N_{prx}\epsilon_{prx}}\mathcal{B}(prx)$$

  - Reduces experimental uncertainties

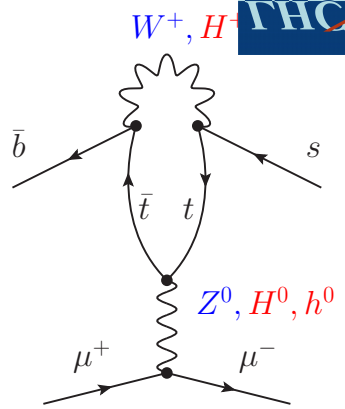
Acceptance correction:

- 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





$B^0_{s(d)} \to \mu^+\mu^-$



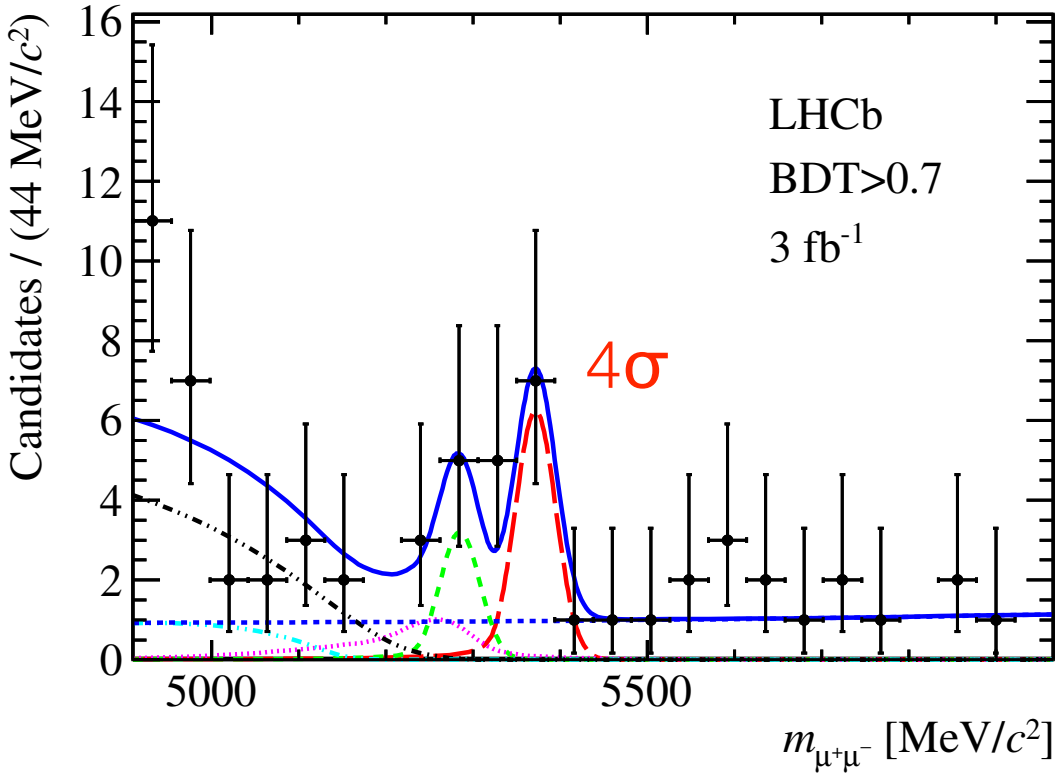
- Golden mode to test New Physics with scalar/pseudo-scalar interactions
- Suppression of B_d over B_s ($|V_{td}|/|V_{ts}|$ in SM) $\to$ test MFV

  $\mathcal{B}(B^0_s \to \mu^+\mu^-)_{SM} = 3.56 \pm 0.3 \times 10^{-9}$ (t avg) $\to$ precise!

  $\mathcal{B}(B^0_d \to \mu^+\mu^-)_{SM} = 0.1 \pm 0.01 \times 10^{-9}$

  Buras et al [Eur.Phys.J. C72 (2012) 2172]]

- Pursued for 30 years (10^{-4} CLEO limit 1984)
- CMS and LHCb see $B^0_s \to \mu^+\mu^-$ at 4σ level
- Combination is above 5σ



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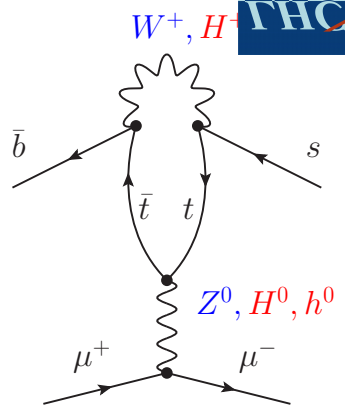

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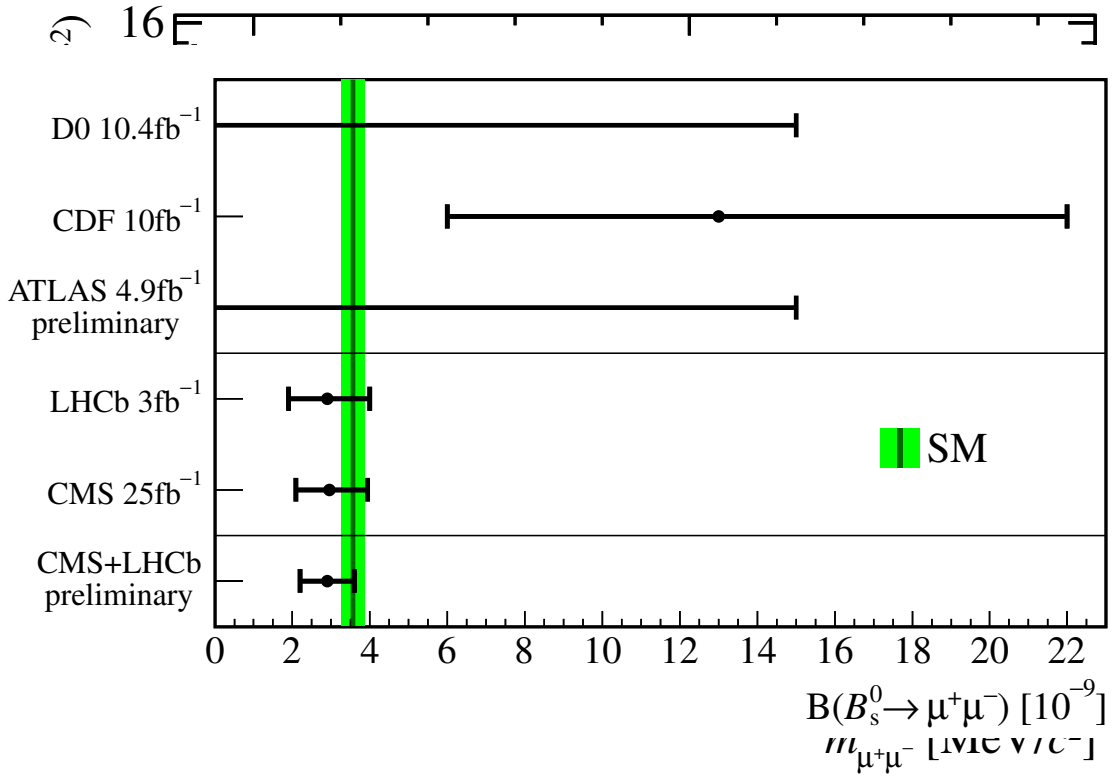

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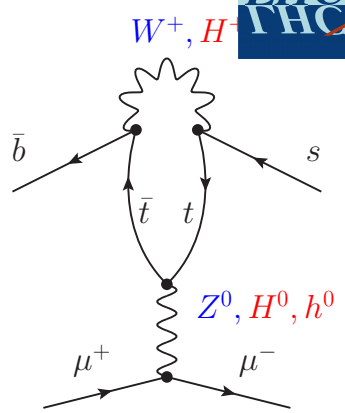

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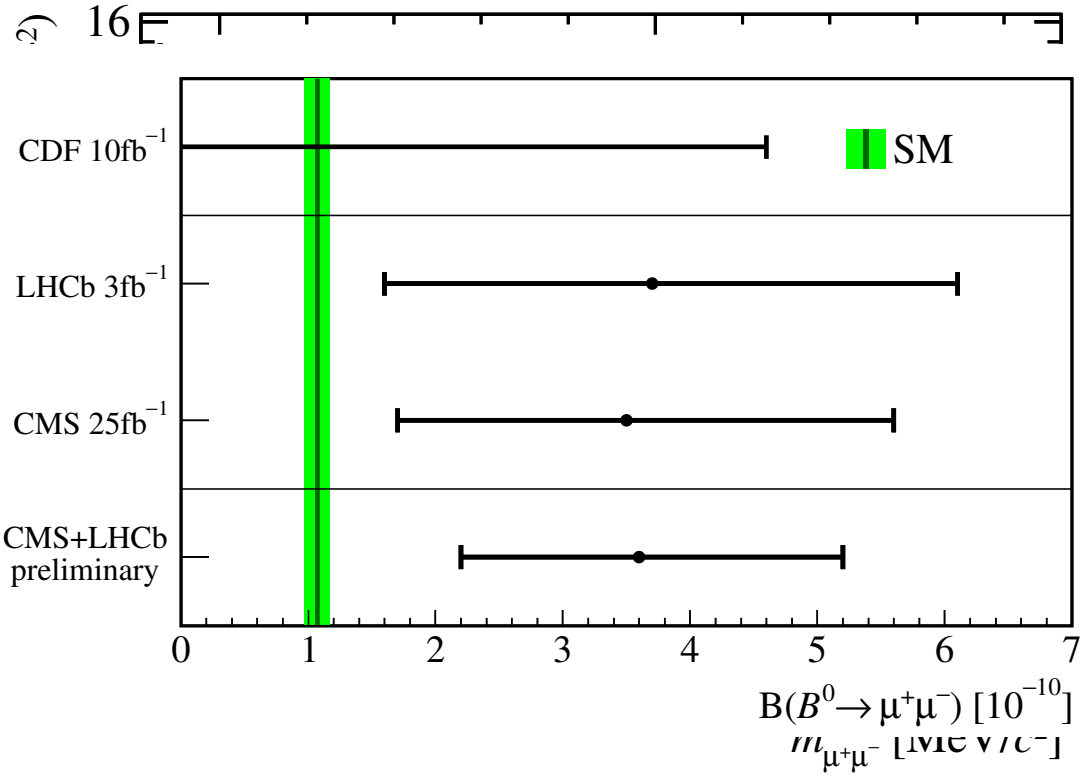
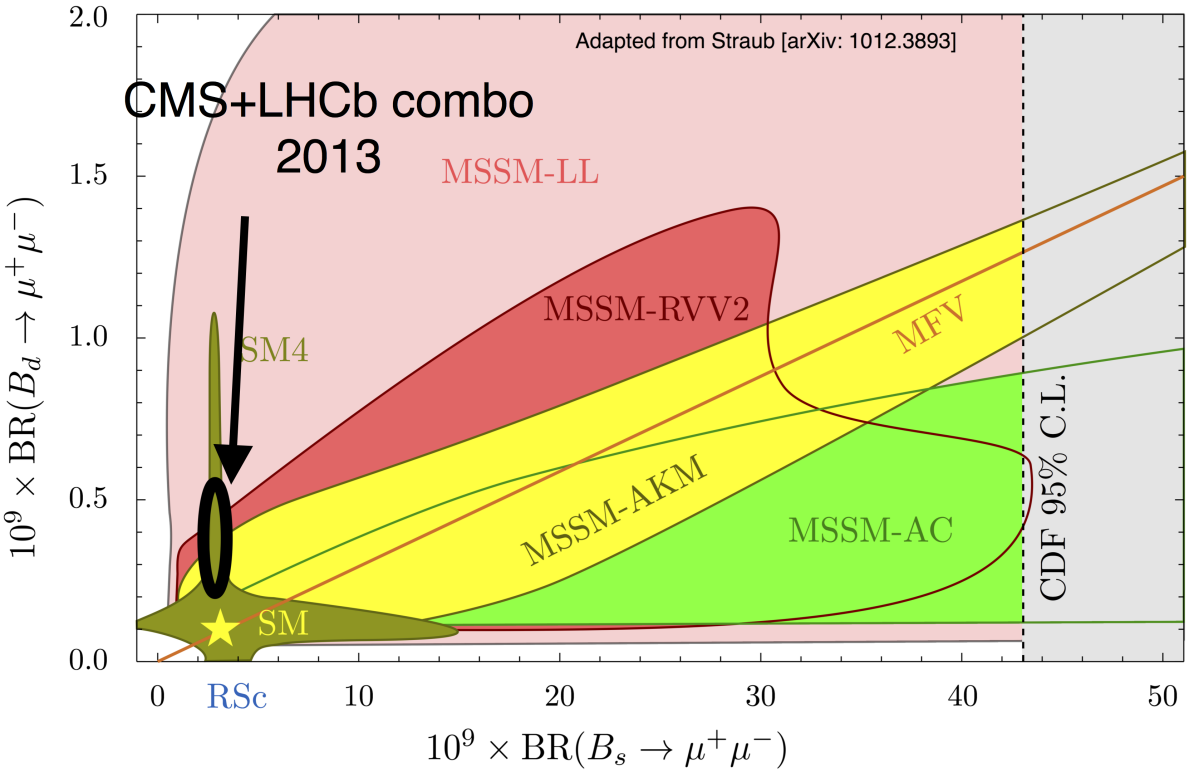
  $\mathcal{B}_{B^0_s} = (2.9 \pm 0.7) \times 10^{-9}$
- No evidence of the B^0_d

  [LHCb-CONF-2013-012]
  [CMS-PAS-BPH-13-007]



$B^0_{s(d)} \to \mu^+\mu^-$

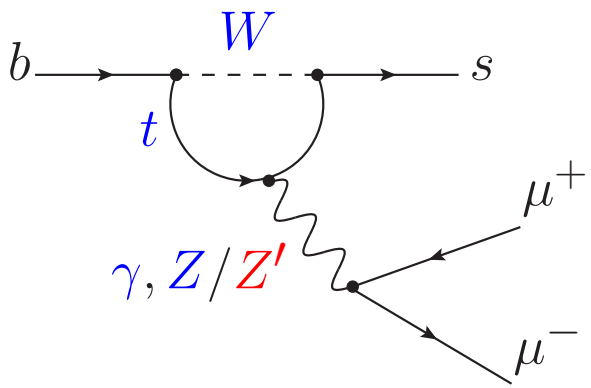
- Extended Higgs sector of MSSM results in $\mathcal{B} \propto \tan^6\beta / M_A^4$
  - Extremely sensitive probe of NP



- Focus now turns to the B^0_d and measure $\mathcal{B}(B^0_s \to \mu^+\mu^-)/\mathcal{B}(B^0_d \to \mu^+\mu^-)$
- With LHCb upgrade ($50\,\mathrm{fb}^{-1}$) measure ratio to 35%

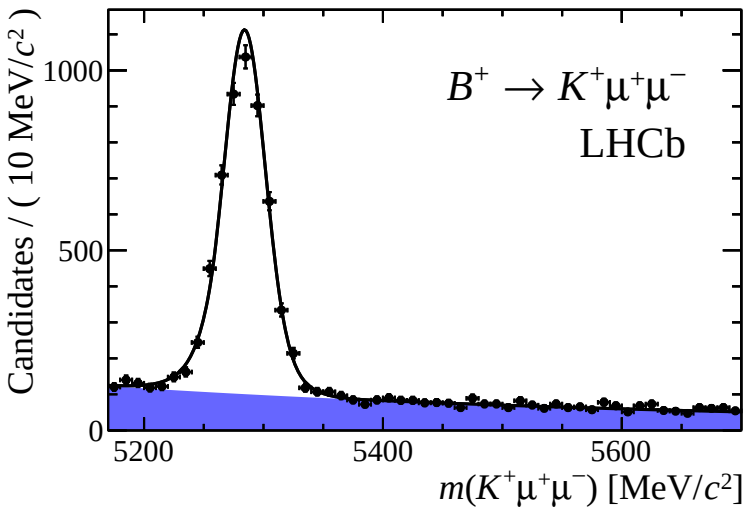
$B^0 \to K^{(*0)}\mu^+\mu^-$ and friends

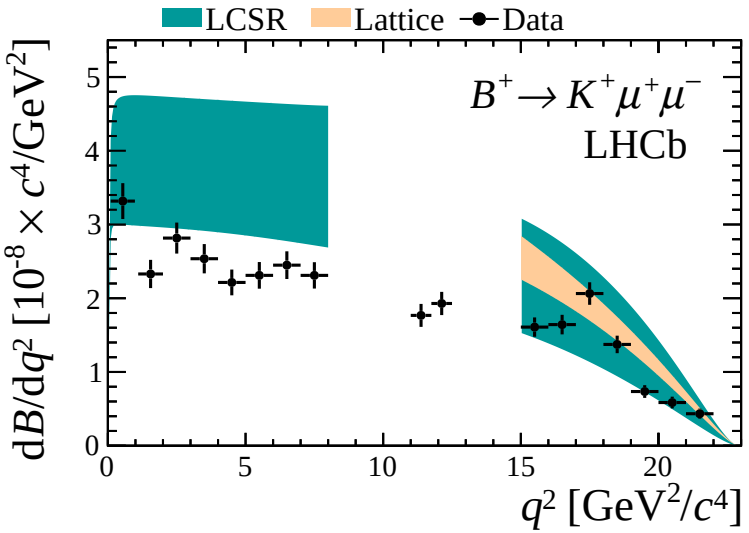
- Measure the decay rate and angular distributions of final state products
- Sensitive to the effects of NP in photon,vector and axial-vector couplings
- Complementary information to $B^0_{s,d} \to \mu^+\mu^-$
- Observables built out of ratios of angular coefficients
  $\to$ Reduce theory uncertainties due to hadronic form factor



$d\mathcal{B}/dq^2$ of $B \to K^{(*)}\mu^+\mu^-$ [1403.8044]

- Differential branching fraction as function of q^2 depends on different combinations of $(C_9 \pm C_9')$, $(C_{10} \pm C_{10}')$ and $(C_7 \pm C_7')$

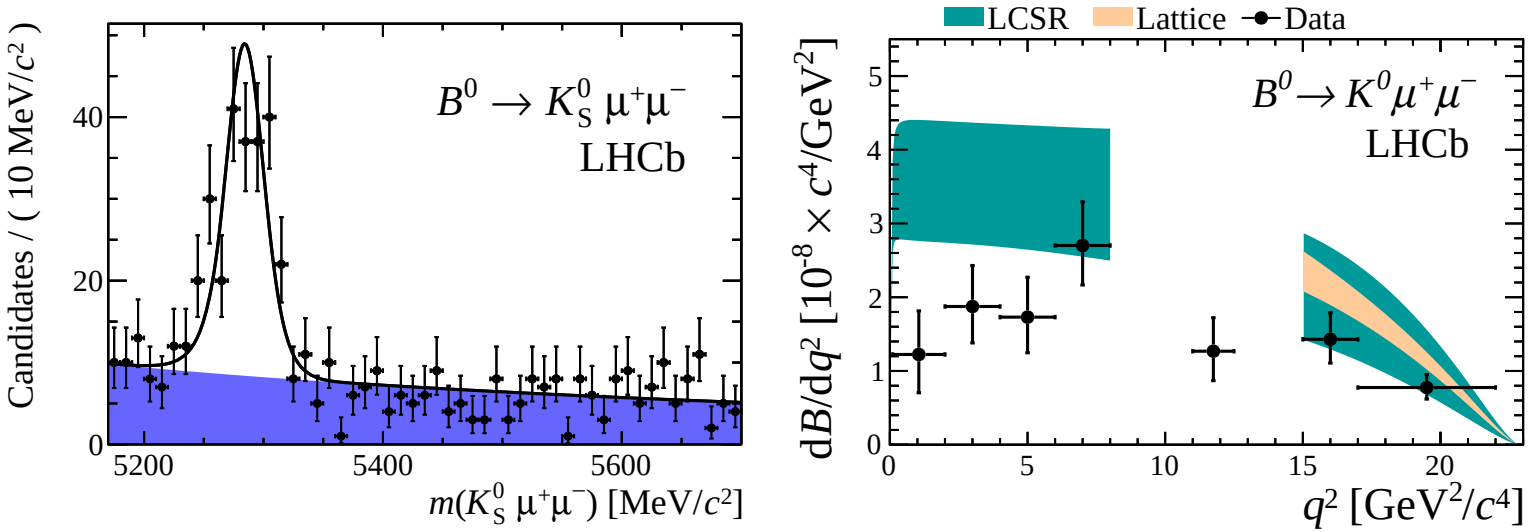




- Using all available LHCb data
- Fit the $K^{(*)}\mu^+\mu^-$ invariant mass distribution in bins of q^2
  - Reconstruct $K_s \to \pi^+\pi^-$ and $K^{*+} \to K_s\pi^+$
  - Large lifetime of K_s means reduction in reconstruction efficiency
  - Normalise to corresponding $B \to J/\psi K^{(*)}$ mode
  - Dominant systematic is value of $\mathcal{B}(B \to J/\psi K^{(*)})$

$d\mathcal{B}/dq^2$ of $B \to K^{(*)}\mu^+\mu^-$ [1403.8044]

- Differential branching fraction as function of q^2 depends on different combinations of $(C_9 \pm C_9')$, $(C_{10} \pm C_{10}')$ and $(C_7 \pm C_7')$



- Using all available LHCb data
- Fit the $K^{(*)}\mu^+\mu^-$ invariant mass distribution in bins of q^2
  - Reconstruct $K_s \to \pi^+\pi^-$ and $K^{*+} \to K_s\pi^+$
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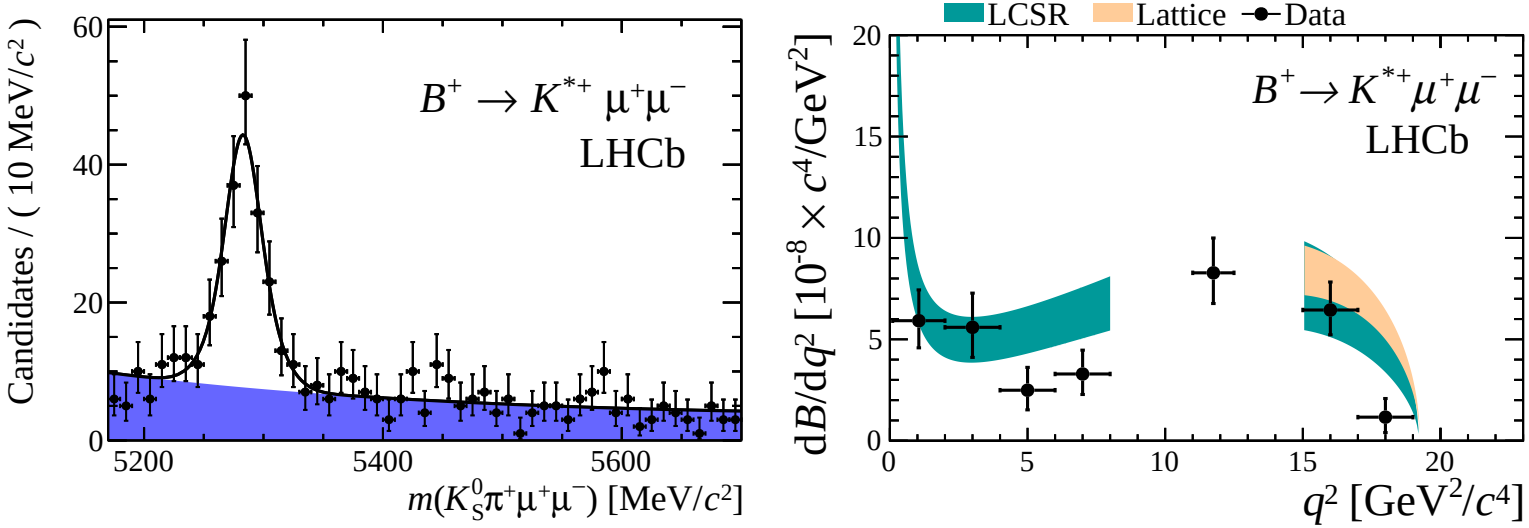

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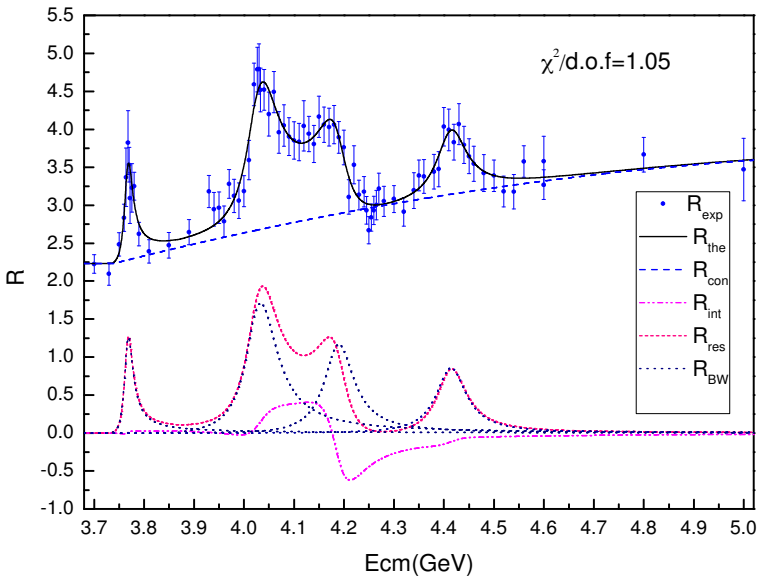
$d\mathcal{B}/dq^2$ at low recoil of $B^+ \to K^+\mu^+\mu^-$

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

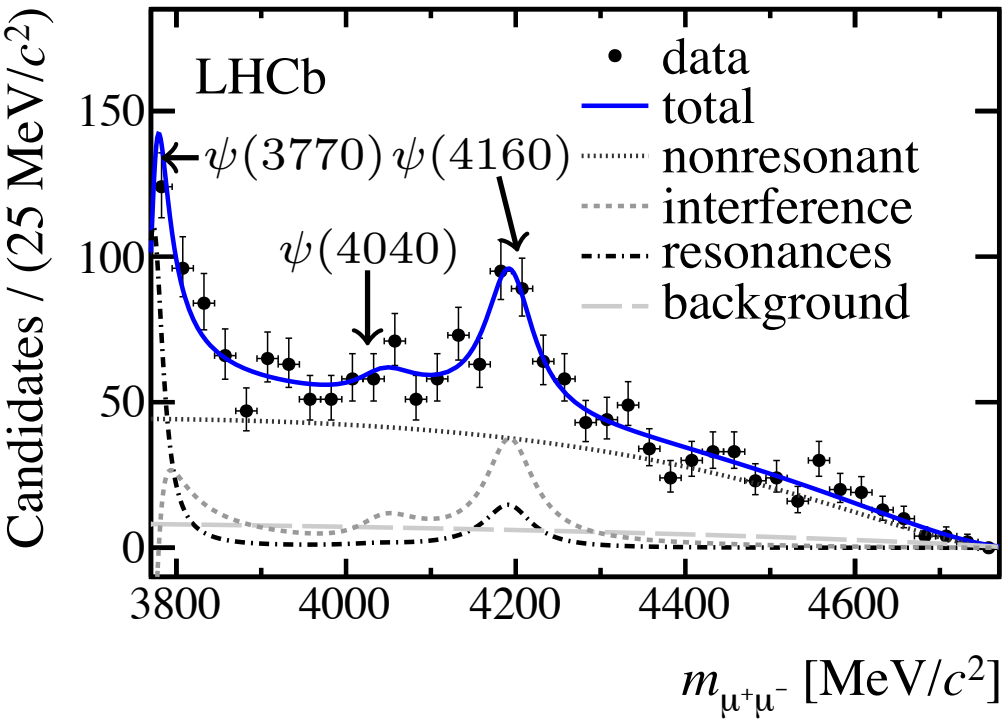


Resonance	Mass [MeV/c^2]	Width [MeV]
$\psi(3770)$	3773.2 ± 0.3	27.2 ± 1.0
$\psi(4040)$	4039.6 ± 4.3	84.5 ± 12.3
$\psi(4160)$	4191.7 ± 6.5	71.8 ± 12.3
$\psi(4415)$	4415.1 ± 7.9	71.5 ± 19.0

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

$d\mathcal{B}/dq^2$ at low recoil of $B^+ \to K^+\mu^+\mu^-$ [PRL 111, 112003 (2013)]

Resonant structures clear in 3 fb^{-1} at low recoil



- Difficult to quantify resonances theoretically
- Predict rates and observables integrated across resonances

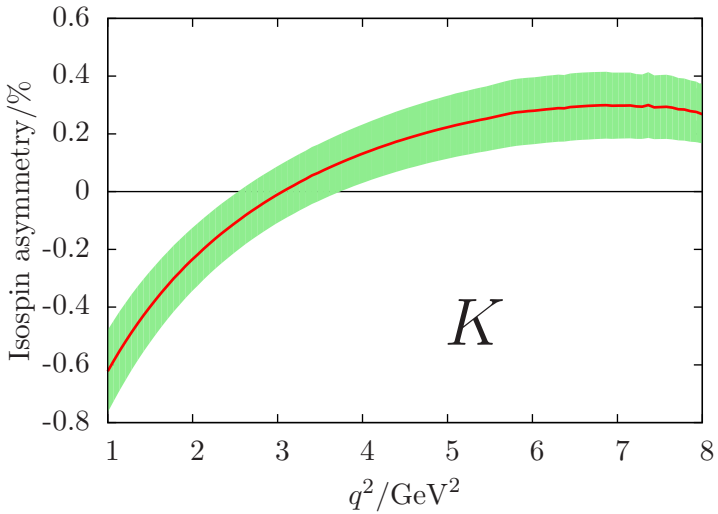
- Sensitive due to interference with large non-resonant component!
- Assume resonances are $1^{--} \to$ only V non-resonant interferes, universal lepton couplings
- Take SM value for $|A^V_{nr}|^2/(|A^V_{nr}|^2 + |A^A_{nr}|^2) = (45 \pm 6)\%$
  e.g Bobeth et al. [JHEP 01 (2012)107]
- $\mathcal{B}(B^+ \to K^+\psi_{4160}(\mu^+\mu^-)) = 3.9^{+0.7}_{-0.6} \times 10^{-9}$!

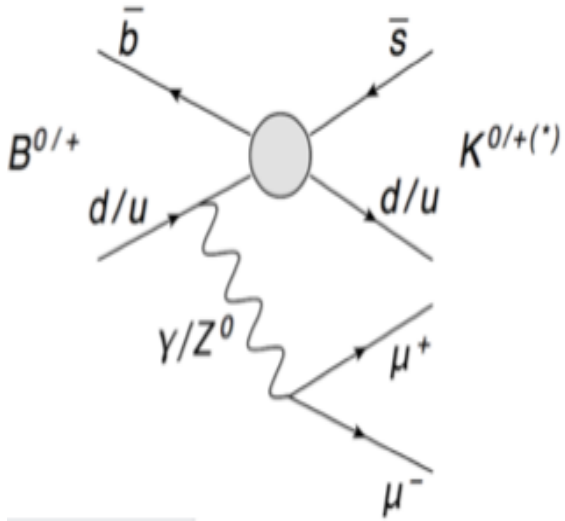
- Presence of resonances has implications on bin choice and interpretation of measurements in this region for all such decays

Isospin asymmetry measurements

$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

J. Lyon, R. Zwicky [1305.4797]

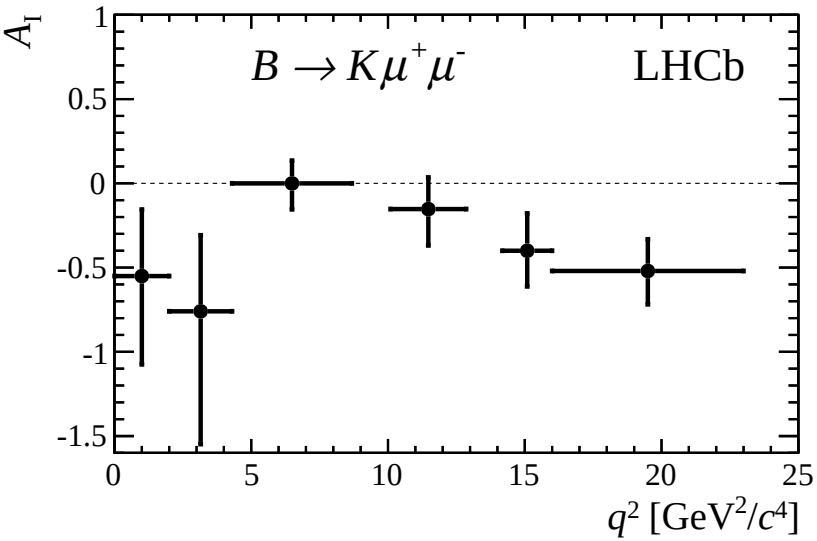


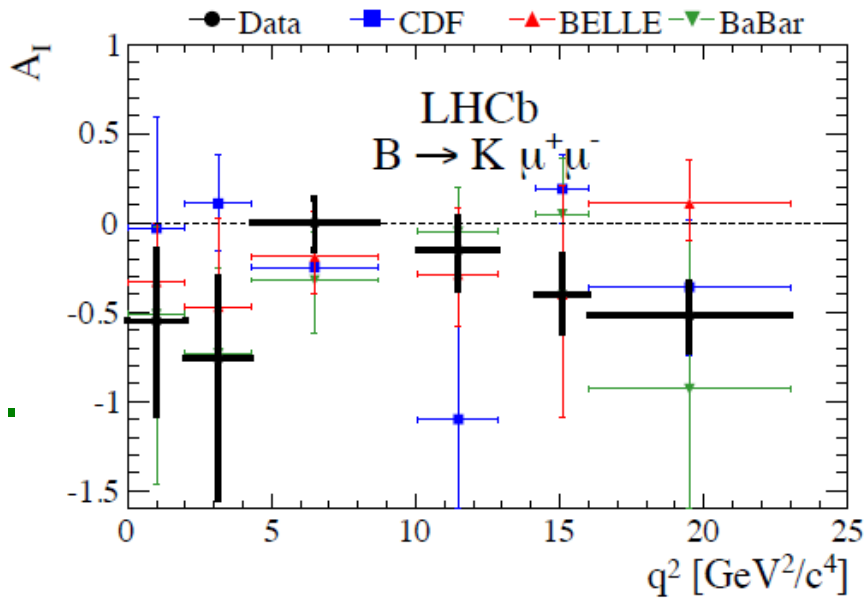


- More precise prediction than $\mathcal{B}$
- In SM expected due to:
  - Photon coupling to u and d
  - C_{uubs} at tree level but C_{ddbs} only loop level

Isospin asymmetry measurements [JHEP 07 (2012) 133]

- LHCb's $1\,\text{fb}^{-1}$ analysis revealed a significantly negative A_I in $B \to K\mu^+\mu^-$
- Measurements from B-factories also hint at low A_I

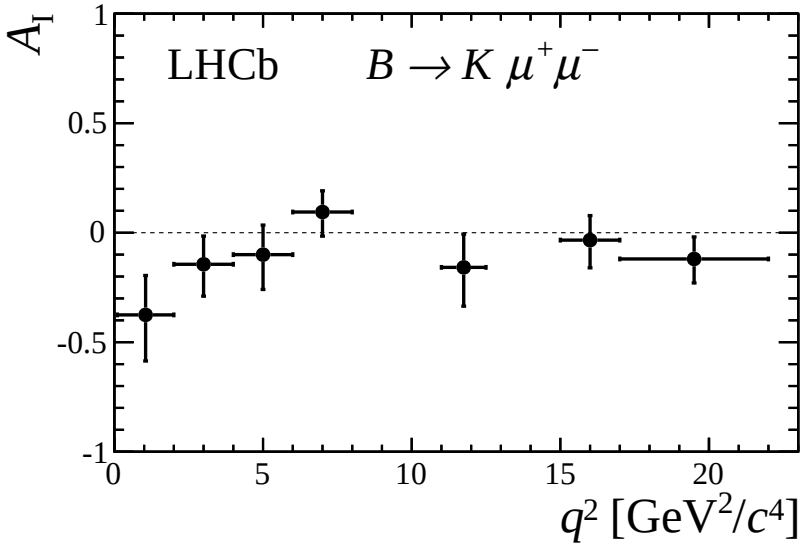


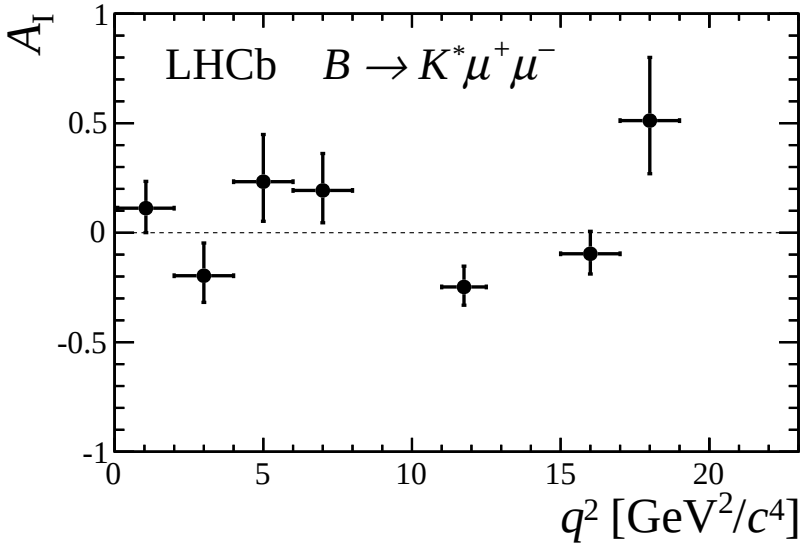


- Significance from SM between 3 and 4 σ (depending on definition of test statistic)
- Very difficult to accomodate in SM or NP models!

Isospin asymmetry measurements [1403.8044]

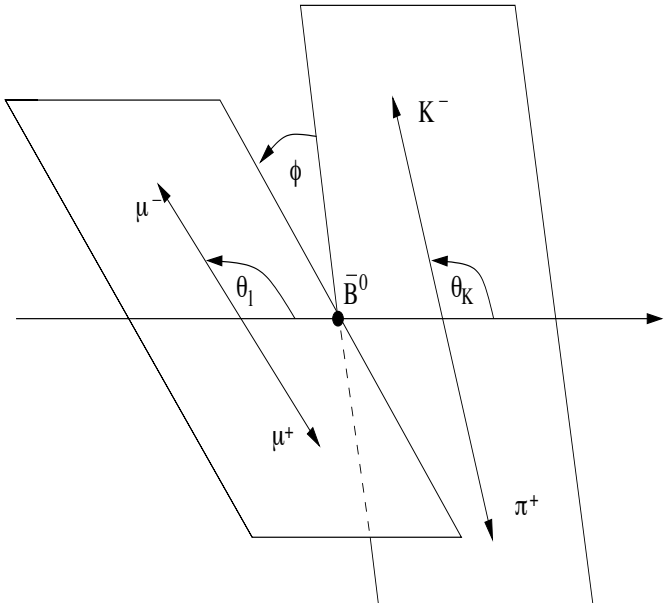
- Updating to full dataset ($3\,\text{fb}^{-1}$)





- Assume A_I in $J/\psi K^*$ modes is zero
  - Uncertainties related to $\mathcal{B}$ cancel
- Estimate p-value for difference from zero assuming data have a constant non-zero value of A_I
- Results consistent with SM, p-value of 11% (1.5σ) for $B \to K\mu^+\mu^-$

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



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

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$
$$+J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi$$
$$+J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big], \qquad (1)$$

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

Angular terms

$$J_{1s} = \frac{(2+\beta_\ell^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2\right] + \frac{4m_\ell^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*}\right) ,$$

$$J_{1c} = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\ell^2}{q^2}\left[|A_t|^2 + 2\mathrm{Re}(A_0^L A_0^{R*})\right] + \beta_\ell^2 |A_S|^2 ,$$

$$J_{2s} = \frac{\beta_\ell^2}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2\right] , \qquad J_{2c} = -\beta_\ell^2\left[|A_0^L|^2 + |A_0^R|^2\right] ,$$

$$J_3 = \frac{1}{2}\beta_\ell^2\left[|A_\perp^L|^2 - |A_\parallel^L|^2 + |A_\perp^R|^2 - |A_\parallel^R|^2\right] , \qquad J_4 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Re}(A_0^L A_\parallel^{L*} + A_0^R A_\parallel^{R*})\right] ,$$

$$J_5 = \sqrt{2}\beta_\ell\left[\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}) - \frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_\parallel^L A_S^* + A_\parallel^{R*} A_S)\right] ,$$

$$J_{6s} = 2\beta_\ell\left[\mathrm{Re}(A_\parallel^L A_\perp^{L*} - A_\parallel^R A_\perp^{R*})\right] , \qquad J_{6c} = 4\beta_\ell\frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_0^L A_S^* + A_0^{R*} A_S) ,$$

$$J_7 = \sqrt{2}\beta_\ell\left[\mathrm{Im}(A_0^L A_\parallel^{L*} - A_0^R A_\parallel^{R*}) + \frac{m_\ell}{\sqrt{q^2}}\mathrm{Im}(A_\perp^L A_S^* - A_\perp^{R*} A_S))\right] ,$$

$$J_8 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Im}(A_0^L A_\perp^{L*} + A_0^R A_\perp^{R*})\right] , \qquad J_9 = \beta_\ell^2\left[\mathrm{Im}(A_\parallel^{L*} A_\perp^L + A_\parallel^{R*} A_\perp^R)\right] , \quad (3)$$

Amplitudes I

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

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

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

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

$$A_t = \frac{N}{\sqrt{q^2}}\sqrt{\lambda}\left\{2(\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}}) + \frac{q^2}{m_\mu}(\mathbf{C_P^{eff}} - \mathbf{C_P^{\prime eff}})\right\}\mathbf{A_0(q^2)}$$

$$A_S = -2N\sqrt{\lambda}(\mathbf{C_S} - \mathbf{C_S})\mathbf{A_0(q^2)}$$

- $\mathbf{C_i^{eff}}$ 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 $\xi_\perp$,$\xi_\parallel$:

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

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

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

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

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

Experimental concerns

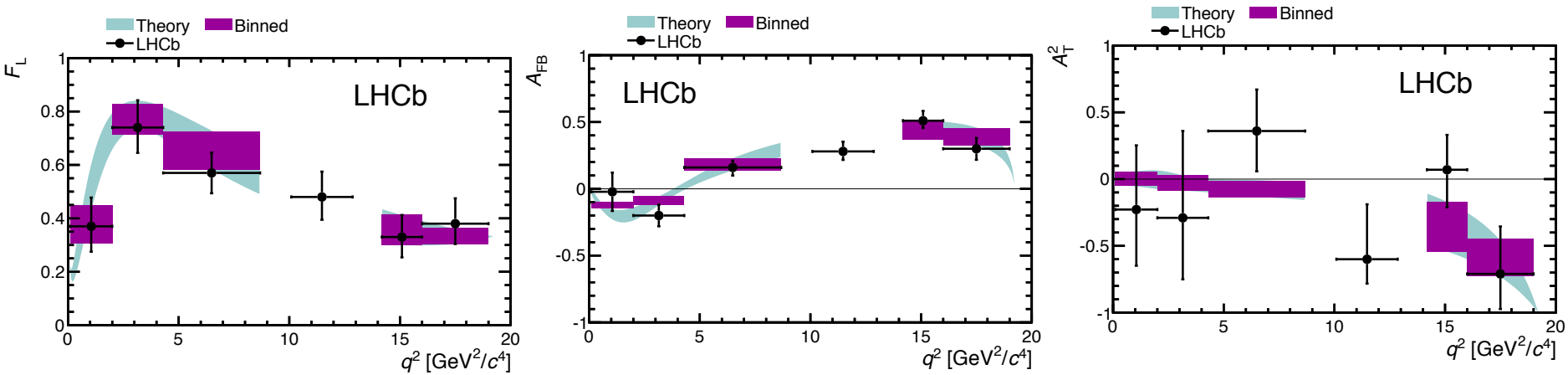
$\sim$1K reconstructed/selected $B^0 \to K^{*0}\mu^+\mu^-$ candidates in $1\,\text{fb}^{-1}$ (more than all B-factory experiments combined!), not enough to perform full angular fit in infinitesimally small bins of q^2

- Notice that can simplify angular distribution by "folding" angles
  - e.g $\phi \to \phi + \pi$ for $\phi < 0$, removes $\cos\phi$ and $\sin\phi$ terms
- Different foldings can give access to different observables

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}} = \frac{9}{16\pi}\Big[F_\mathrm{L}\cos^2\theta_K + \frac{3}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K) - F_\mathrm{L}\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) - S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_\mathrm{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi} \Big]$$

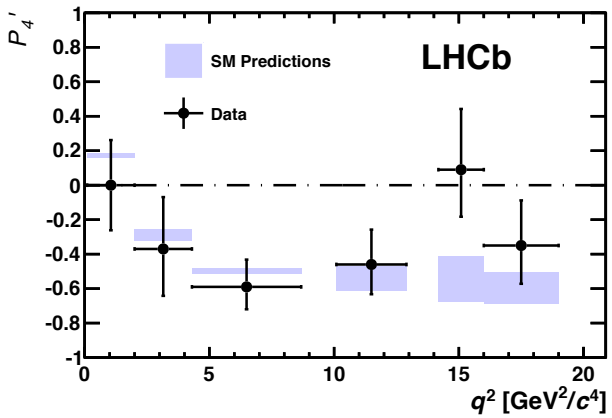
- Perform fit in bins of q^2.
- Bias from not accounting for S-wave in $K\pi$ negligible with these stats. Needs to be dealt with with $3\,\text{fb}^{-1}$ Egede et al. [JHEP 03(2013)027]

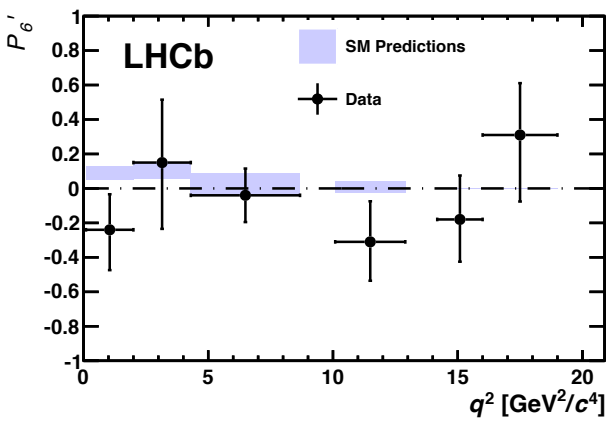
Results [JHEP 08(2013)131]

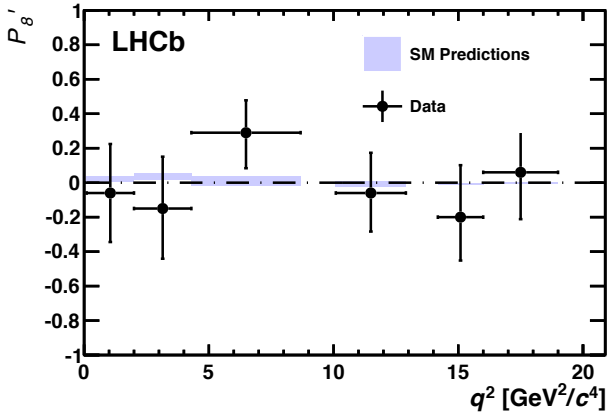


- F_L: Fraction of longitudinally polarised K^{*0}
- A_{FB}: Forward backward asymmetry of muons
- A_T^2: Asymmetry between $A_\perp$ and $A_\parallel$ amplitudes
- Most precise measurements using $1\,\text{fb}^{-1}$ of data
- First ever measurements of A_{FB} zero crossing point: $q_0^2 = 4.9 \pm 0.9\,\text{GeV}^2$.
  - ▷ SM: $q_0^2 = 4.36^{+0.33}_{-0.31}\,\text{GeV}^2$ Beneke et al. [Eur. Phys. J. C41 (2005)173]

Results: New observables [PRL 111,191801(2013)]

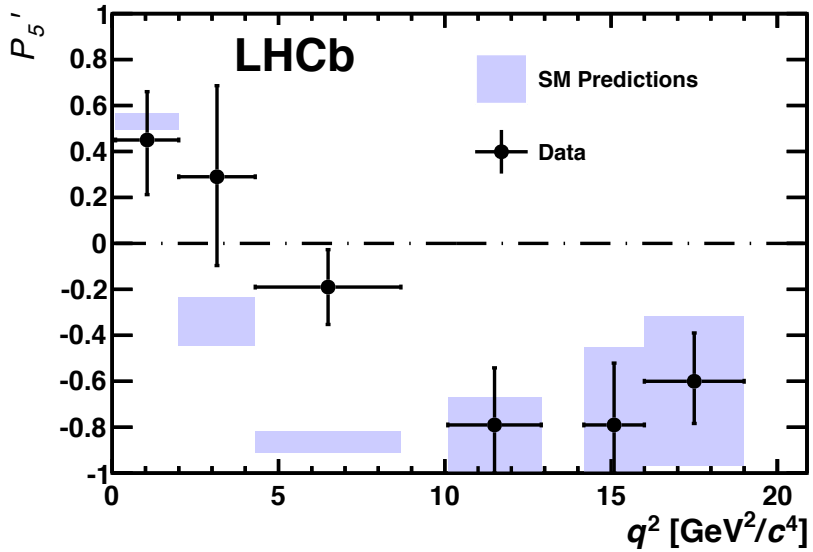






Theory: Descote-Genon et al. [JHEP 05(2013)137]

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

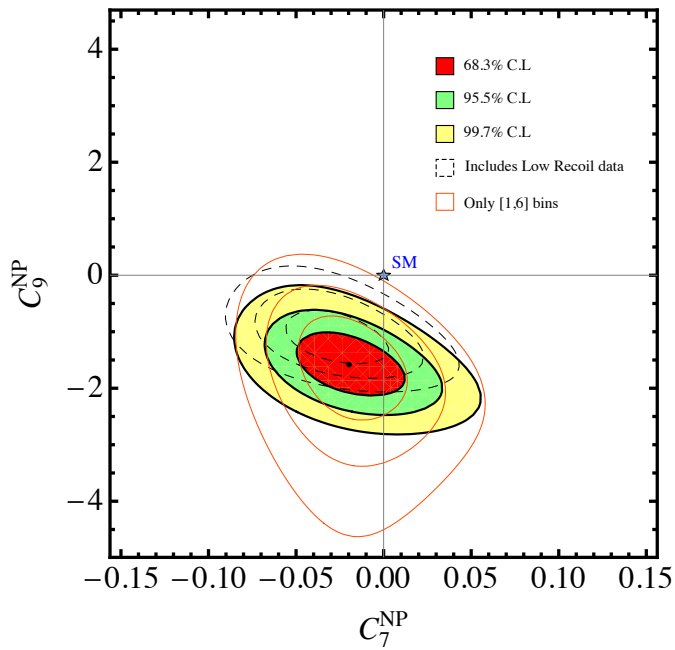


Hint of new physics?

- Combine $B_s \to \mu\mu, B \to K^{(*)}\mu\mu, B \to X_s\gamma, B \to K^*\gamma$ measurements to constrain New Physics
- Indicate significant deviation in di-leptonic vector operator (C_9)

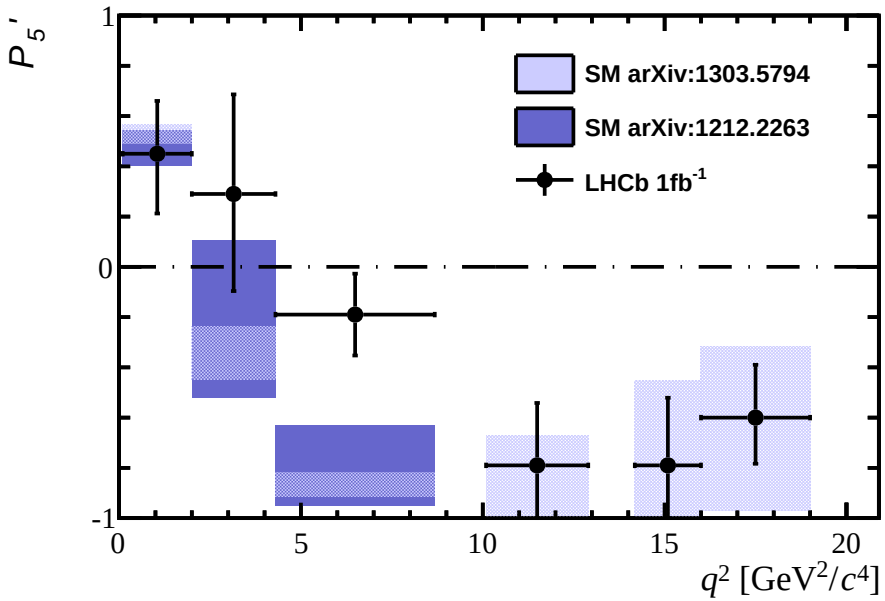
Descote-Genon et al. [arXiv:1307.5683]]

- Numerous 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]
- Demonstrates the power of these searches!
- Difficult to accomodate within MSSM

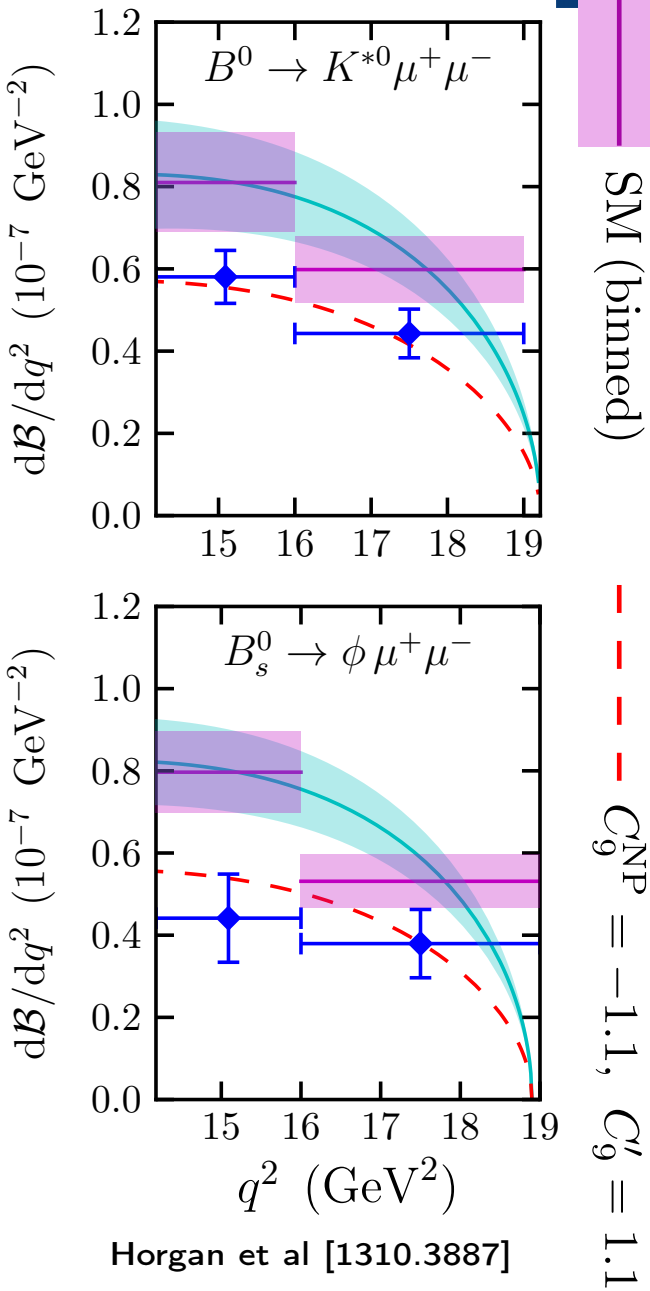


Theory uncertainties

- Unfortunately not that simple...Observables are theoretically clean at leading order



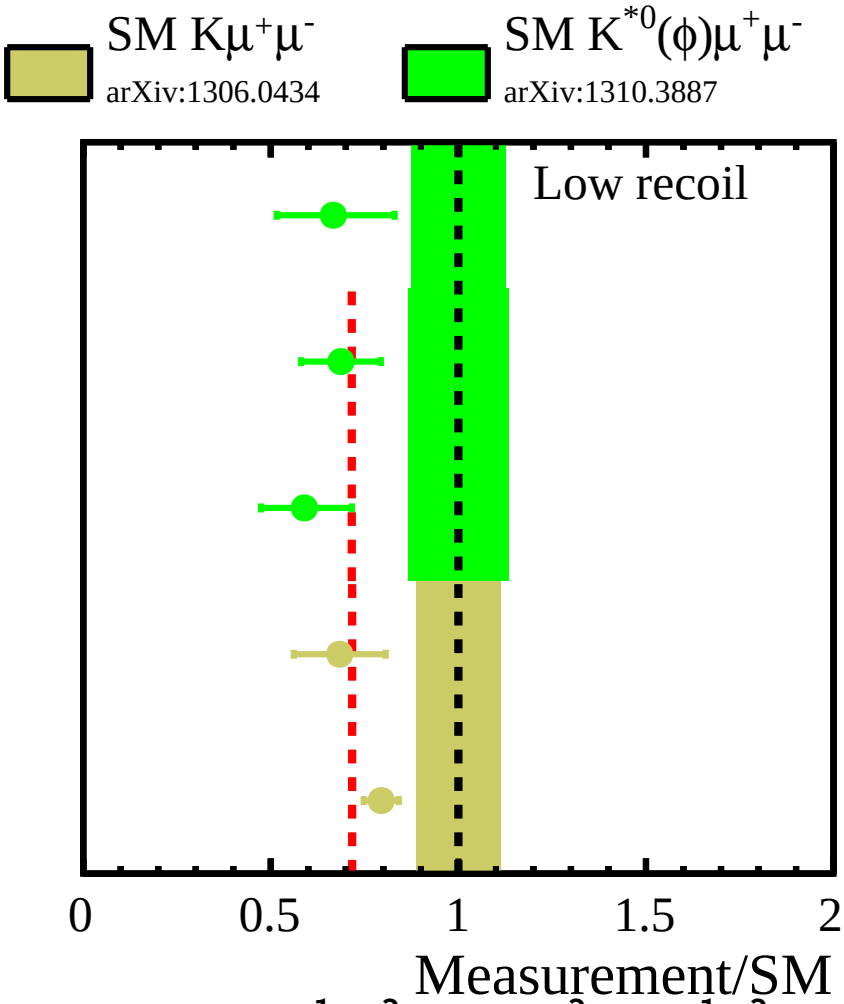
- But! Uncertainties of higher order corrections can potentially dilute the significance
- Lattice QCD predictions can help clarify situation at high $q^2 \rightarrow$ picture consistent with other interpretations!



Horgan et al [1310.3887]

A consistent picture emerging?

Branching Fraction measurements at high q^2 in tension with SM predictions from the Lattice, but consistent with best fit point for NP from low q^2 data! $\rightarrow$ NP or unaccounted QCD effects? **Something new to understand!**



1fb^{-1} BF($B_s^0 \rightarrow \phi\mu^+\mu^-$)

1fb^{-1} BF($B^0 \rightarrow K^{*0}\mu^+\mu^-$)

3fb^{-1} BF($B^+ \rightarrow K^{*+}\mu^+\mu^-$)

3fb^{-1} BF($B^0 \rightarrow K^0\mu^+\mu^-$)

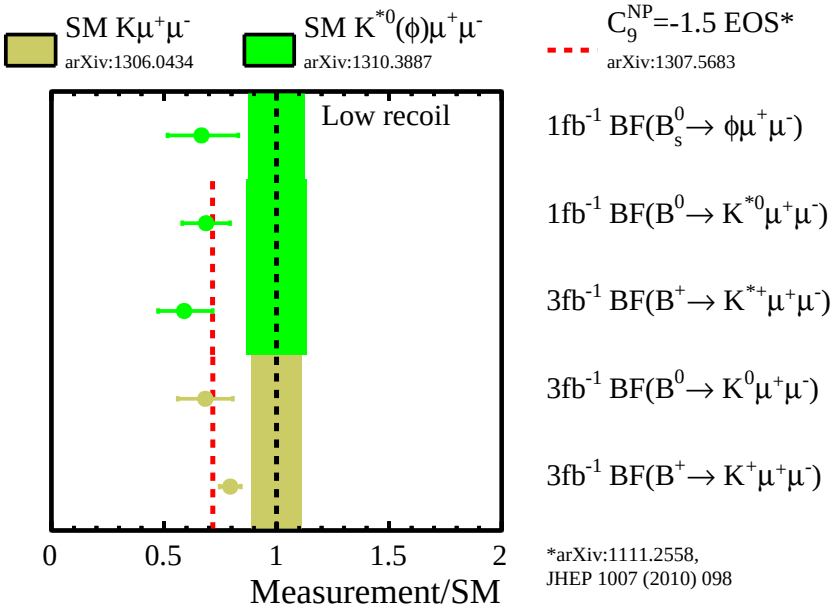
3fb^{-1} BF($B^+ \rightarrow K^+\mu^+\mu^-$)

*arXiv:1111.2558, JHEP 1007 (2010) 098

$B \rightarrow K$ **prediction, $O_{1..6}$, O_8 @ 1-loop. 2-loop moves $\mathcal{B}$ closer to experiment**

A consistent picture emerging?

Branching Fraction measurements at high q^2 in tension with SM predictions from the Lattice, but consistent with best fit point for NP from low q^2 data! $\rightarrow$ NP or unaccounted QCD effects? **Something new to understand!**



- Perform measurements in related channels (e.g $b \rightarrow d\mu^+\mu^-$ reveal information on MFV nature of NP)
- Measurements quantities with prestine theory predictions
  - e.g (semi)-inclusive $B \rightarrow X_{s,d}\ell^+\ell^-$, $B \rightarrow X_{s,d}\gamma$ Belle [1402.7134], BaBar [1312.5364]
  - Belle2 will provide precision measurements (how about LHCb?)

So what is next

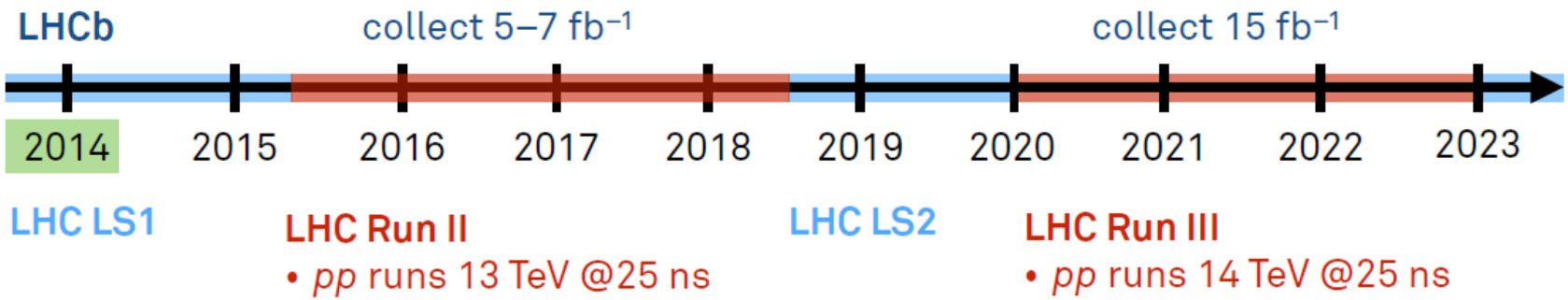
Full exploitation of available data:

- Update of $B^0 \to K^{*0}\mu^+\mu^-$ measurements with $3\,\text{fb}^{-1}$ in preparation
- $d\mathcal{B}/dq^2$ measurement will also include a measurement of the S-wave in $K\pi$ system
- Angular analysis to extract all experimental observables and their correlations from a single fit
  - Measurement of observables in bins of q^2
  - Measurement of K^* helicity amplitudes in a q^2 dependent way
  - Direct extraction of Wilson coefficients from angular distribution
- New and updates of all analyses to $3\,\text{fb}^{-1}$: $B_s \to \phi\mu^+\mu^-$, $B^+ \to \pi^+\mu^+\mu^-$, $B_{s,d} \to \pi\pi\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$, $\Lambda_b \to pK\mu^+\mu^-$, $B \to K^{*0}e^+e^-$, $B_s \to \phi\gamma$

RunII data means $\sim 5\,\text{fb}^{-1}$ expected to be collected

- 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)
- Look for final states with τ's (?)(experimentally more challenging)
- Perform inclusive measurements (?)

LHCb upgrade



- Current conditions: L_{inst} up to $4 \times 10^{32} cm^{-2} s^{-1}$, $\mu \sim 1.7$
- 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...
- Current trigger design has bottleneck at 1 MHz of L0
- More flexible trigger, reading out full detector at 40 MHz and HLT output at 20 kHz
- Upgrade VELO and tracking
- New photo detectors for RICH1,2 and re-optimise optics of RICH1

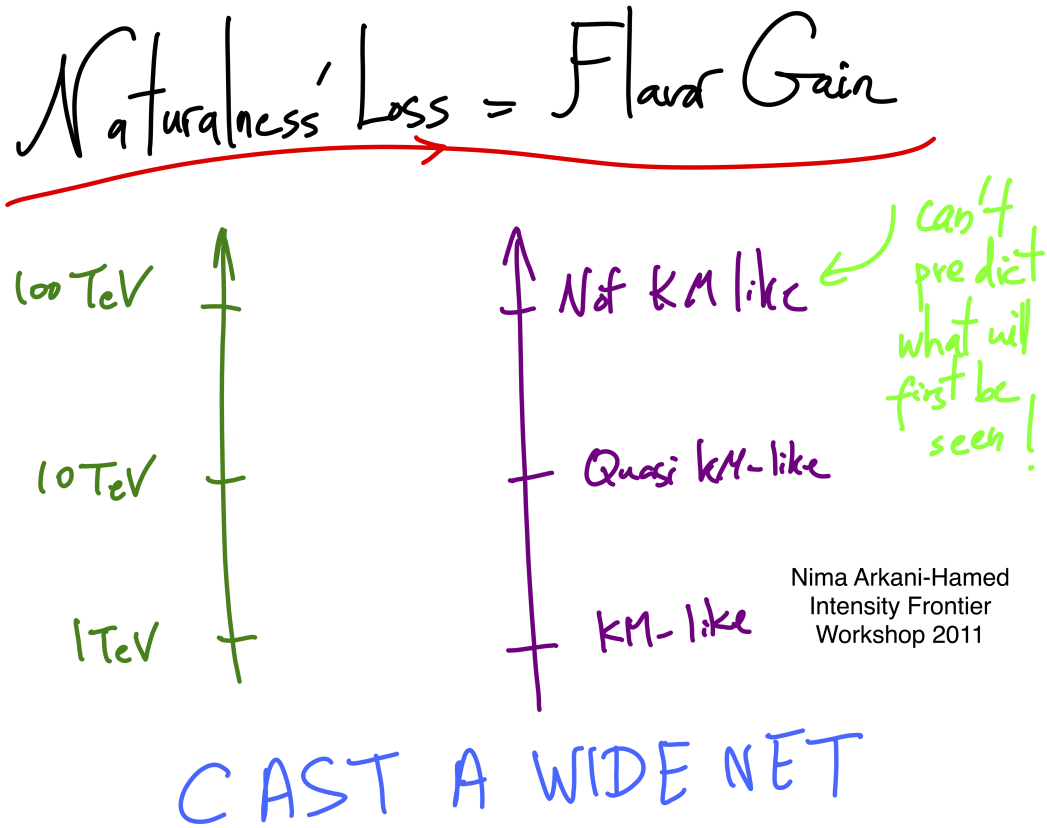
[LHCb-TDR-013], [LHCb-TDR-014], [LHCb-TDR-015]

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 %	~ 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}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\, K_S^0)$	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}	–

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

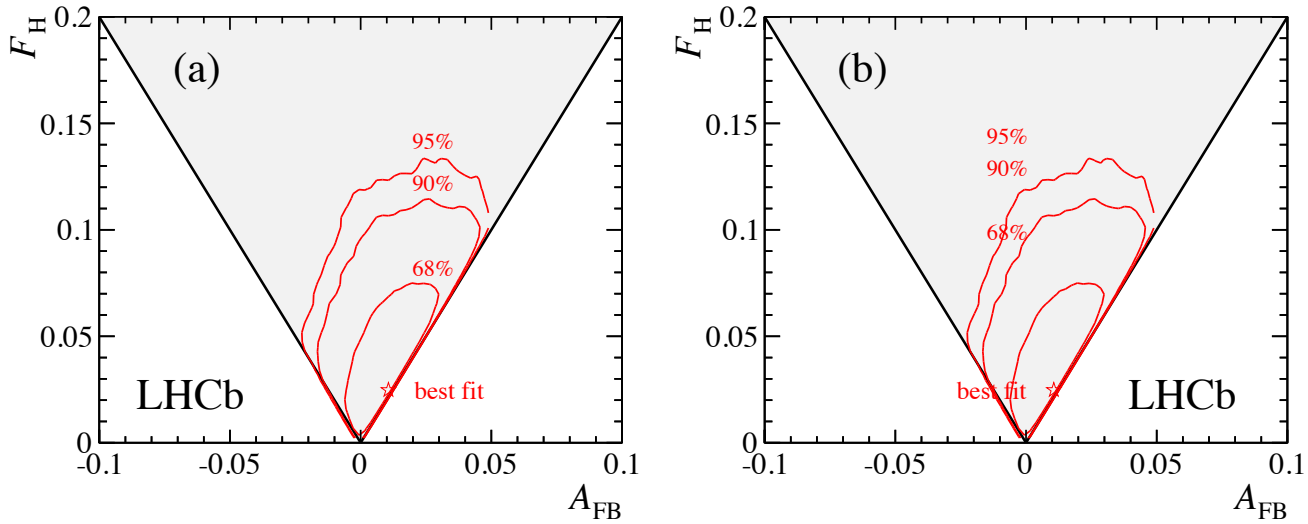


Backup

Angular analysis of $B^+ \to K^+\mu^+\mu^-$ [1403.8045]

Using 3 fb^{-1} of data

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_l} = \frac{3}{4}(1 - F_{\mathrm{H}})(1 - \cos^2\theta_l) + \frac{1}{2}F_{\mathrm{H}} + A_{\mathrm{FB}}\cos\theta_l$$



- F_H: "Flat" parameter sensitive to scalar and tensor contributions
- A_{FB}: Forward-backward asymmetry of the muons
- Best fit point and SM lie at boundary of physical region of pdf
- We have made these confidence intervals for each bin in q^2 available in ascii format for people to use

Belle2 and LHCb post RunI

Dolezal EPS 2013	Belle' 06 (~0.5ab^{-1})	5ab^{-1}	50ab^{-1}
$\Delta S(\phi K^0)$	0.22	0.073	0.029
$\Delta S(\eta' K^0)$	0.11	0.038	0.020
$\Delta S(K_S K_S K_S)$	0.33	0.105	0.037
$\Delta S(K_S \pi^0 \gamma)$	0.32	0.10	0.03
$Br(X_s \gamma)$	13%		
$A_{CP}(X_s \gamma)$	0.058	0.01	0.005
C_9 [A_{FB}(K*ll)]	---	11%	4%
C_{10} [A_{FB}(K*ll)]	---	13%	4%
$Br(B^+ \to K^+ \nu\nu)$	<9Br(SM)	33ab^{-1} for 5σ discovery	
$Br(B^+ \to \tau\nu)$	3.5σ	10%	3%
$Br(B^+ \to \mu\nu)$	<2.4Br(SM)	4.3ab^{-1} for 5σ discovery	
$Br(B^+ \to D\tau\nu)$	---	7.9%	2.5%
$Br(\tau \to \mu\gamma)$	<45	<30	<8
$Br(\tau \to \mu\eta)$	<65	<20	<4
$Br(\tau \to 3\mu)$	<209	<10	<1
$\Delta \sin 2\phi_1$	0.026	0.016	0.012
$\Delta\Phi_2$ ($\rho\pi$)	68°—95°	3°	1°
$\Delta\Phi_3$(Dalitz)	20°	7°	2.5°
ΔV_{ub} (incl.)	7.3%	6.6%	6.1%

X10^{-9}

Belle II

Data-taking starts 2014-2015!
50 ab^{-1} by 2021

LHCb

	Observable	Current precision	LHCb 2018	**Upgrade** (50 fb^{-1})
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\,\phi$)	0.10 [9]	0.025	0.008
	$2\beta_s$ ($B_s^0 \to J/\psi\, f_0(980)$)	0.17 [10]	0.045	0.014
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Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.08 [14]	0.025	0.008
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	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.25 [15]	0.08	0.025
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %
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	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	$\sim$ 10–12° [19, 20]	4°	0.9°
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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}

Upgrade data-taking starts 2019-2020 [LHCB-TDR-012]

- Two experiments offering vital complementarity and cross-checks