LHCb results on rare B decays

T. Blake on behalf of the LHCb collaboration

Zurich Phenomenology Workshop, 2015

Outline

- Review of recent LHCb results on rare b-hadron decays from `Run I` of the LHC.
  1. Observation of $B_s^0 \to \mu^+\mu^-$.
  2. Up-down asymmetry and $b \to s\gamma$ photon polarisation.
  3. $B \to K^{(*)}\mu^+\mu^-$ branching fractions and angular distribution.
  4. Tests of MFV in $b \to \ell^+\ell^-$ decays.
- Most results are now based on the full dataset of $3\,\mathrm{fb}^{-1}$ of integrated luminosity collected in 2011 ($1\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7\,\mathrm{TeV}$) and 2012 ($2\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$).

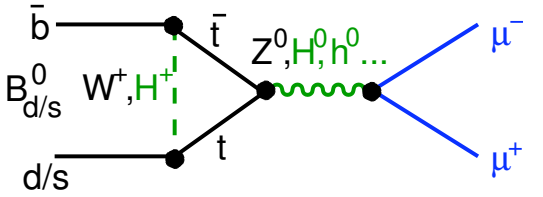
$$B^0_{(s,d)} \to \mu^+\mu^-$$

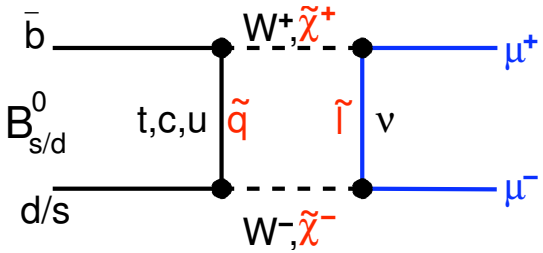
$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

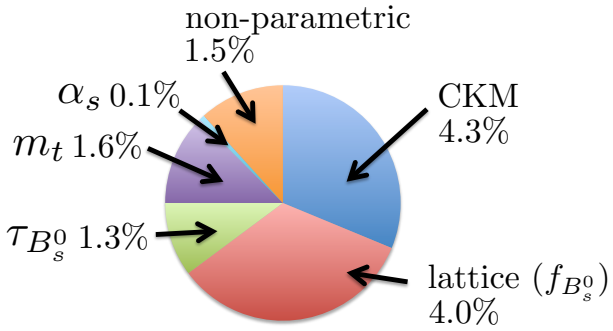
- B^0 and $B_s^0 \to \mu^+\mu^-$ are loop, CKM and helicity suppressed in the SM.
- Sensitive probe of models with reduced helicity suppression
  e.g. models with extended Higgs sectors (e.g. MSSM, 2HDM, ...)
- Predicted precisely in the SM:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

[Bobeth et al. PRL 112 101801 (2014)]





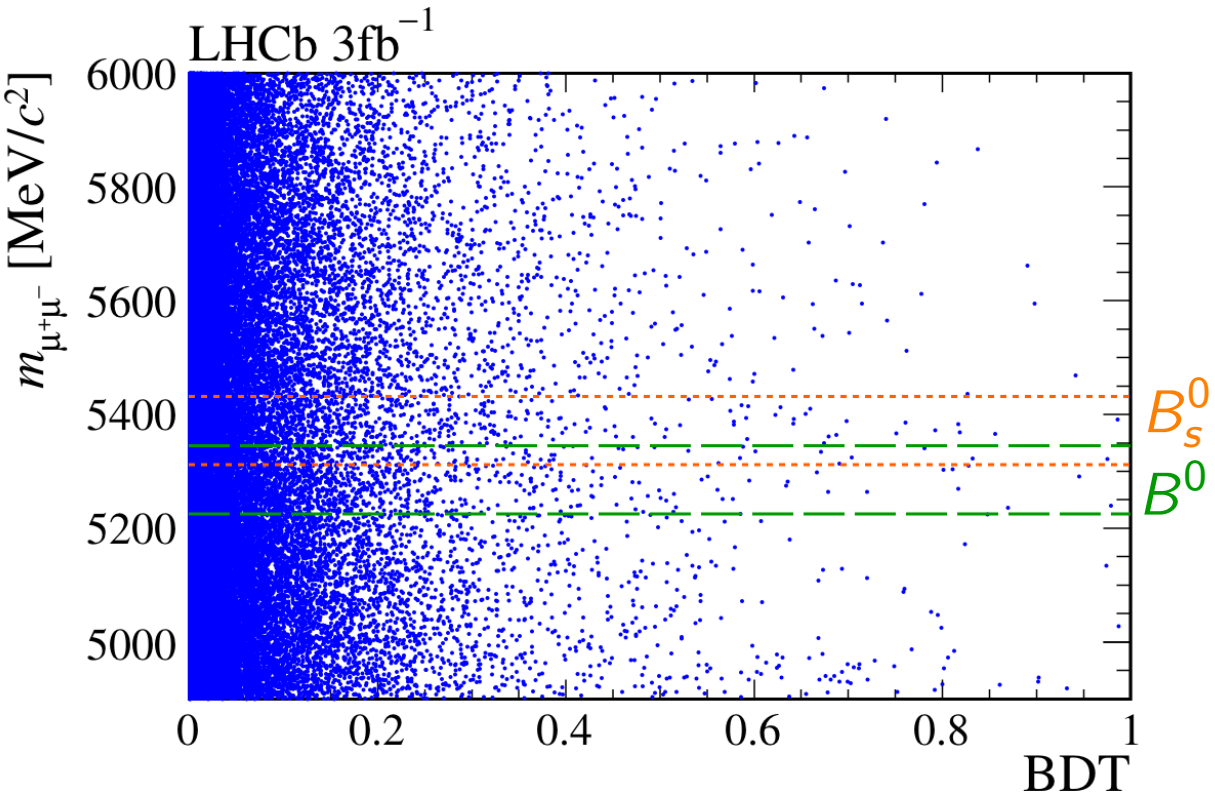


Bobeth et al. PRL 112 101801 (2014)

- $B^0 \to \mu^+\mu^-$ decay suppressed by further factor of $|V_{td}/V_{ts}|^2$. An important test of the MFV hypothesis.

$B_s^0 \to \mu^+\mu^-$ searches

- Background rejection key for rare decay searches $\to$ use multivariate classifiers (BDTs) and tight particle identification requirements.

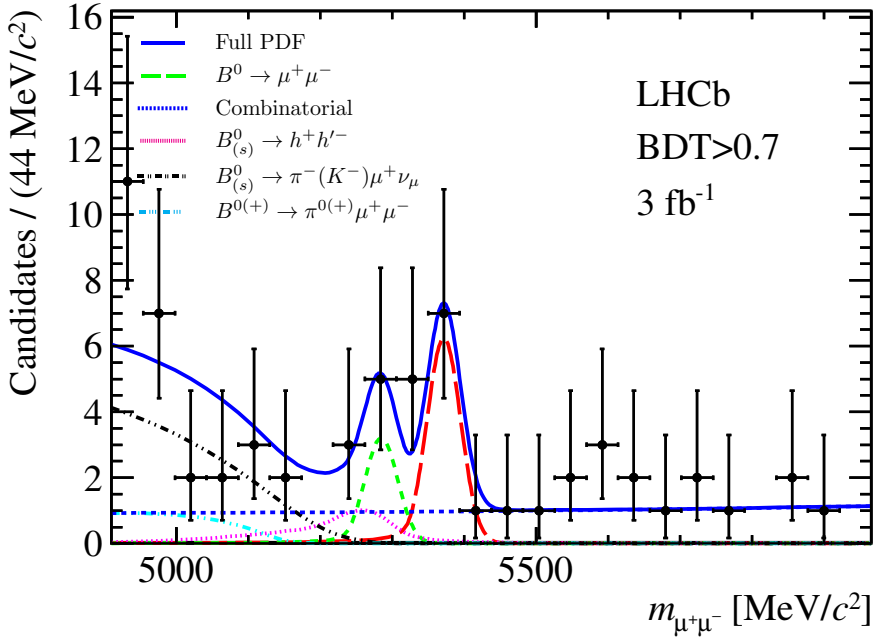


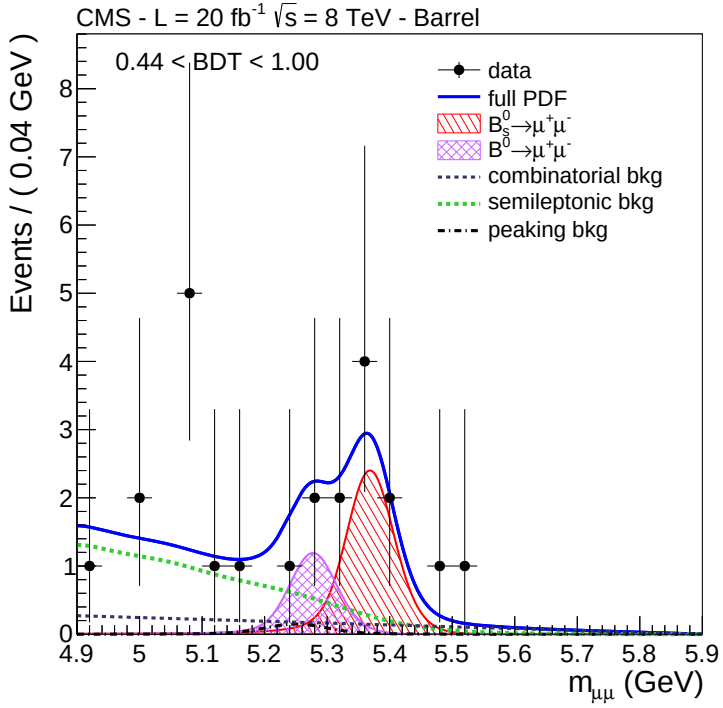
Calibrate the BDT response on MC or data ($B \to h^+h^-$).

Normalise branching fraction w.r.t. a control mode (e.g. $B^+ \to J/\psi K^+$)

Correct for B_s^0/B^0 production using f_s/f_d.

$B_s^0 \to \mu^+\mu^-$ at the LHC

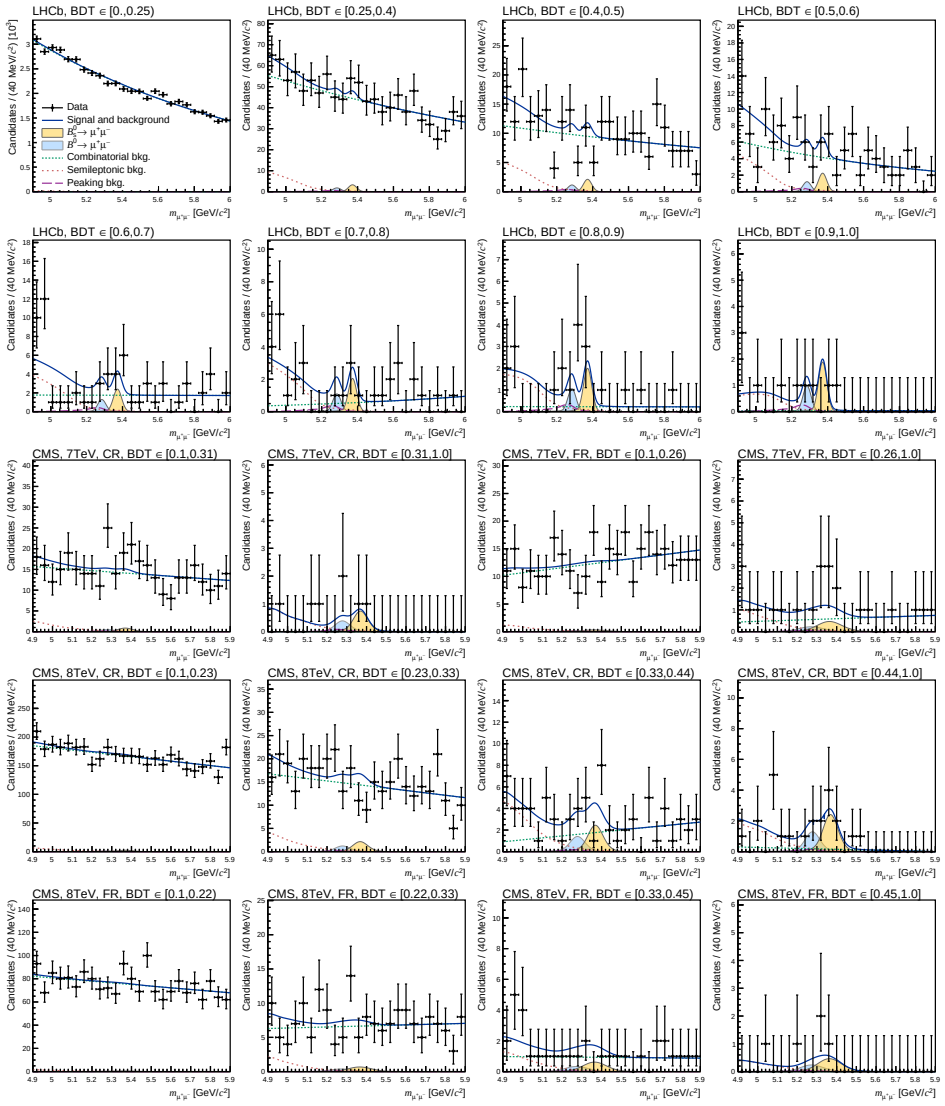




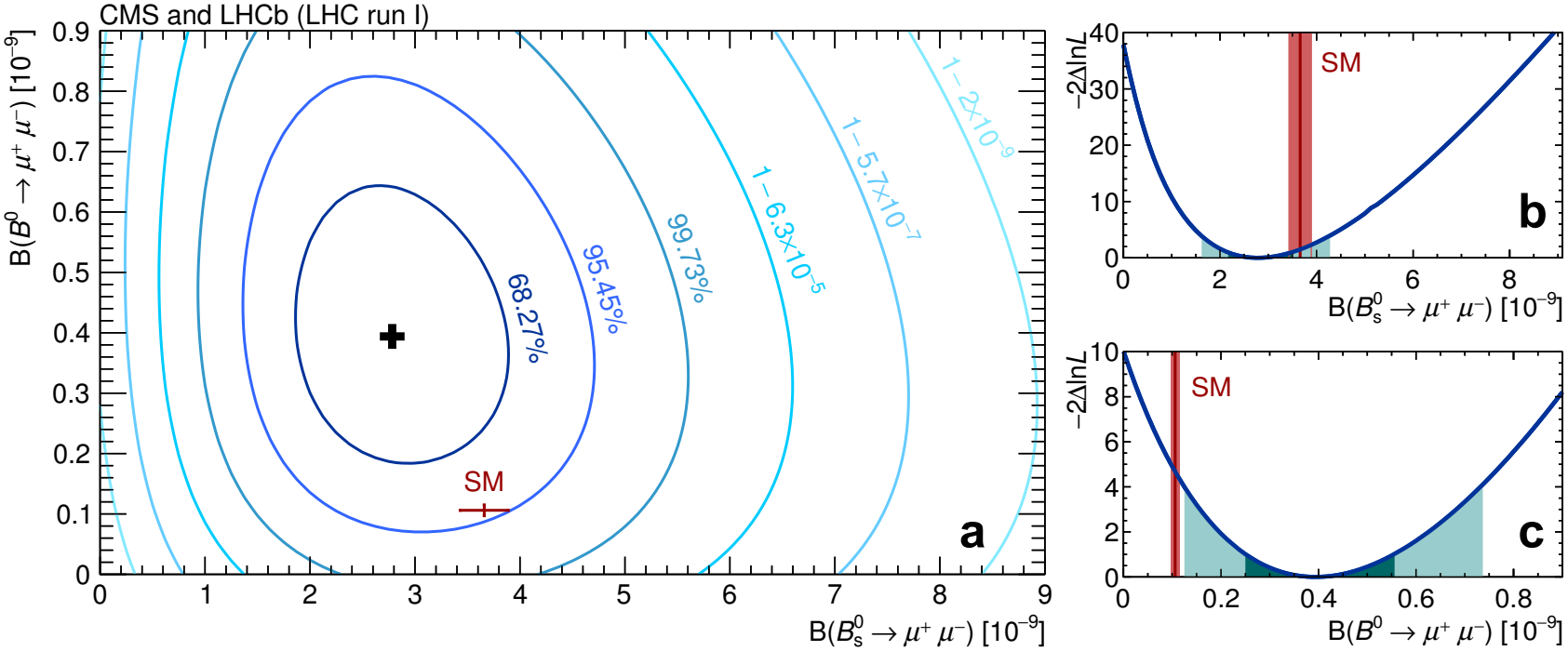
- In 3 fb^{-1} LHCb sees evidence for $B_s^0 \to \mu^+\mu^-$ at 4.0σ with $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}{}^{+0.3}_{-0.1}) \times 10^{-9}$. [PRL 111 (2013) 101805]
- In 20 fb^{-1} CMS sees evidence for $B_s^0 \to \mu^+\mu^-$ at 4.3σ with $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$. [PRL 111 (2013) 101804]

CMS & LHCb $B^0_{(s,d)} \to \mu^+\mu^-$ combination

- Simultaneous analysis of the LHCb and CMS datasets, with shared signal parameters and nuisance parameters (where appropriate).
- Data binned in BDT response for both experiments and by barrel and encamp regions for CMS.



CMS & LHCb $B^0_{(s,d)} \to \mu^+\mu^-$ combination



- Observe $B^0_s \to \mu^+\mu^-$ & see first evidence for $B^0 \to \mu^+\mu^-$ (3σ), with

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

- Small correlation between B^0 and B^0_s due to mass resolution.

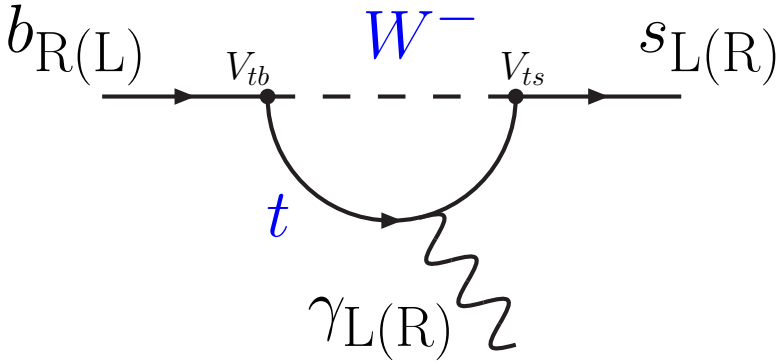
$\to$ Compatible with SM at 1.2σ (B^0_s) and 2.2σ (B^0)

Photon polarisation in $b \to s\gamma$

Photon polarisation in $b \to s\gamma$ decays

- $B^0 \to K^{*0}\gamma$ was the first penguin decay ever observed, by CLEO in 1992 .[PRL 71 (1993) 674]
- We know from the B-factories that $\mathcal{B}(b \to s\gamma)$ is compatible with SM expectation. What else do we know?

$\rightsquigarrow$ In the SM, photons from $b \to s\gamma$ decays are predominantly left-handed ($C_7/C_7' \sim m_b/m_s$) due to the charged-current interaction.



Can test C_7/C_7' using:

$\rightsquigarrow$ Mixing-induced CP violation [Atwood et al PRL 79 (1997) 185-188],

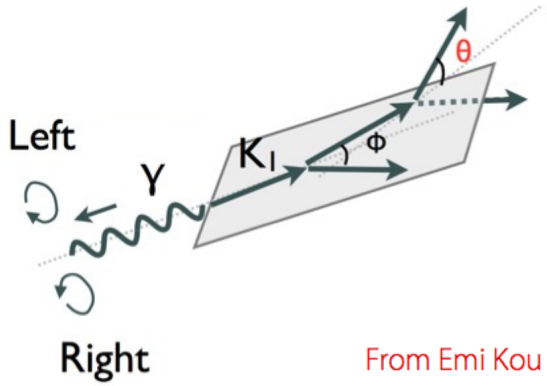
$\rightsquigarrow$ Λ_b^0 baryons [Hiller & Kagan PRD 65 (2002) 074038],

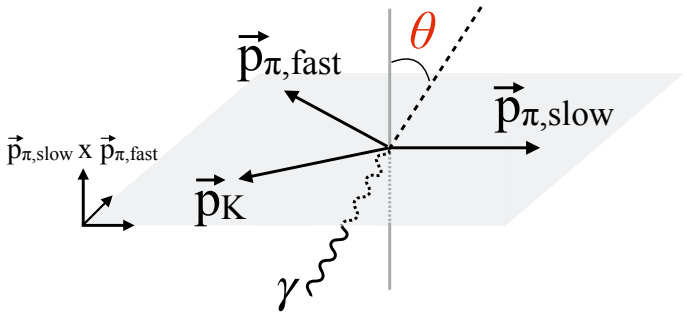
$\rightsquigarrow$ $B^0 \to K^{*0}\ell^+\ell^-$ at large recoil.

Photon polarisation from $B^+ \to K^+\pi^-\pi^+\gamma$

or $B \to K^{**}\gamma$ decays such as $B^+ \to K_1(1270)\gamma$.
[Gronau & Pirjol PRD 66 (2002) 054008]

- Can infer the photon polarisation from the up-down asymmetry of the photon direction in the $K^+\pi^-\pi^+$ rest-frame. Unpolarised photons would have no asymmetry.
- This is conceptionally similar to the Wu experiment, which first observed parity violation.

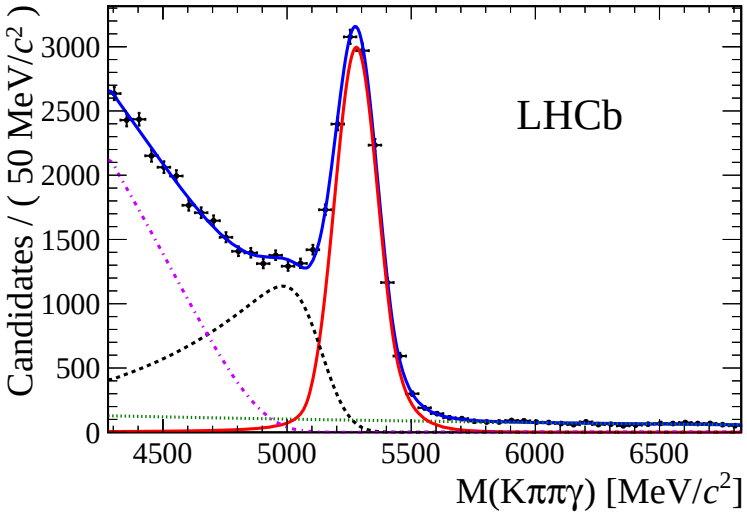


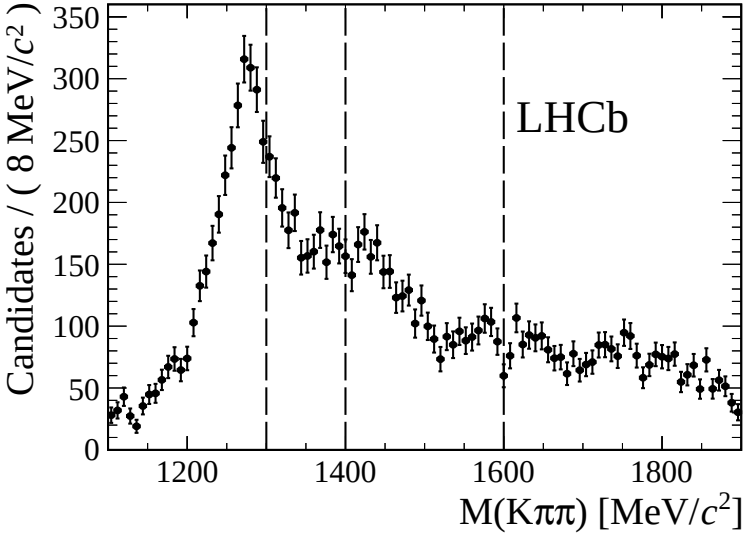


$B^+ \to K^+\pi^-\pi^+\gamma$ at LHCb

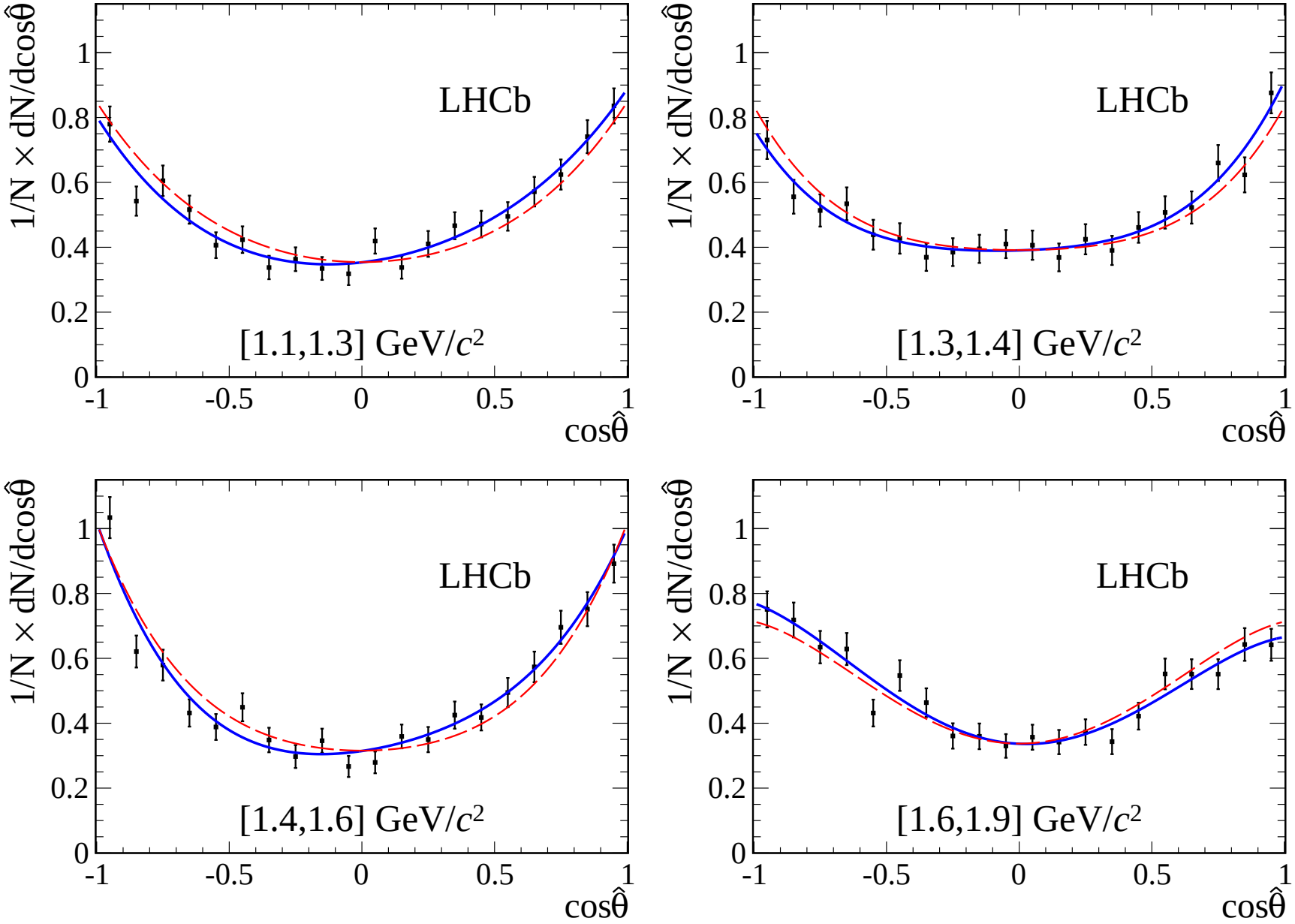
[PRL 112 (2014) 161801]

- At LHCb we reconstruct $B^+ \to K^+\pi^-\pi^+\gamma$ decays using unconverted photons.
- Observe $\sim 13,000$ signal candidates in $3\,\mathrm{fb}^{-1}$.
- There are a large number of overlapping resonances in the $M(K^+\pi^-\pi^+)$ mass spectra. No attempt is made to separate these in the analysis, we simply bin in 4 bins of $M(K^+\pi^-\pi^+)$.





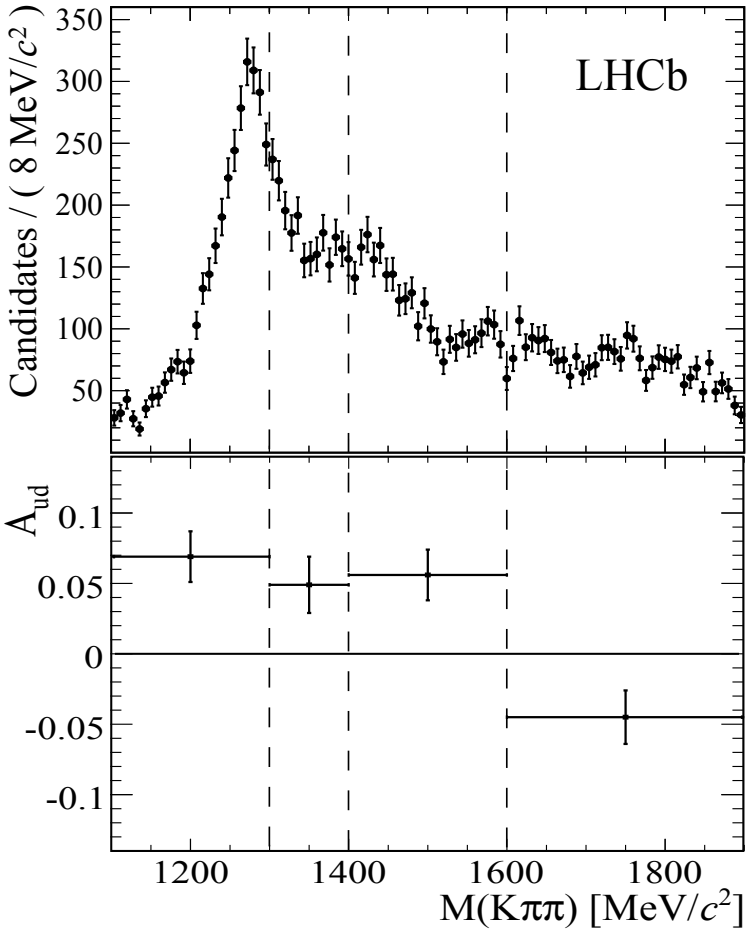
Best fit, Unpolarised ($C_7 = C_7'$)



Up-down asymmetry

[PRL 112 (2014) 161801]

- Combining the 4 bins, observe non-zero photon polarisation at 5.2σ.
- Unfortunately you need to understand the hadronic system to know if the polarisation is predominantly left-handed, as expected in the SM.



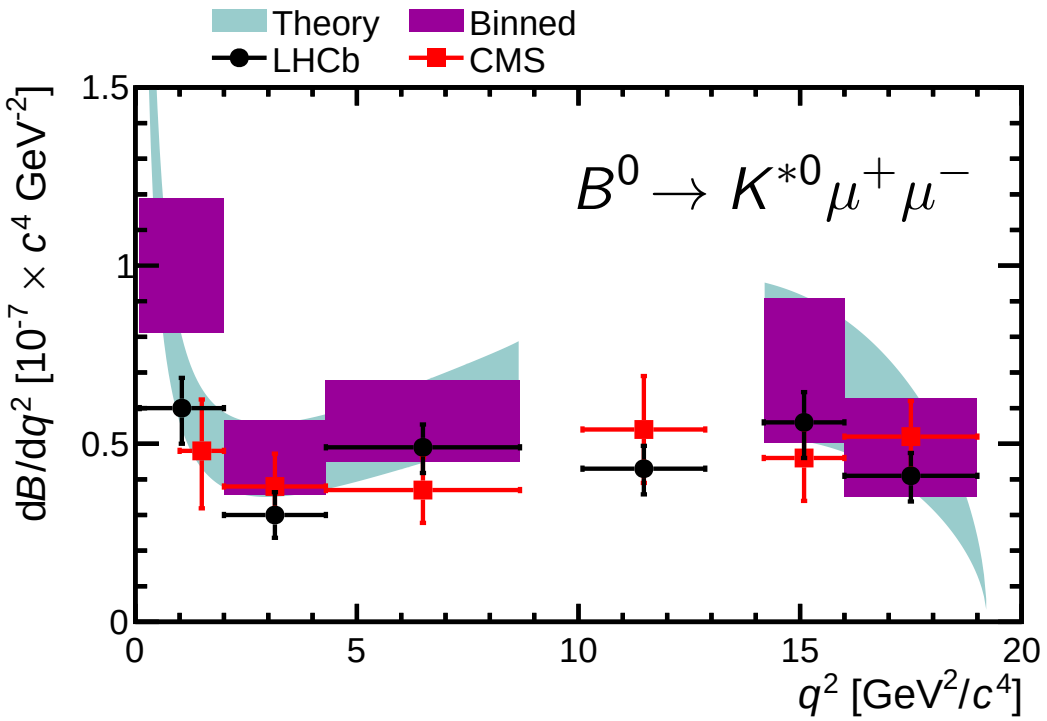
$\rightarrow$ First observation of photon polarisation in $b \rightarrow s\gamma$ decays

$$b \to s\ell^+\ell^-$$

branching fractions and asymmetries

Branching fraction of $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 08 (2013) 13]

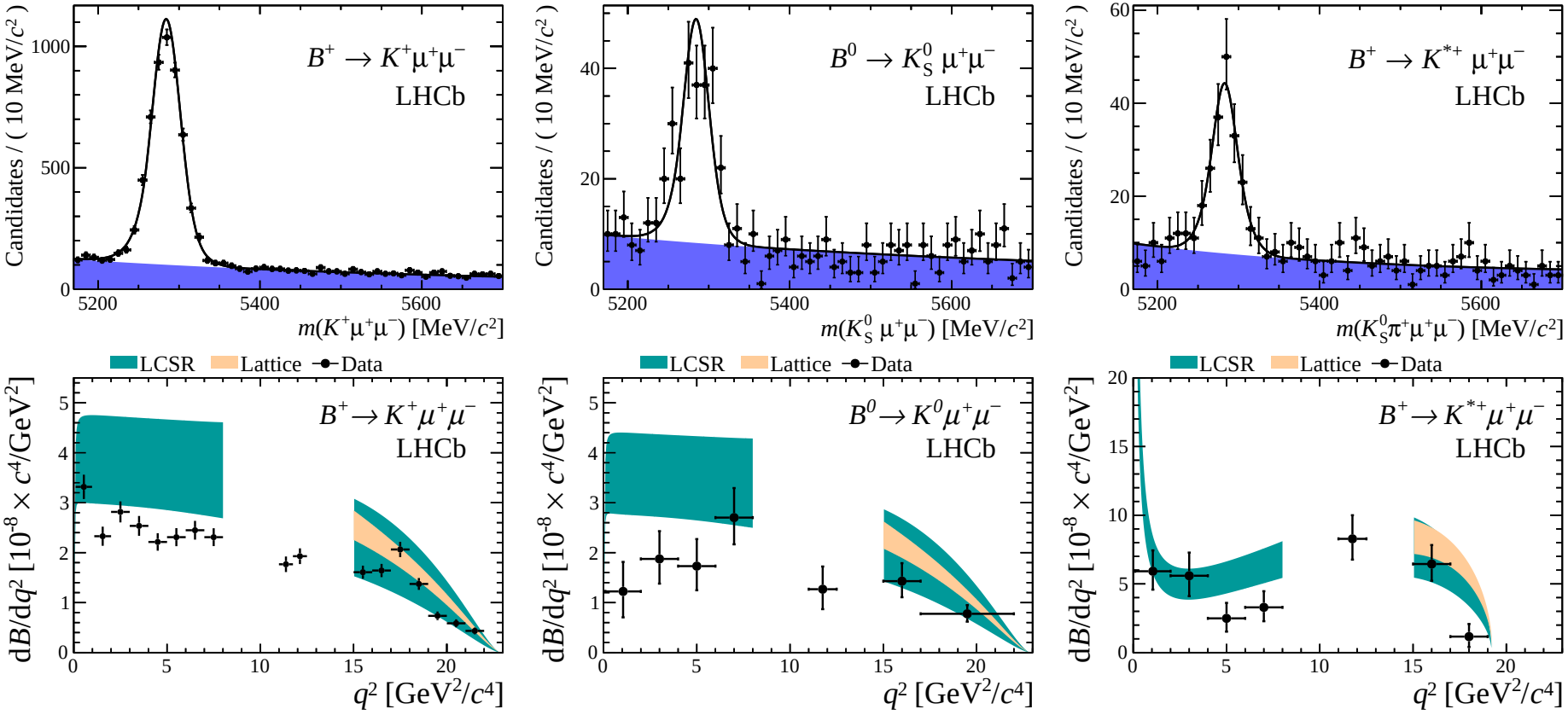
- At the LHC we are able to profit from the large $\sigma_{b\bar{b}}$ to reconstruct large samples of exclusive $b \to s\ell^+\ell^-$ decays.
- Large increase in yields over B-factories for $\ell^\pm = \mu^\pm$.



Theory prediction from C. Bobeth et al. [JHEP 07 (2011) 067] (and references therein)

- Data set is split into bins of $q^2 = m(\mu^+\mu^-)^2$ to measure $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$.
- Normalise signal w.r.t. known $B \to J/\psi K^{(*)}$ branching fraction (largest source of systematic uncertainty).

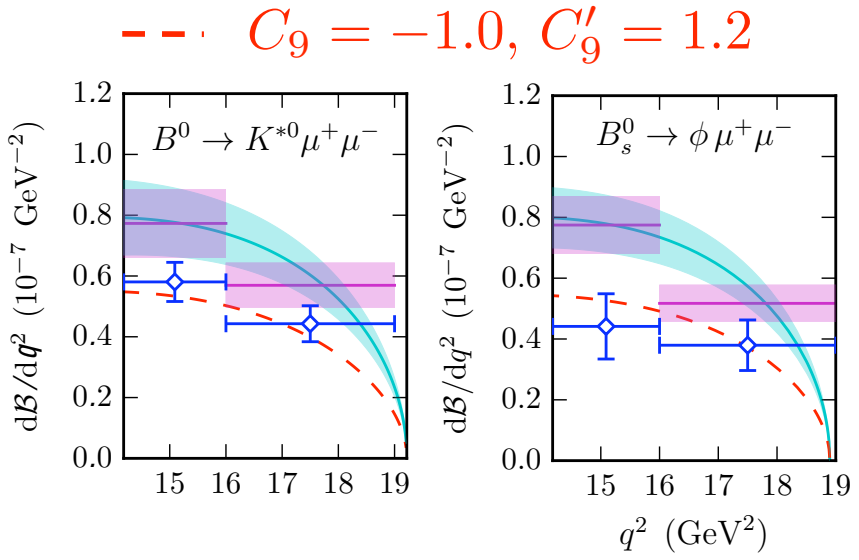
Branching fraction of $B \to K^{(*)}\mu^+\mu^-$ [JHEP 06 (2014) 133]



- SM predictions based on
  [JHEP 07 (2011) 067], [JHEP 01 (2012) 107]
  [PRL 111 (2013) 162002], [PRL 112 (2014) 212003].

Comment on branching fraction measurements

- There is a general tendency for the measured branching fractions to be smaller than the corresponding SM expectation. This trend is seen at both low and high q^2.
- Behaviour also seen in $B_s^0 \to \phi\mu^+\mu^-$ decays. [JHEP 07 (2013) 084]



Horgan et al [arXiv:1310.3887]

Isospin asymmetries

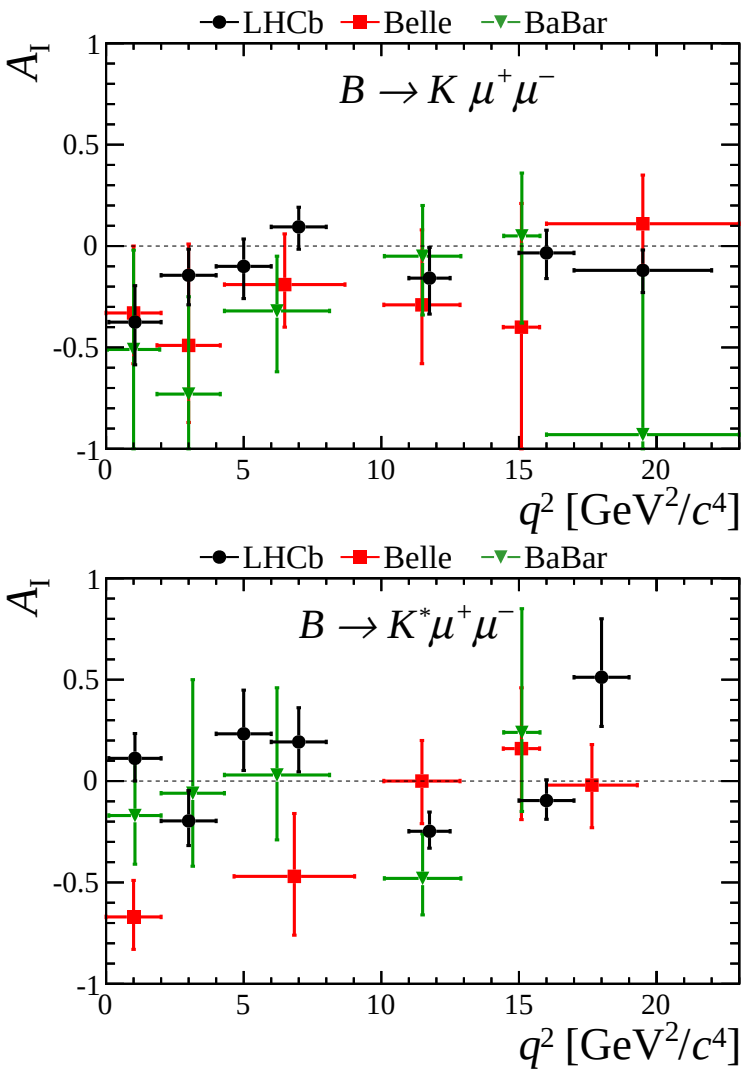
[JHEP 06 (2014) 133]

- In the SM expect the partial widths of rare B^+ and B^0 decays to be almost identical

$$A_{\mathrm{I}} = \frac{\Gamma[B^+ \to K^{(*)+}\mu^+\mu^-] - \Gamma[B^0 \to K^{(*)0}\mu^+\mu^-]}{\Gamma[B^+ \to K^{(*)+}\mu^+\mu^-] + \Gamma[B^0 \to K^{(*)0}\mu^+\mu^-]}$$

A_{I} is of $\mathcal{O}(1\%)$

- Sensitive to spectator quark differences in the form-factors (exchange and annihilation processes).
- Updated measurements are consistent with zero isospin asymmetry.



Belle [PRL 103 (2009) 171801]

BaBar [PRD 86 (2012) 032012]

Direct CP asymmetries [JHEP 09 (2014) 177]

- Direct CP asymmetries

$$\mathcal{A}_{CP} = \frac{\Gamma[\overline{B} \to \overline{K}^{(*)}\mu^+\mu^-] - \Gamma[B \to K^{(*)}\mu^+\mu^-]}{\Gamma[\overline{B} \to \overline{K}^{(*)}\mu^+\mu^-] + \Gamma[B \to K^{(*)}\mu^+\mu^-]}$$

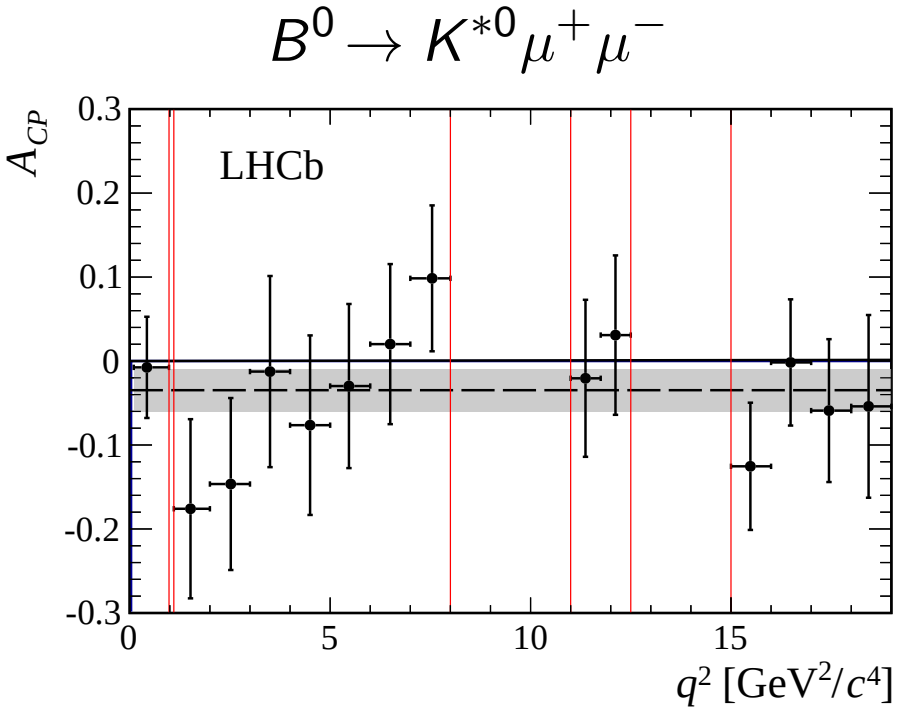
  expected to be tiny in SM, due to small size of $|V_{ub}V_{us}^*|$.
- Correct the observed asymmetry $\mathcal{A}_{\mathrm{RAW}}$ for production ($\mathcal{A}_{\mathrm{P}}$) and detection ($\mathcal{A}_{\mathrm{D}}$) asymmetries using $B \to K^{(*)}J/\psi$.

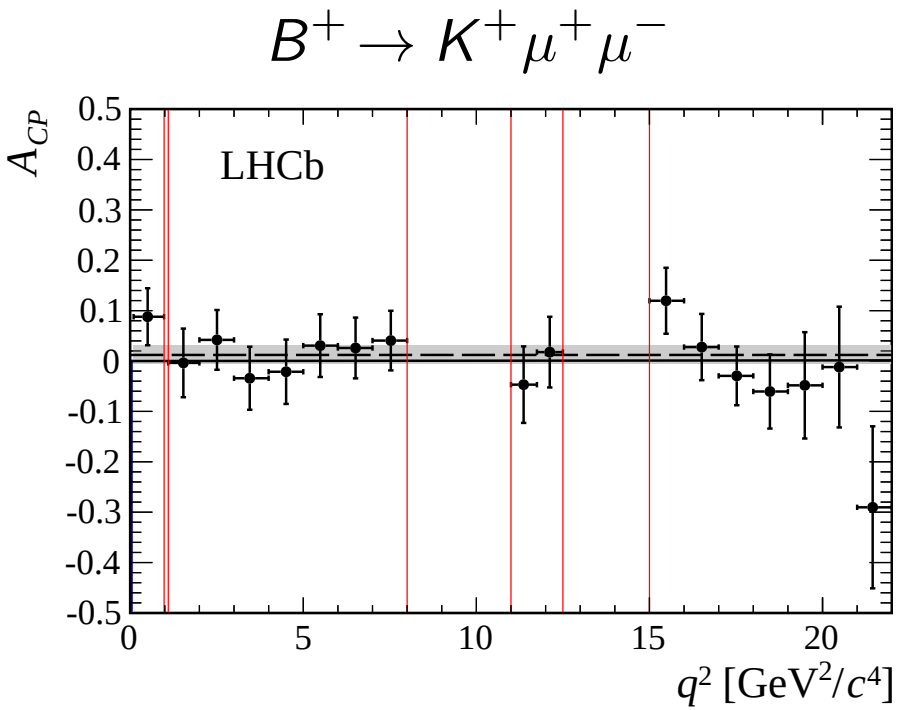
$$\mathcal{A}_{CP}(B \to K^{(*)}\mu^+\mu^-) = \mathcal{A}_{\mathrm{RAW}} - \mathcal{A}_{\mathrm{D}} - \kappa\mathcal{A}_{\mathrm{P}} \approx \mathcal{A}_{\mathrm{RAW}} - \mathcal{A}_{\mathrm{RAW}}^{K^{(*)}J/\psi}$$

- Kinematic differences between $B \to K^{(*)}J/\psi$ and $B \to K^{(*)}\mu^+\mu^-$ accounted for by re-weighting.
- Additional cancellation of left-right detector asymmetries by averaging data taken with $+ve$ and $-ve$ magnet polarities.

Direct CP asymmetries

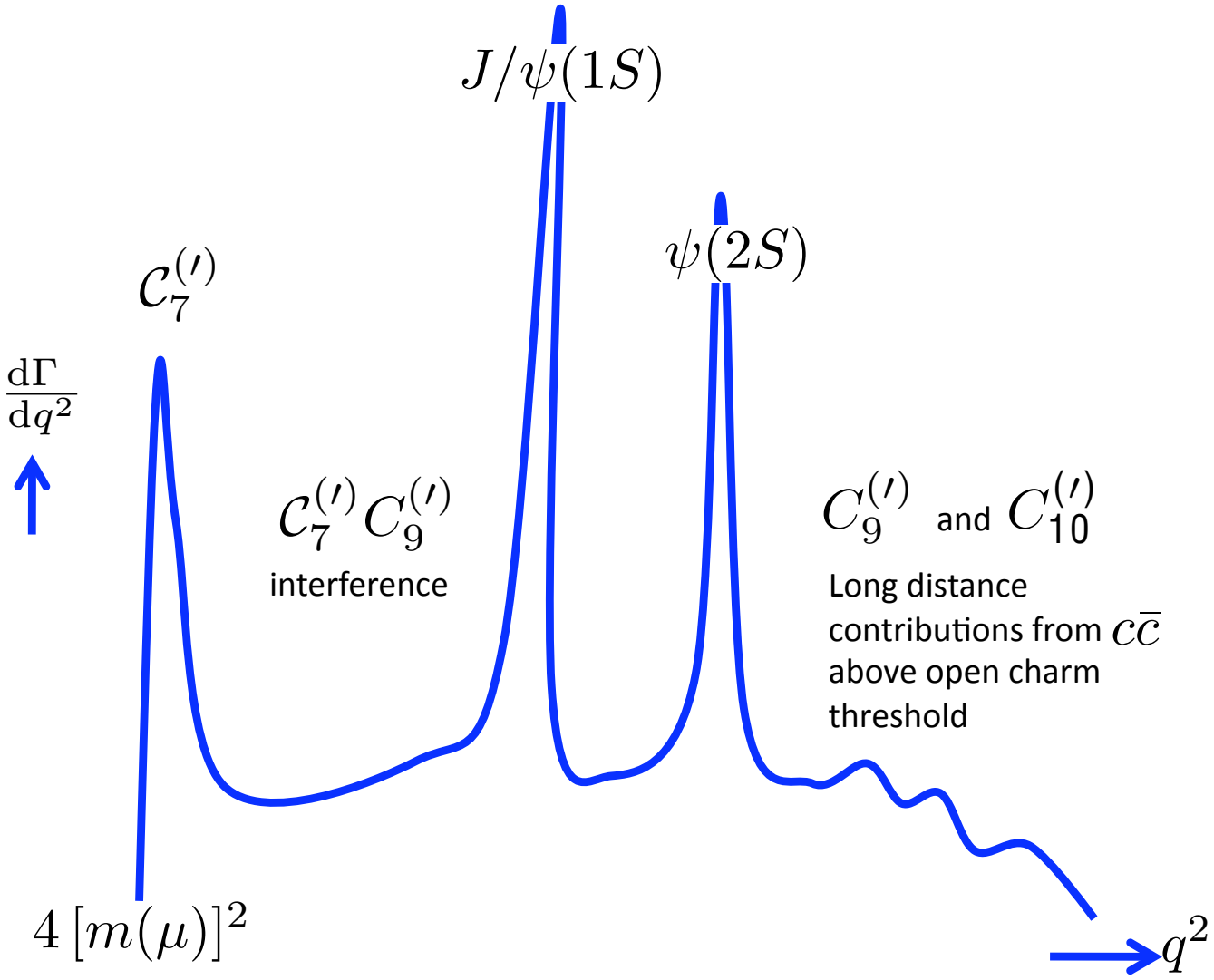
[JHEP 09 (2014) 177]





- Results are consistent with $\mathcal{A}_{CP} = 0$, i.e. consistent with SM expectation.

Anatomy of the $B^0 \to K^{*0}\mu^+\mu^-$ decay



No photon (C_7) enhancement of $B \to K\mu^+\mu^-$ decays at low q^2.

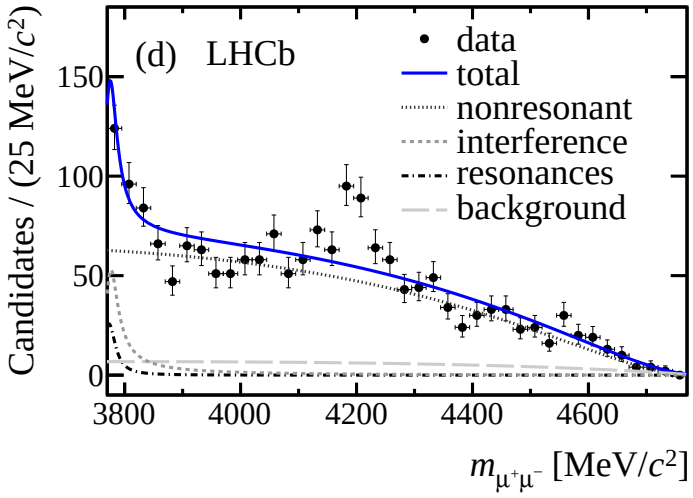
Broad $c\bar{c}$ contributions at high q^2

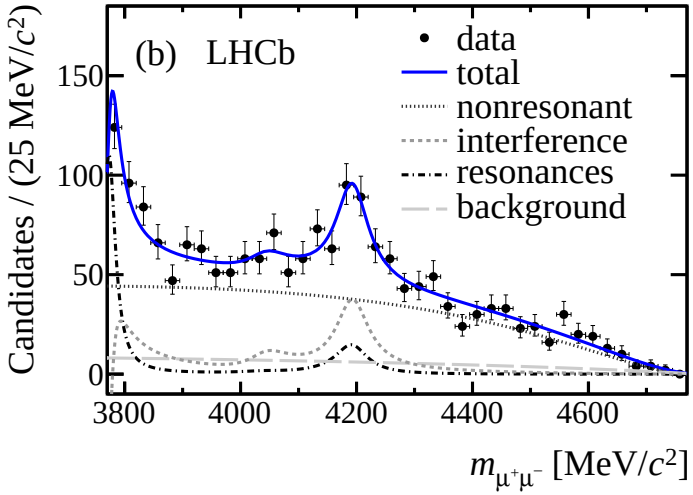
[PRL 111 (2013) 112003]

- $B^+ \to K^+\mu^+\mu^-$ data shows clear resonant structure.

→ First observation of $B^+ \to \psi(4160)K^+$ and $\psi(4160) \to \mu^+\mu^-$. [PRL 111 (2013) 112003]

- Beylich, Buchalla & Feldman Theory calculations take $c\bar{c}$ contributions into account (through an OPE) but not their resonant structure. [EPJC 71 (2011) 1635]





$$b \to s\ell^+\ell^-$$

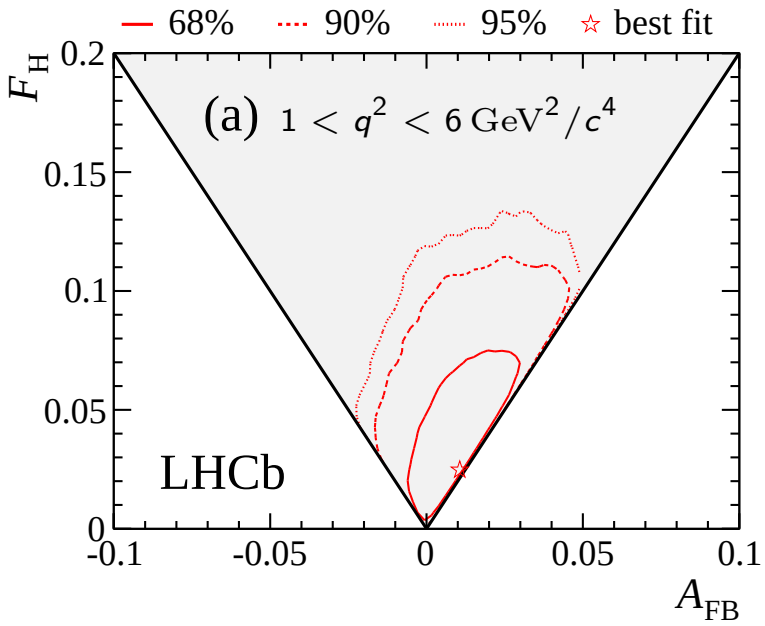
angular distributions

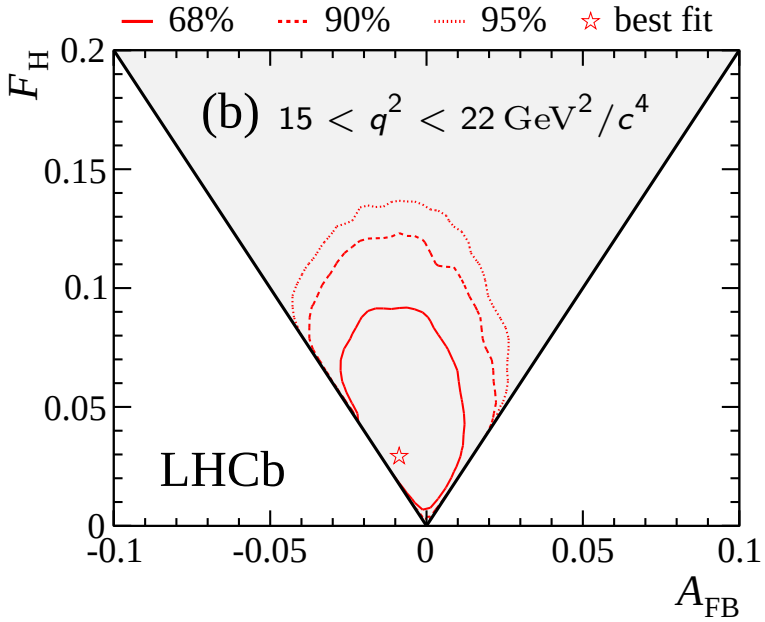
$B^+ \to K^+\mu^+\mu^-$ angular distribution [JHEP 05 (2014) 082]

- Single angle (θ_l) and two parameters describe the decay

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

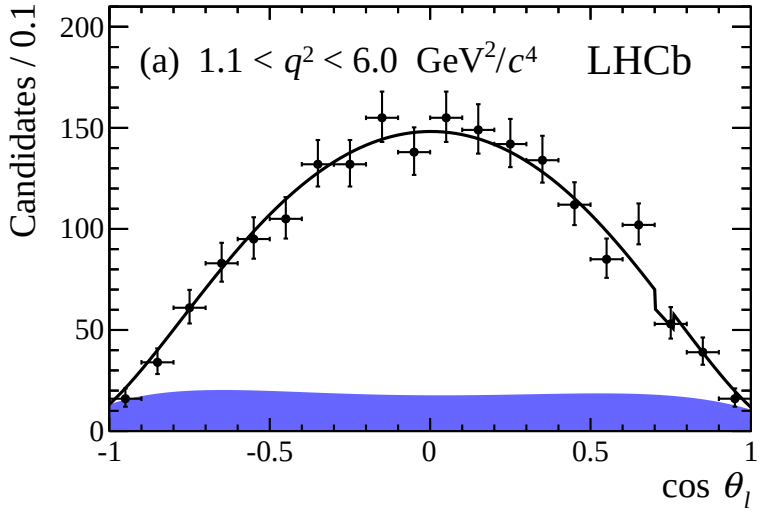
- F_{H} corresponds to the fractional contribution of (pesudo)scalar and tensor operators to Γ.
- Angular distribution is only +ve for $A_{\mathrm{FB}} \leq F_{\mathrm{H}}/2$ and $F_{\mathrm{H}} \geq 0$.
- In SM expect of $A_{\mathrm{FB}} \approx 0$ and $F_{\mathrm{H}} \approx 0$.

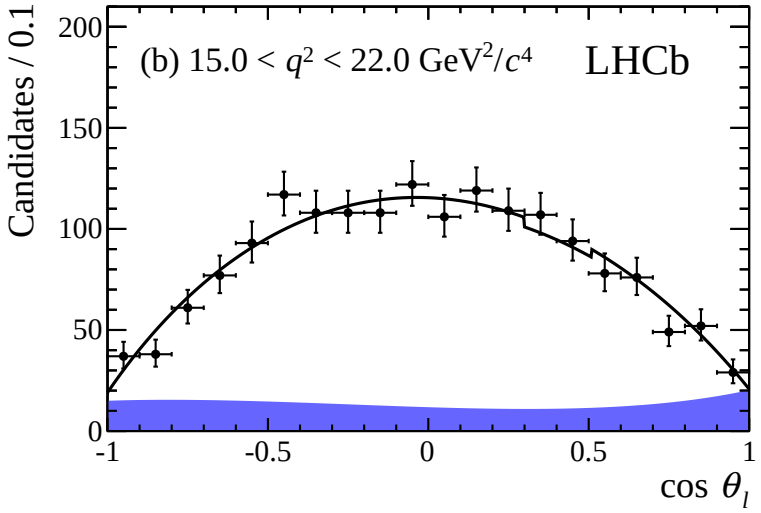




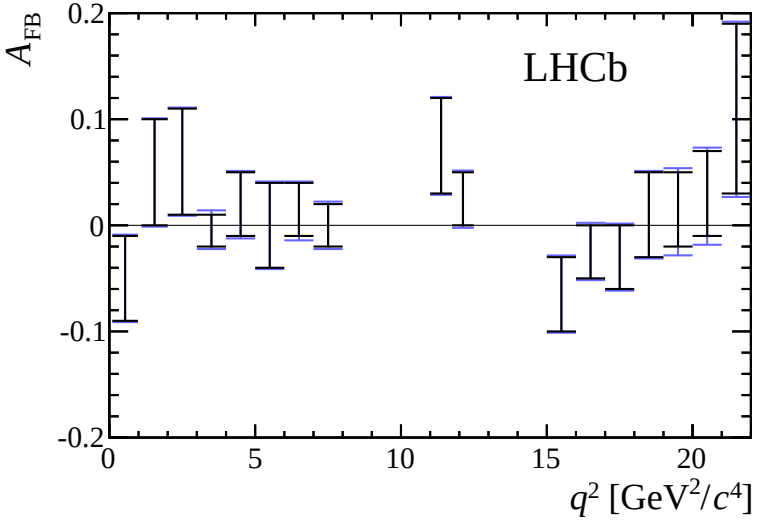
$B^+ \to K^+\mu^+\mu^-$ angular distribution

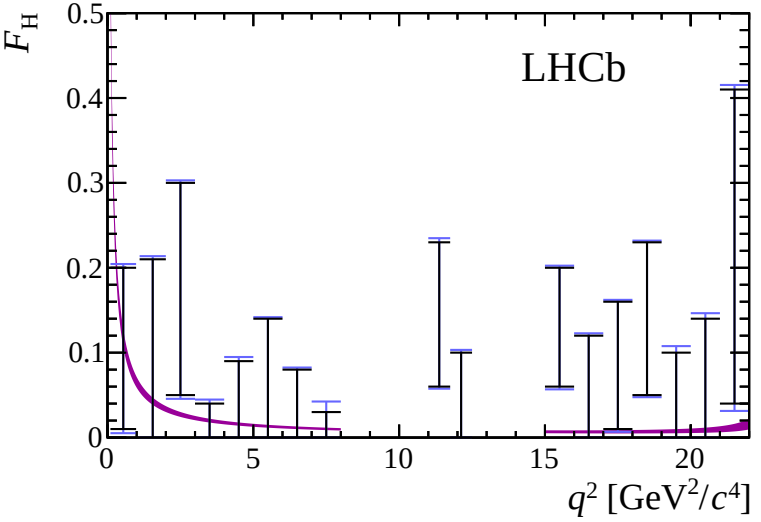
- Perform two-dimensional likelihood fit to $M(K^+\mu^+\mu^-)$ and $\cos\theta_l$





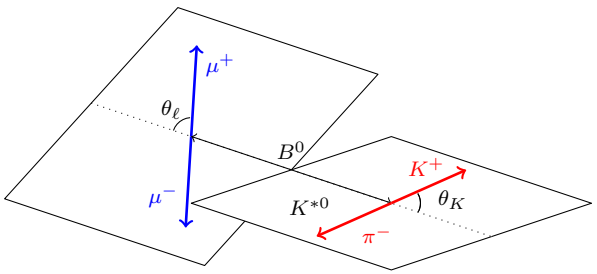
to determine A_{FB} and F_{H} in bins of q^2



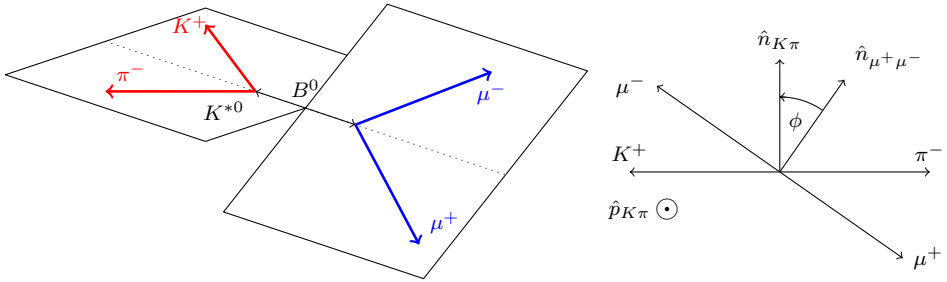


$B^0 \to K^{*0}\mu^+\mu^-$ angular distribution

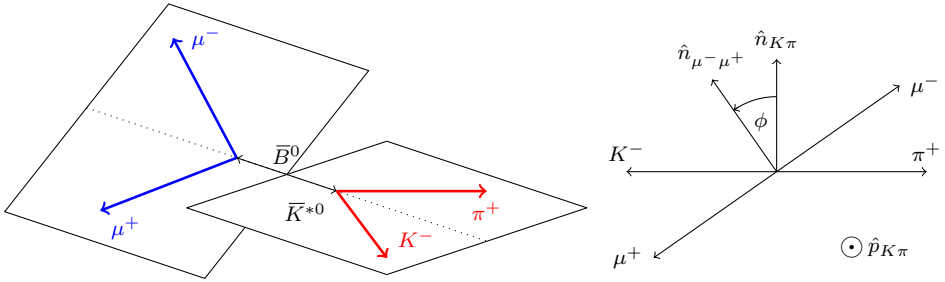
- Angular distribution of the $B^0 \to K^{*0}\mu^+\mu^-$ decay is sensitive to the virtual photon polarisation and new left- and right-handed (axial)vector currents.
- Decay described by three angles $(\theta_\ell, \theta_K, \phi)$ and the dimuon invariant mass squared, q^2.
- Build *CP* averaged observables, $S_i = (J_i + \bar{J}_i)/(\Gamma + \bar{\Gamma})$, or *CP* asymmetries.



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



(b) ϕ definition for the B^0 decay



(c) ϕ definition for the $\overline{B}^0$ decay

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

- Angular distribution depends on 11 angular terms:

$$\frac{\mathrm{d}^4\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\, J_1^s \sin^2\theta_K + J_1^c\cos^2\theta_K + J_2^s\sin^2\theta_K\cos 2\theta_\ell + J_2^c\cos^2\theta_K\cos 2\theta_\ell + J_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + J_5\sin 2\theta_K\sin\theta_\ell\cos\phi + J_6^s\sin^2\theta_K\cos\theta_\ell + J_7\sin 2\theta_K\sin\theta_\ell\sin\phi + J_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + J_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi \,\Big]$$

where the J_i's are bilinear combinations of seven decay amplitudes $A_\parallel^{L,R}$, $A_\perp^{L,R}$, $A_0^{L,R}$ & A_t (L/R for the chirality of the $\mu^+\mu^-$ system).

- Large number of terms simplified by angular folding, e.g. $\phi \to \phi + \pi$ if $\phi < 0$ to cancel terms in $\cos\phi$ and $\sin\phi$, or integration.

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

- Angular distribution depends on 11 angular terms:

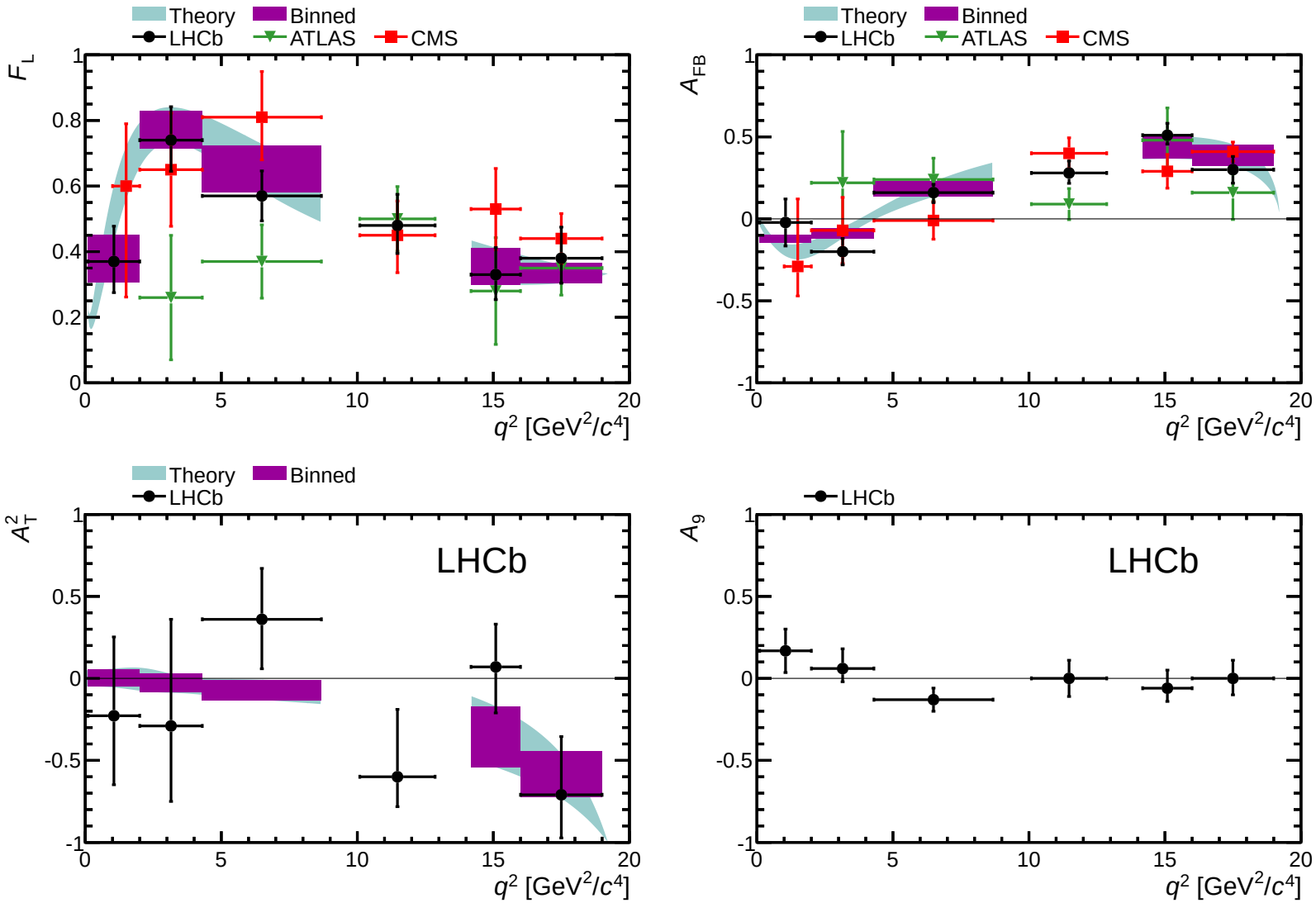
$$\frac{\mathrm{d}^4\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\, J_1^s \sin^2\theta_K + J_1^c\cos^2\theta_K + J_2^s\sin^2\theta_K\cos 2\theta_\ell + J_2^c\cos^2\theta_K\cos 2\theta_\ell + J_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \cancel{J_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi} + \cancel{J_5\sin 2\theta_K\sin\theta_\ell\cos\phi} + J_6^s\sin^2\theta_K\cos\theta_\ell + \cancel{J_7\sin 2\theta_K\sin\theta_\ell\sin\phi} + \cancel{J_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi} + J_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi \,\Big]$$

where the J_i's are bilinear combinations of seven decay amplitudes $A_\parallel^{L,R}$, $A_\perp^{L,R}$, $A_0^{L,R}$ & A_t (L/R for the chirality of the $\mu^+\mu^-$ system).

- Large number of terms simplified by angular folding, e.g. $\phi \to \phi + \pi$ if $\phi < 0$ to cancel terms in $\cos\phi$ and $\sin\phi$, or integration.

$B^0 \to K^{*0}\mu^+\mu^-$ observables [JHEP 08 (2013) 131]

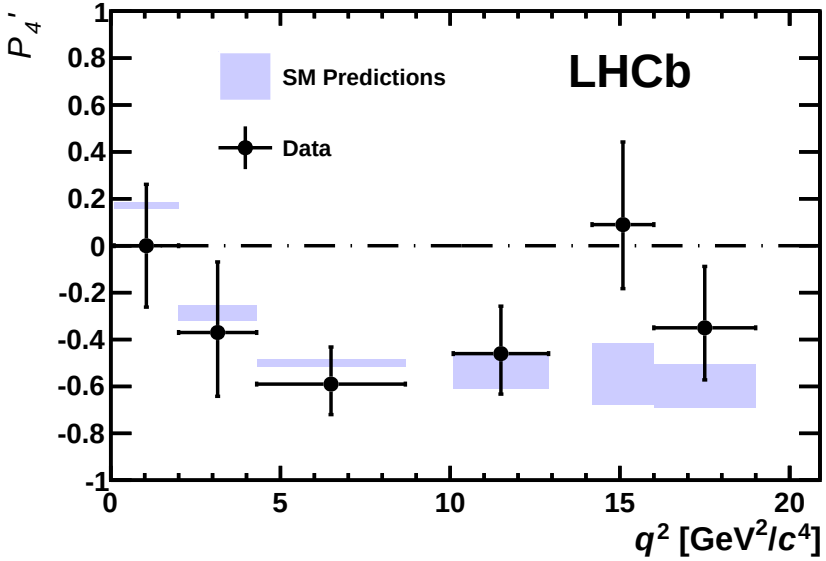
ATLAS (prelim.) [ATLAS-CONF-2013-038] , CMS 5.2 fb^{-1} [PLB 727 (2013) 77] , LHCb 1 fb^{-1} [JHEP 08 (2013) 131]

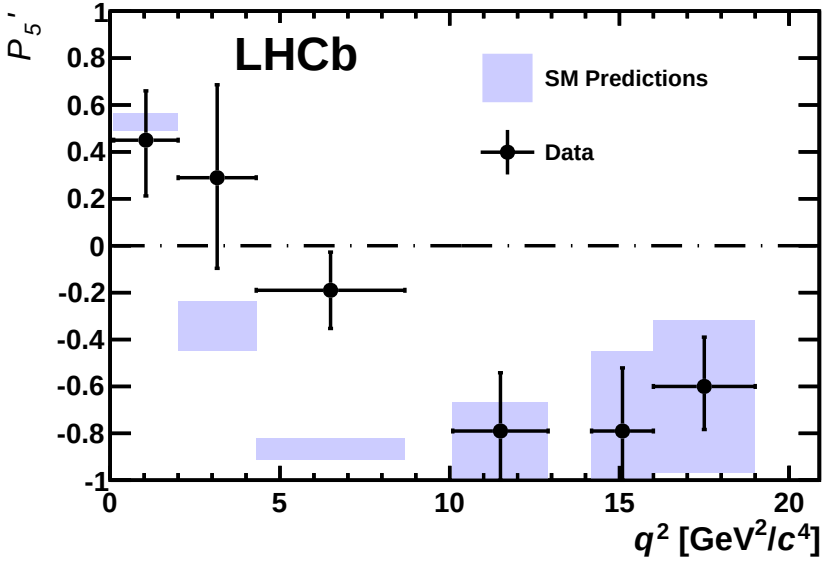


Theory prediction from Bobeth et al. [JHEP 07 (2011) 067] and references therein.

P_5' anomoly [PRL 111 191801 (2013)]

- Can also apply different angular foldings to access other terms.





SM predictions from [Decotes-Genon et al. JHEP 05 (2013) 137]

- Focus on observables where leading form-factor uncertainties cancel, e.g. $P'_{4,5} = S_{4,5}/\sqrt{F_{\rm L}(1-F_{\rm L})}$.
- In $1\,\text{fb}^{-1}$, LHCb observes a local discrepancy of 3.7σ in P_5' (probability that at least one bin varies by this much is 0.5%).

Lepton Universality

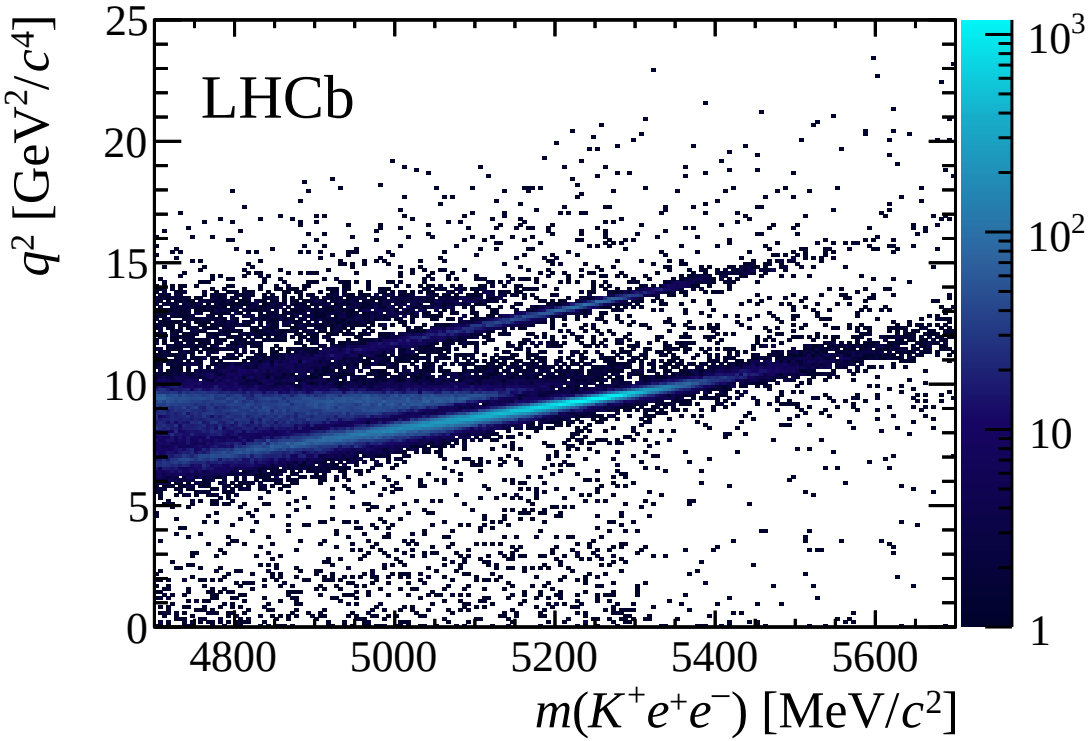
Lepton universality? [PRL 113 (2014) 151601]

- Dominant SM processes couple with equal strength to leptons:

$$R_{\mathrm{K}}[1,6] = \frac{\Gamma[B^+ \to K^+\mu^+\mu^-]}{\Gamma[B^+ \to K^+e^+e^-]} = 1 \pm \mathcal{O}(10^{-3}) \ .$$

- Small differences from unity come from Higgs penguin contributions & phasespace.

Conceptually simple, but experimentally challenging (due to bremstrahlung emission from the $e^{\pm}$).



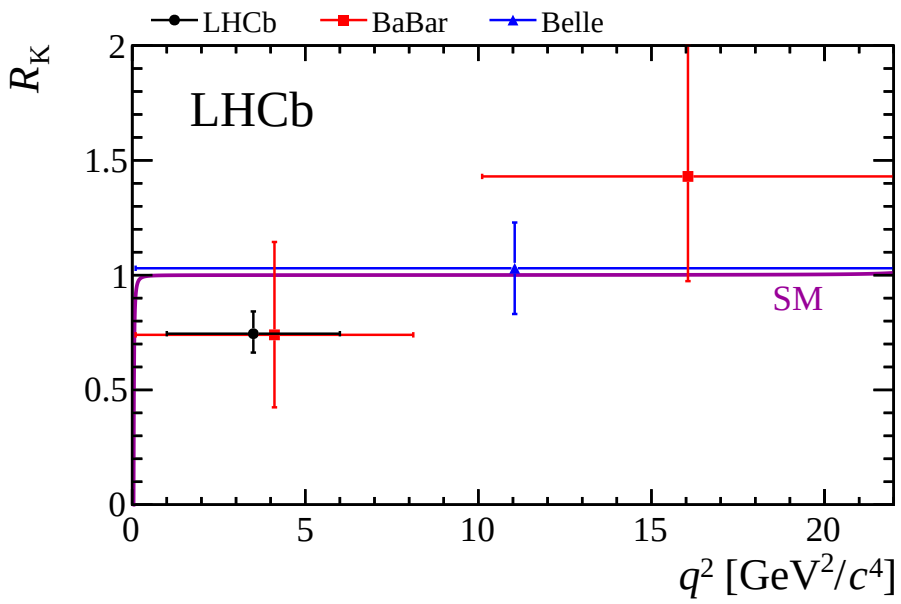
R_K experimental status [PRL 113 (2014) 151601]

- Take double ratio with $B^+ \to J/\psi K^+$ decays to cancel possible systematic biases from electron/muon reconstruction.
- Correct for migration of events in and out of $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$ using MC and J/ψ line-shape in data.
- Have also checked that R_K at $q^2 = m^2_{J/\psi}$ is consistent with unity within uncertainties.

In $3\,\mathrm{fb}^{-1}$ LHCb determines

$R_K = 0.745^{+0.090}_{-0.074}(\mathrm{stat})^{+0.036}_{-0.036}(\mathrm{syst})$

which is consistent with SM expectation at 2.6σ.



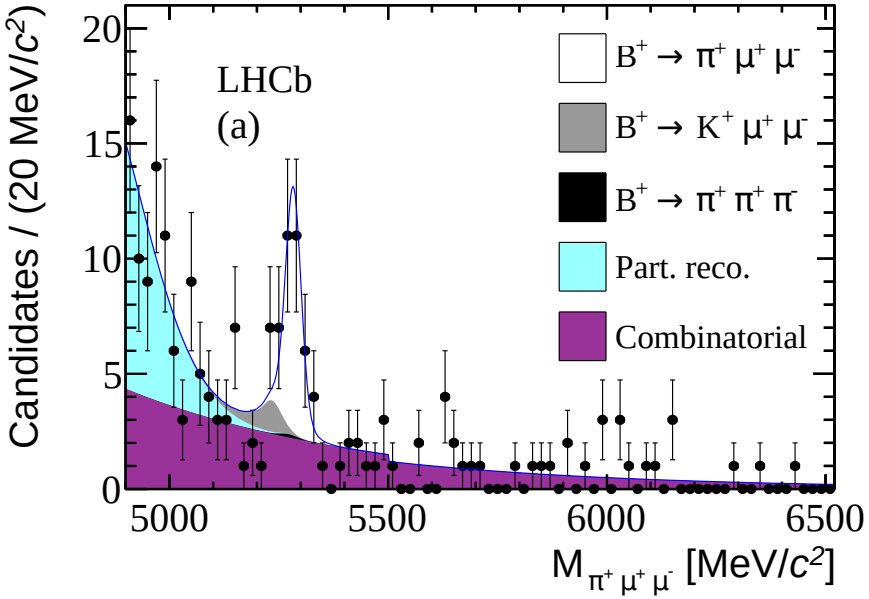
Belle PRL 103 (2009) 171801, BaBar PRD 86 (2012) 032012

$$b \to d\ell^+\ell^-$$

Observation of $B^+ \to \pi^+\mu^+\mu^-$ [JHEP 12 (2012) 125]

- In SM, rate of $b \to d$ process is suppressed by $|V_{td}/V_{ts}|^2$ with respect to $b \to s$.

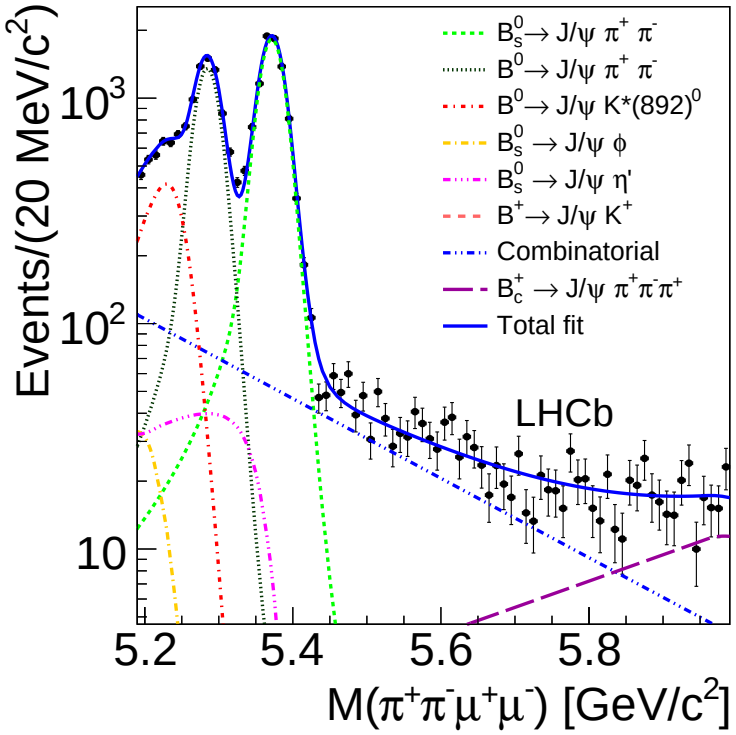
- Using $1\,\text{fb}^{-1}$ of integrated luminosity we observed the decay $B^+ \to \pi^+\mu^+\mu^-$.
- Key challenge is controlling combinatorial background and background from $B^+ \to K^+\mu^+\mu^-$ where the $K^\pm$ is incorrectly identified as a $\pi^\pm$.

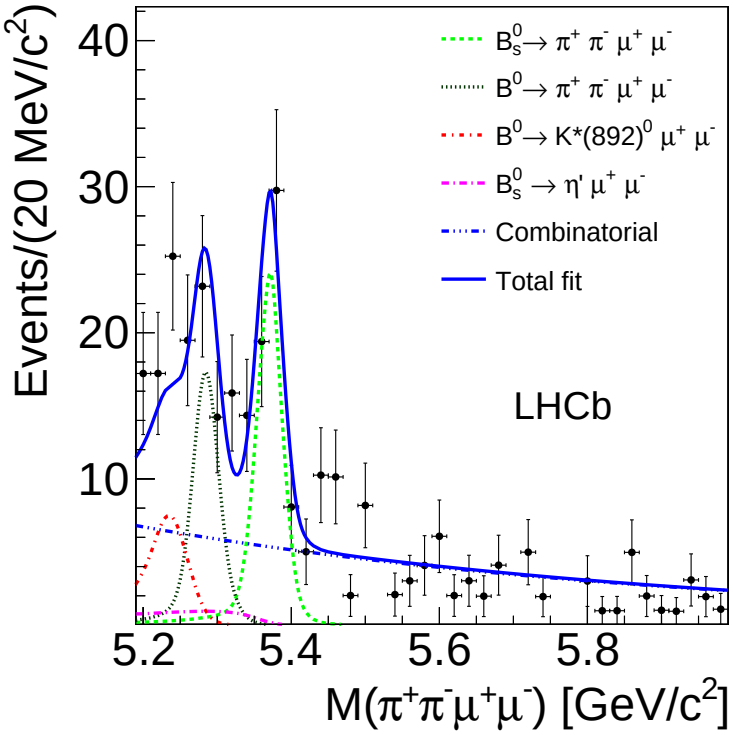


- Measured brancing fraction

$$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (2.3 \pm 0.6 \pm 0.1) \times 10^{-8}$$

is consistent with the SM expectation.





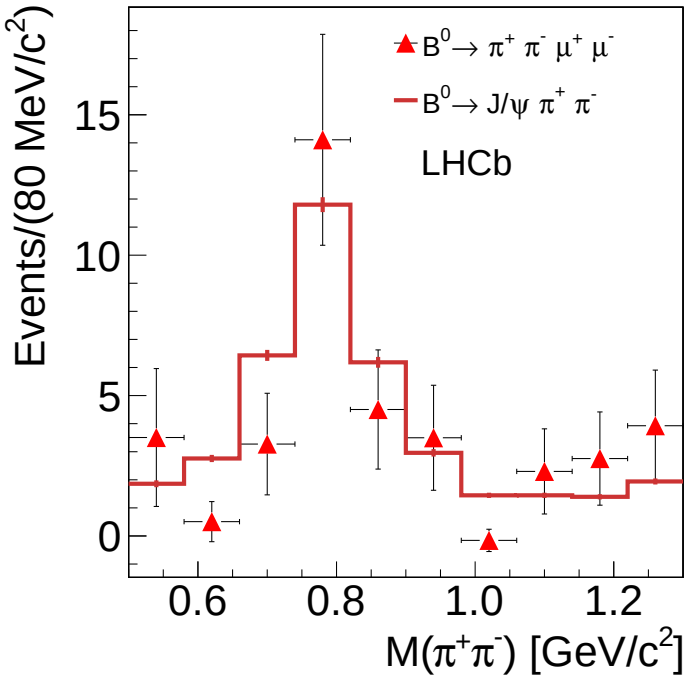
- In $3\,\mathrm{fb}^{-1}$, observe B^0_s signal and see evidence for B^0 (at 4.8σ), with

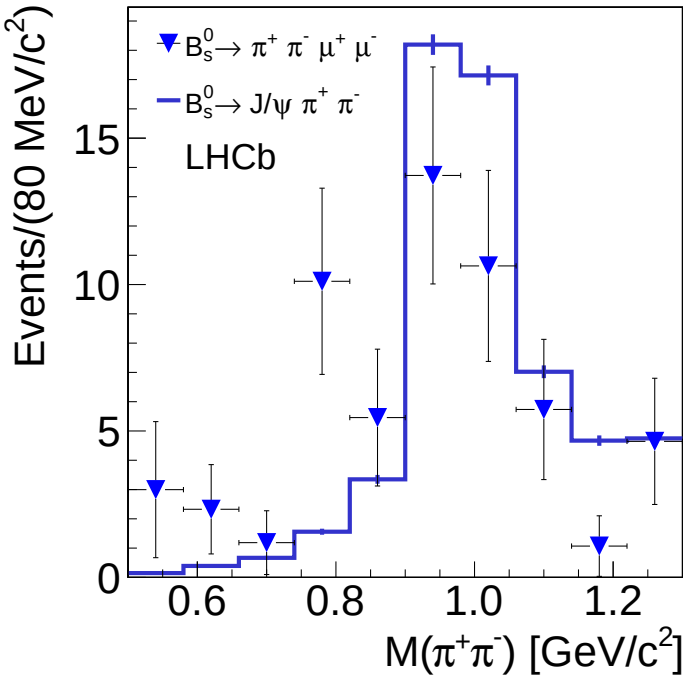
$$\mathcal{B}(B^0_s \to \pi^+\pi^-\mu^+\mu^-) = (8.6 \pm 1.5\,(\mathrm{stat}) \pm 0.7\,(\mathrm{syst}) \pm 0.7\,(\mathrm{norm})) \times 10^{-8}$$

$$\mathcal{B}(B^0 \to \pi^+\pi^-\mu^+\mu^-) = (2.11 \pm 0.51\,(\mathrm{stat}) \pm 0.15\,(\mathrm{syst}) \pm 0.16\,(\mathrm{norm})) \times 10^{-8}$$

in $0.5 < m(\pi^+\pi^-) < 1.3\,\mathrm{GeV}/c^2$.

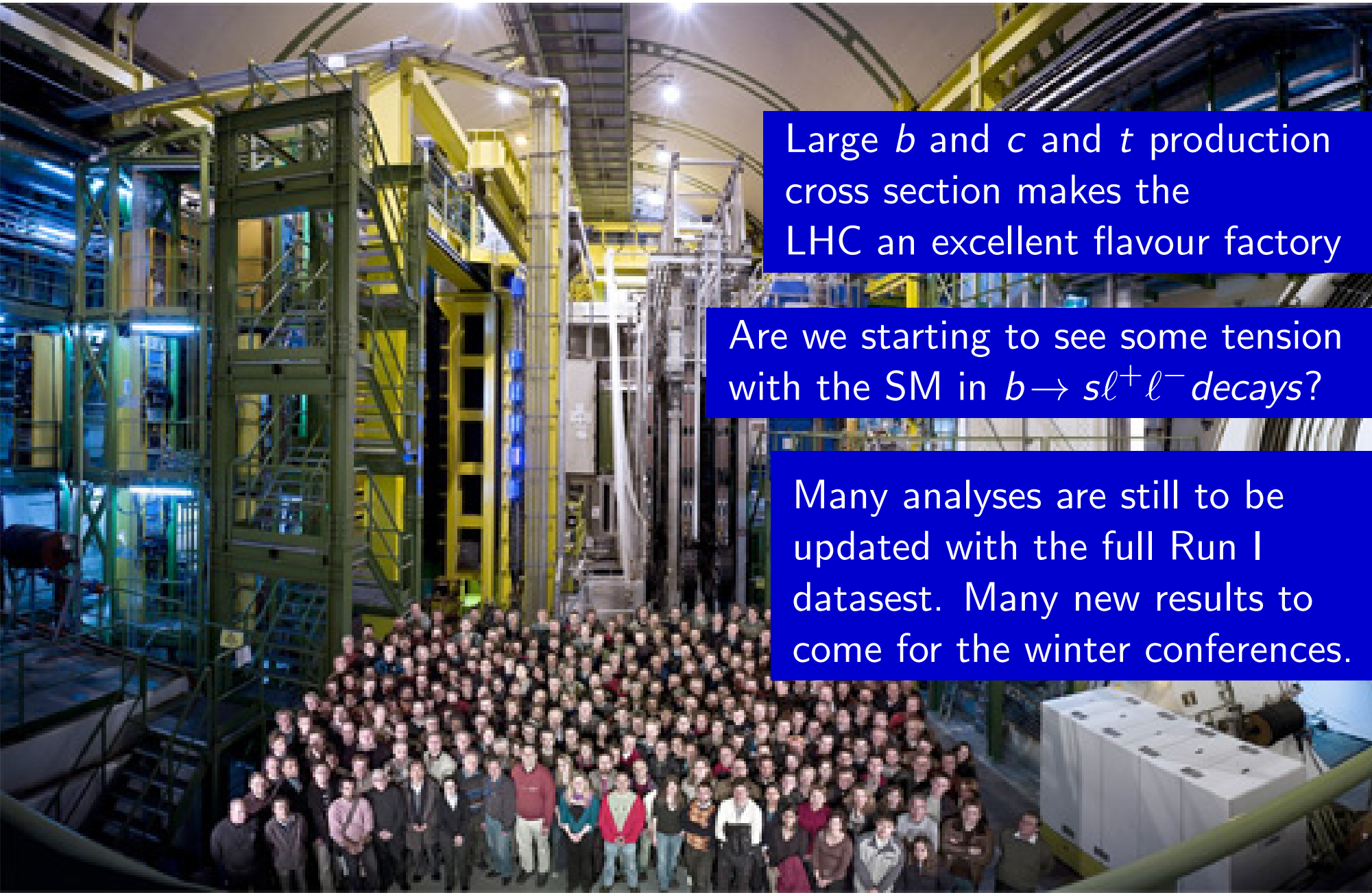
- $\pi^+\pi^-$ system consistent with $\rho(770)$ and $f_0(980)$ for the B^0 and B_s^0, respectively.





- We are starting to build up the necessary ingredients to perform global analyses of $b \to d$ processes.

Summary



Large b and c and t production cross section makes the LHC an excellent flavour factory

Are we starting to see some tension with the SM in $b \to s\ell^+\ell^-$ *decays*?

Many analyses are still to be updated with the full Run I datasest. Many new results to come for the winter conferences.

Fin

Angular observables $J_i(q^2)$ for $B^0 \to K^{*0}\mu^+\mu^-$

For completeness

$$J_1^s = \frac{(2+\beta_\mu^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)\right] + \frac{4m_\mu^2}{q^2}\Re(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*})$$

$$J_1^c = A_0^L|^2 + |A_0^R|^2 + \frac{4m_\mu^2}{q^2}\left[|A_t|^2 + 2\Re(A_0^L A_0^{R*})\right]$$

$$J_2^s = \frac{\beta_\mu^2}{4}\left\{|A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)\right\}$$

$$J_2^c = -\beta_\mu^2\left\{|A_0^L|^2 + (L \to R)\right\}$$

$$J_3 = \frac{\beta_\mu^2}{2}\left\{|A_\perp^L|^2 - |A_\parallel^L|^2 + (L \to R)\right\}$$

$$J_4 = \frac{\beta_\mu^2}{\sqrt{2}}\left\{\Re(A_0^L A_\parallel^{L*}) + (L \to R)\right\}$$

$$J_5 = \sqrt{2}\beta_\mu\left\{\Re(A_0^L A_\perp^{L*}) - (L \to R)\right\}$$

$$J_6 = 2\beta_\mu\left\{\Re(A_\parallel^L A_\perp^{L*}) - (L \to R)\right\}$$

$$J_7 = \sqrt{2}\beta_\mu\left\{\Im(A_0^L A_\parallel^{L*}) - (L \to R)\right\}$$

$$J_8 = \frac{\beta_\mu^2}{\sqrt{2}}\left\{\Im(A_0^L A_\perp^{L*}) + (L \to R)\right\}$$

$$J_9 = \beta_\mu^2\left\{\Im(A_\parallel^{L*} A_\perp^L) + (L \to R)\right\}$$

J_i depend on 7 complex amplitudes: $A_\parallel^{L,R}$, $A_\perp^{L,R}$ and $A_0^{L,R}$, A_t

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

At "leading order"

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

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

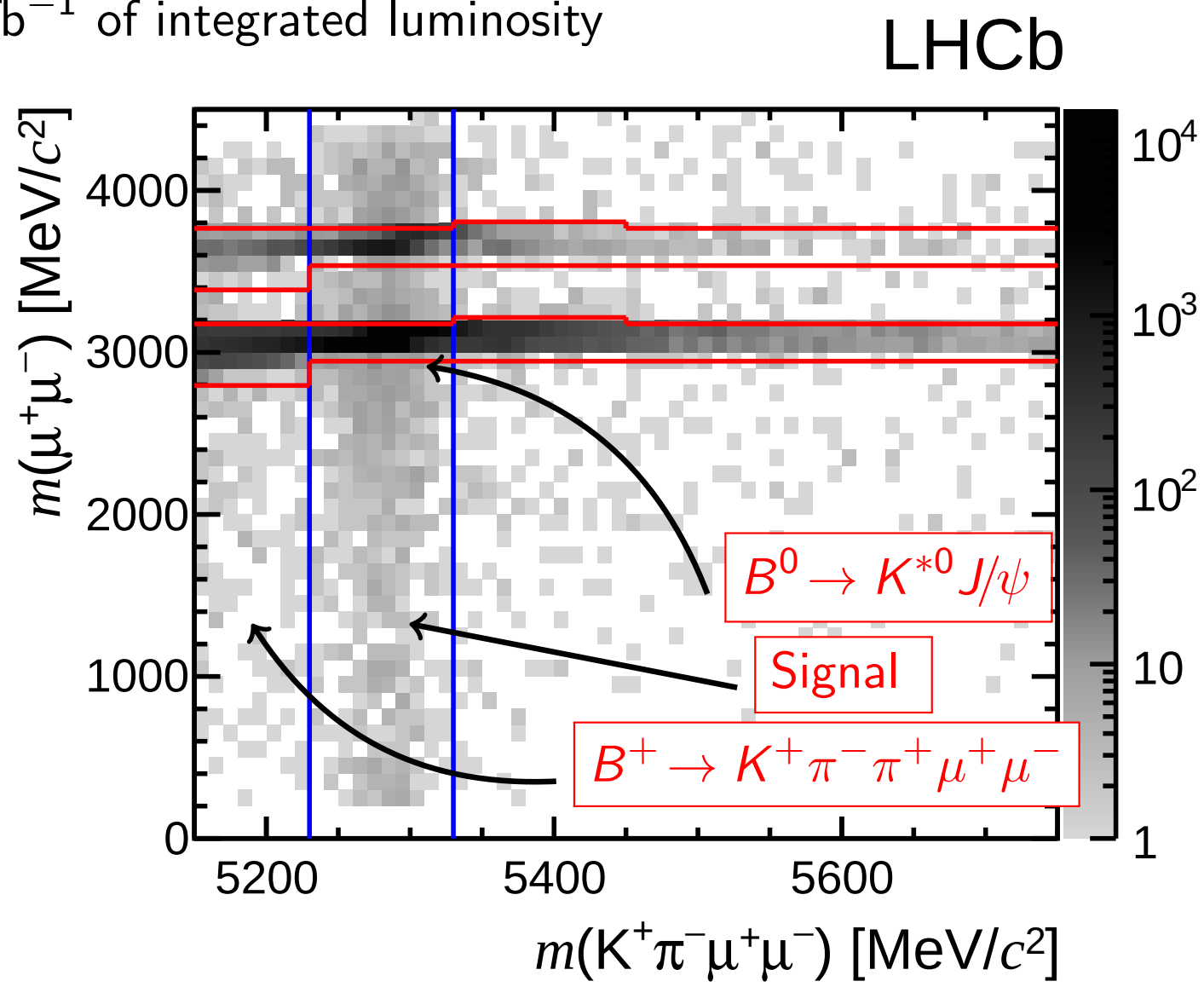
$$A_0^{L(R)} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}})\right]\left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})\mathbf{A_1(q^2)} - \lambda\frac{\mathbf{A_2(q^2)}}{m_B + m_{K^*}}\right]\right.$$
$$\left.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

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

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

- C_i are Wilson coefficients that we want to measure (they depend on the heavy degrees of freedom).
- A_0, A_1, A_2, T_1, T_2 and V are form-factors (these are effectively nuisance parameters).

Using 1 fb^{-1} of integrated luminosity



Comments on angular distribution

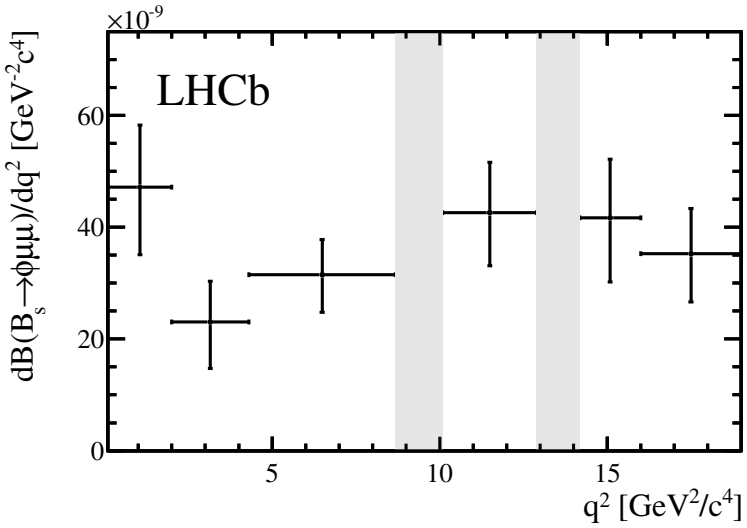
- The L & R indices refer to the chirality of the leptonic system.
  - Different due to the axial vector contribution to the amplitudes.
- If $C_{10} = 0$, $A^L_{0,\parallel,\perp} = A^R_{0,\parallel,\perp}$ and the angular distribution reduces to the one for $B^0 \to K^{*0} J/\psi$.
- Zero-crossing point of $A_{\rm FB}$ comes from interplay between the different vector-like contributions.
- In the SM there are 7 different amplitudes that contribute, corresponding to different polarisations states:

$$K^* \text{ on-shell} \to 3 \text{ polarisation states } \epsilon_{K^*}(m = +, -, 0)$$
$$V^* \text{ off-shell} \to 4 \text{ polarisation states } \epsilon_{K^*}(m = +, -, 0, t)$$

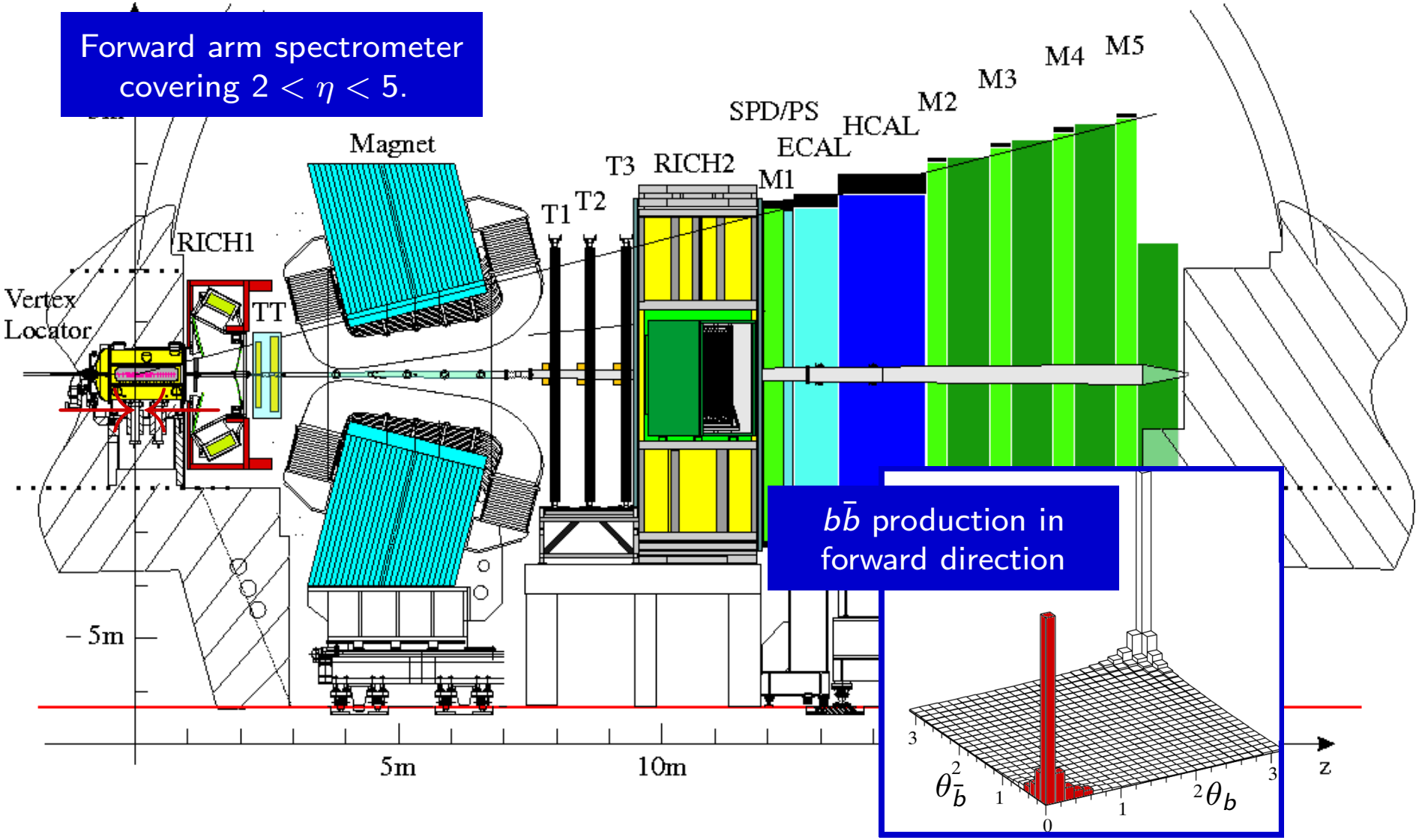
- A_t corresponds to a longitudinally polarised K^* and time-like $\mu^+\mu^-$. It's suppressed, so can be neglected.

$B_s^0 \to \phi\mu^+\mu^-$ at LHCb

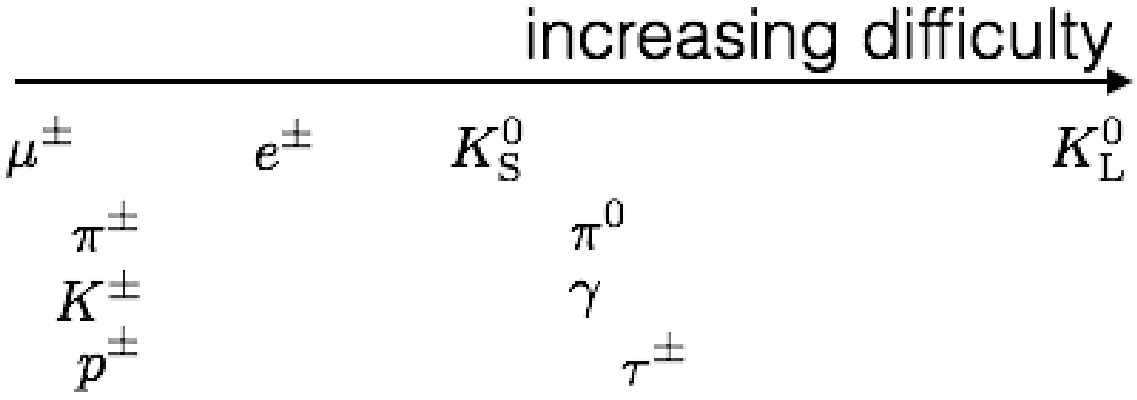
- Analysis conceptually similar to that of $B^0 \to K^{*0}\mu^+\mu^-$ decay, except can not separate B_s^0 and $\overline{B}_s^0$ final states.
- Normalise w.r.t. $B_s^0 \to J/\psi\,\phi$ to determine $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$.
- The LHCb results are consistent with those of CDF.



The LHCb detector



Reconstructing rare b-hadrons at LHCb



- No beam constraint at LHC and large detector occupancy.
  - Signatures with missing energy are difficult to reconstruct.
- Determine branching fractions / asymmetries normalised w.r.t. $B \to J/\psi K^{(*)}$ decays to cancel possible systematic effects.
  - Improvement in $\mathcal{B}(B \to J/\psi K^{(*)})$ from B-factories would reduce our systemic uncertainties.