Rare Decays at LHCb

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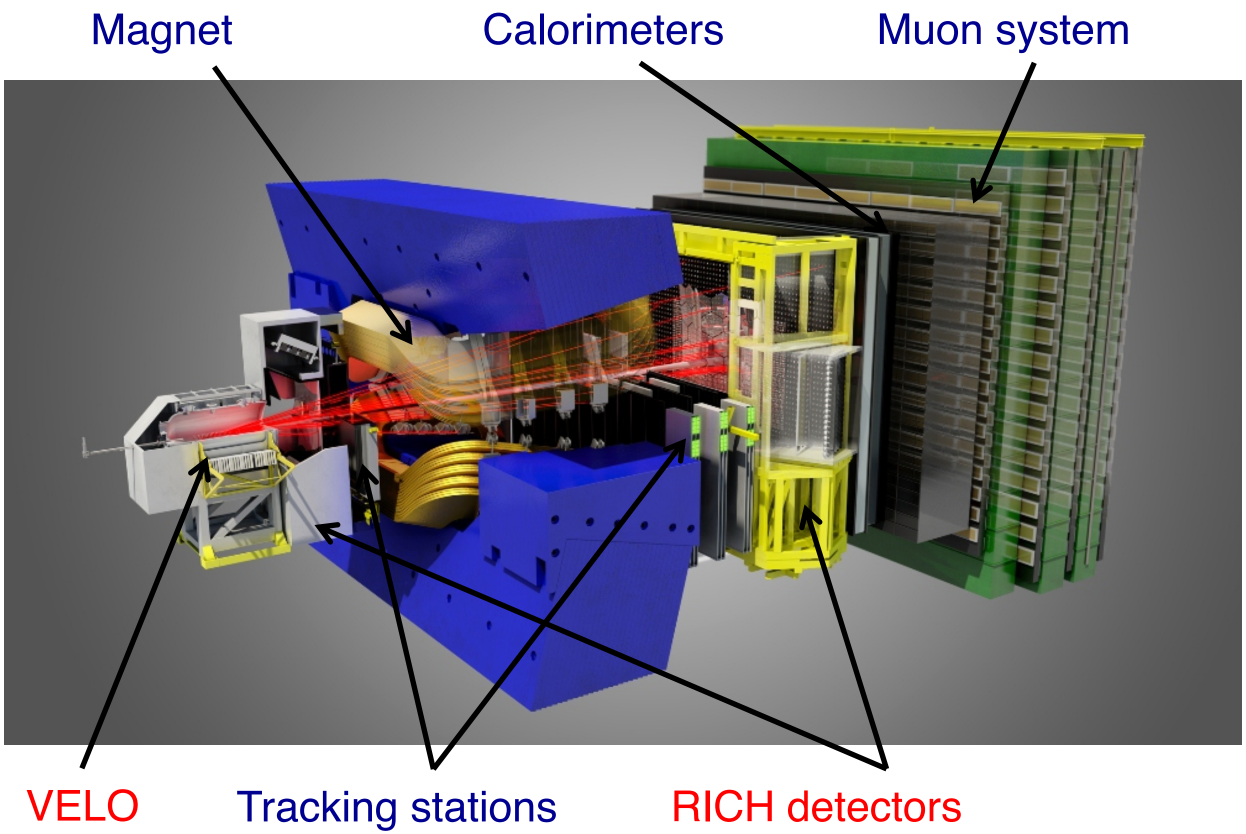
3 September 2015

LHCb

LHCb is a forward-arm spectrometer fully instrumented in the forward region ($2 < \eta < 5$) including:

- Excellent vertex resolution from a silicon strip detector surrounding the interaction point (VELO)
- Particle identification from two ring-imaging Cherenkov (RICH) detectors, calorimeter and muon system



LHCb's core physics programme is to test the Standard Model at high precision and perform indirect searches for new physics in the decays of beauty and charm hadrons.

Int. J. Mod. Phys. A 30 (2015) 1530022

Rare decays

FCNC decays proceed via loops in the SM

- Highly suppressed (hence rare)
- Can receive significant modifications from NP

In this talk:

<u>b → s transitions</u>

$B^0 \to K^{*0}\mu^+\mu^-$ LHCb-CONF-2015-002

$B_s^0 \to \phi^0\mu^+\mu^-$ arXiv:1506.08777

$\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$ JHEP 06 (2015) 115

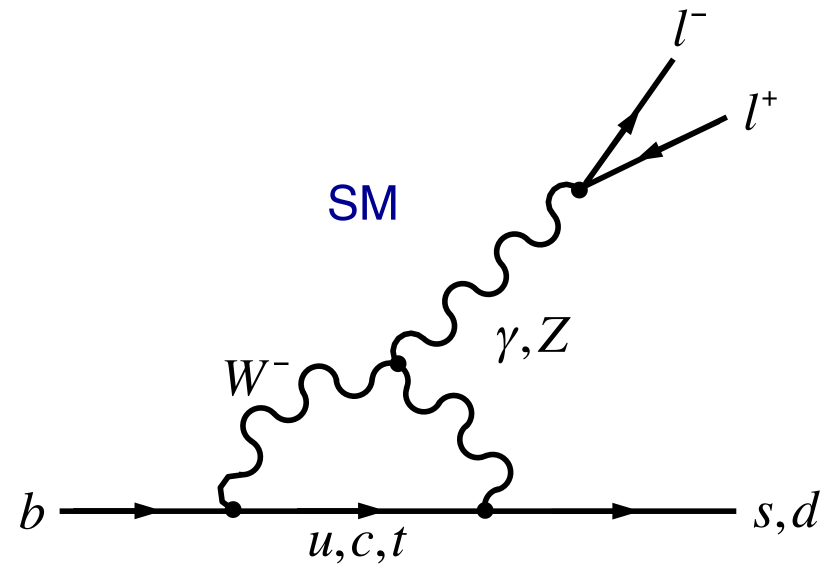
<u>b → d transition</u>

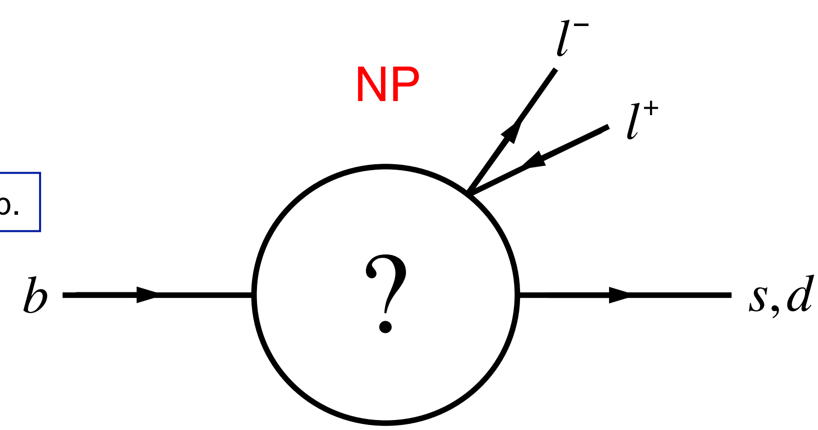
$B^+ \to \pi^+\mu^+\mu^-$ Preliminary, LHCb-PAPER-2015-035 in prep.

<u>Search for dark bosons using</u>

$B^0 \to K^{*0}\chi^0\left(\to \mu^+\mu^-\right)$ arXiv:1508.04094

All use Run I $3fb^{-1}$ data set.





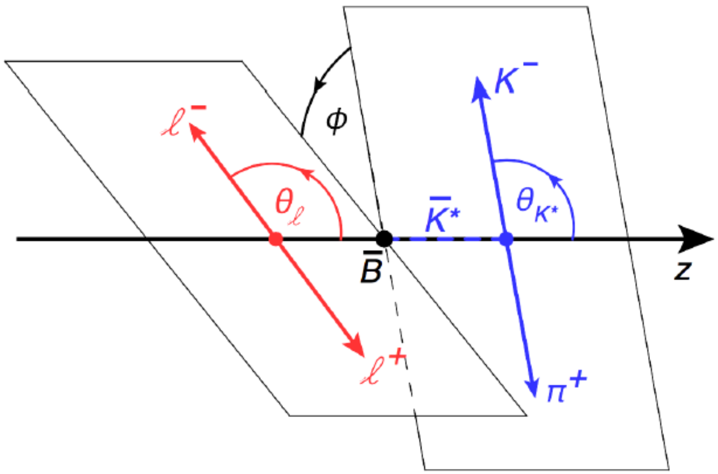
$$B^0 \to K^{*0}\mu^+\mu^-$$

LHCb-CONF-2015-002

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

Parameterise the decay in terms of three angles (θ_l, θ_k, ϕ) and $q^2 = m_{\mu\mu}$.

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



Can also calculate observables that have less form factor dependence e.g.

$$P'_{4,5} = S_{4,5}/\sqrt{F_\mathrm{L}(1-F_\mathrm{L})} \qquad A_\mathrm{T}^{(2)} = S_3/(1-F_\mathrm{L})$$

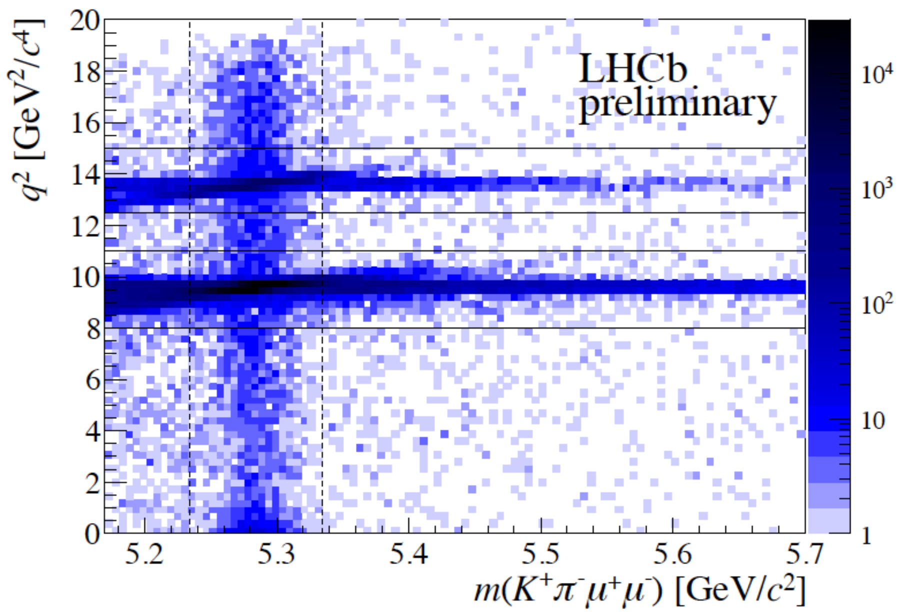
$B^0 \to K^{*0}\mu^+\mu^-$

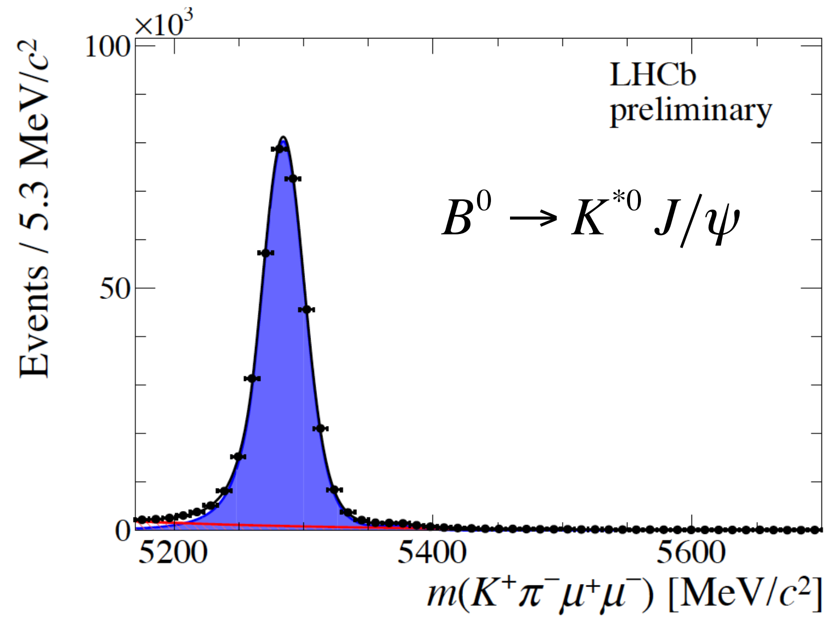
Selection:

Boosted Decision Tree reduces combinatorial background

- Trained on data (signal: $B^0 \to K^{*0} J/\psi$, background: upper mass side-band)
- Uses kinematic, geometric, PID and isolation information

Peaking backgrounds vetoed using kinematic cuts and PID

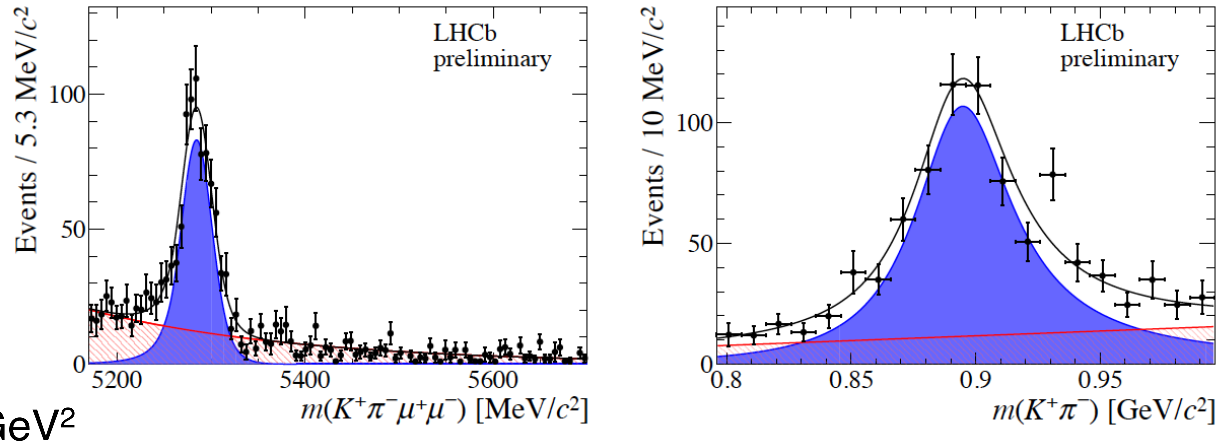




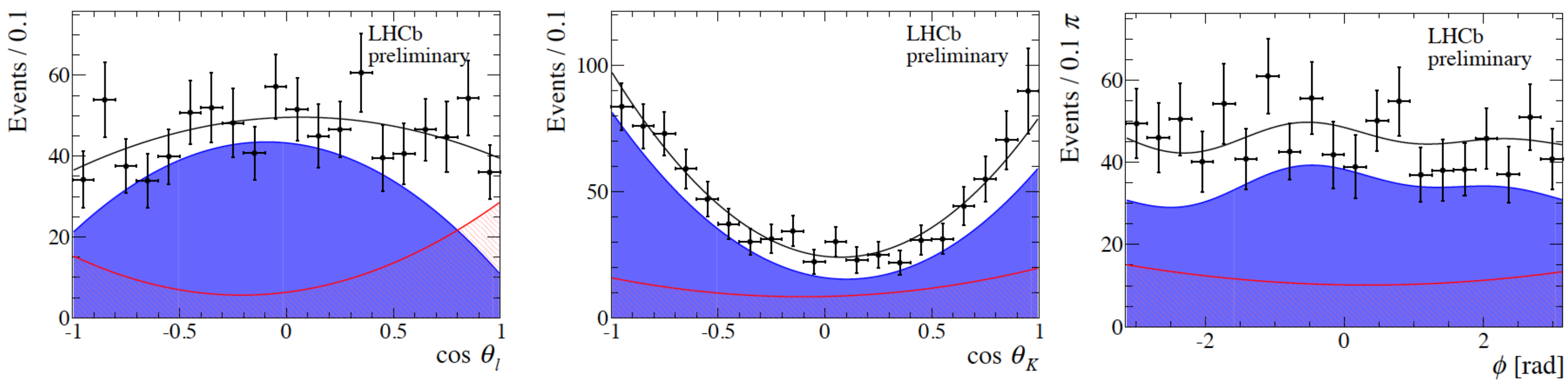
$B^0 \to K^{*0}\mu^+\mu^-$

Angular fit performed in bins of q^2 to extract observables:

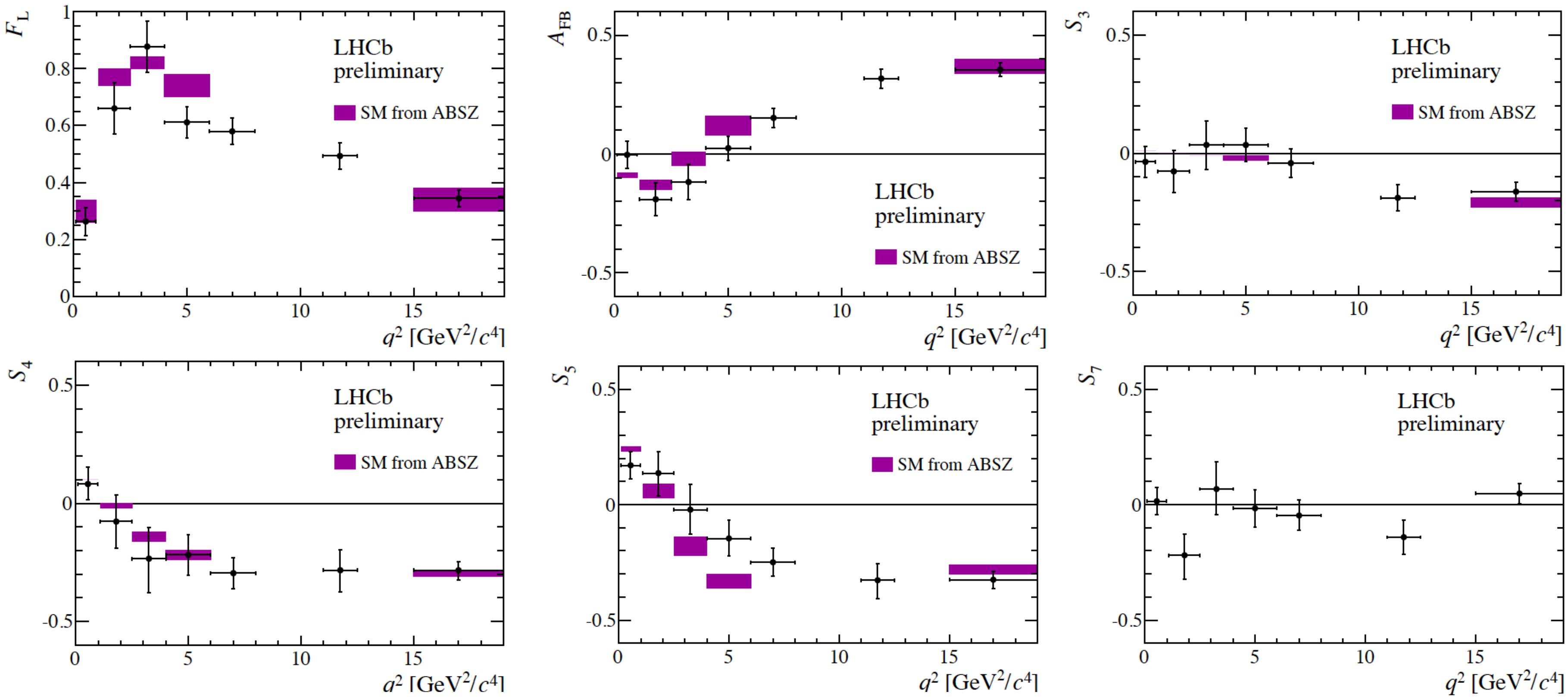
- Unbinned ML fit in m_B, m_{K^*}, θ_l, θ_k, ϕ
- S-wave pollution accounted for in the fit
- Angular acceptance taken from MC

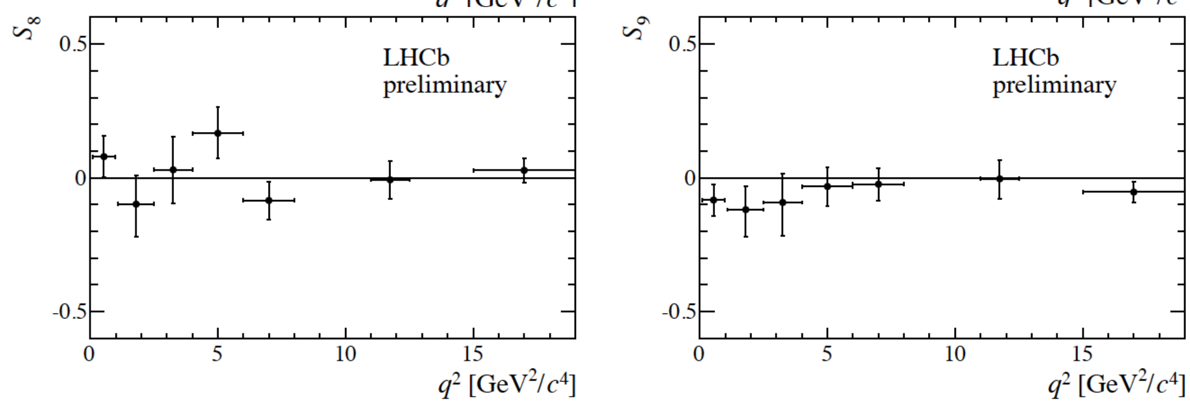


$q^2 = [1.1 – 6.0\ ]\ GeV^2$



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





Zero crossing point in A_{FB} =

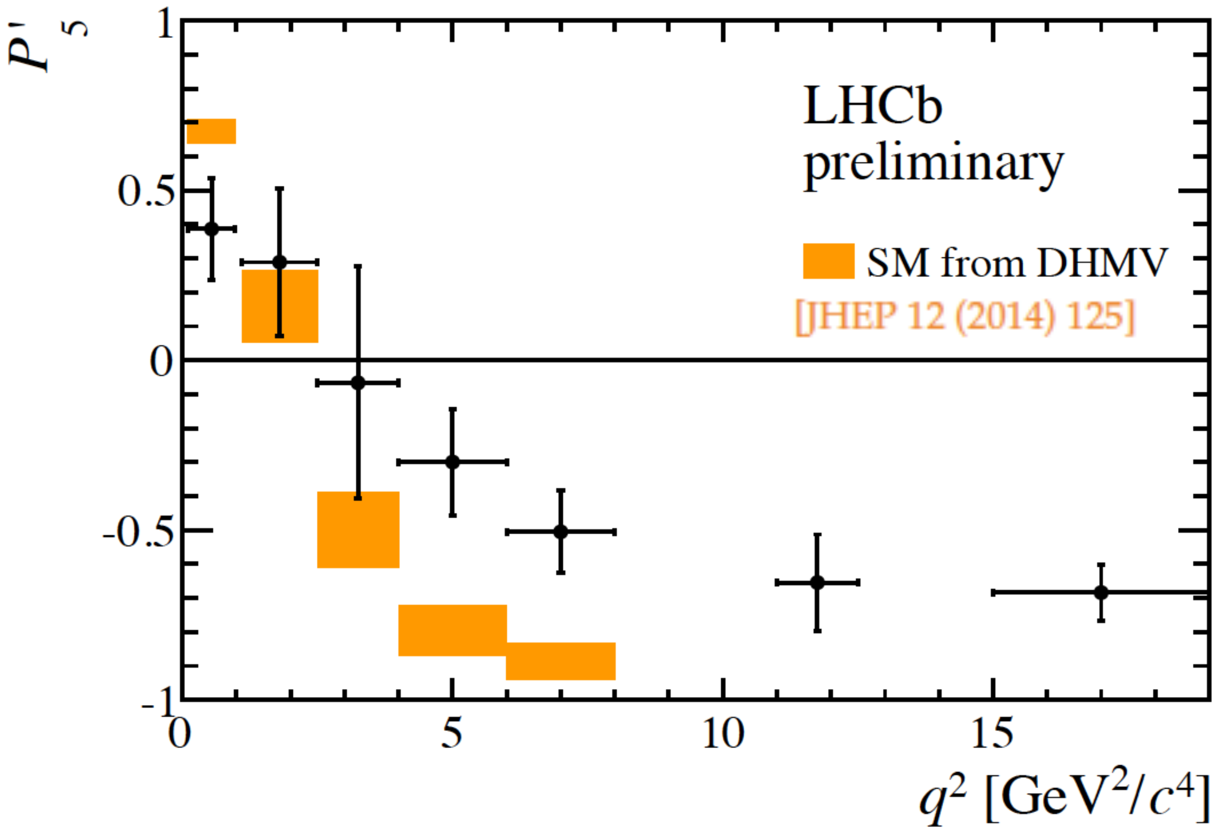
$$(3.7^{+0.8}_{-1.1})\ \mathrm{GeV}^2/c^4$$

Agrees with SM.

[arXiv:1503.05534]

[arXiv:1411.3161]

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



- Deviation from SM at 2.9σ in [4.0-6.0] and [6.0-8.0] GeV^2
- Tension with SM at 3.7σ
- Possible explanations: Z', leptoquark or charm-loops.

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

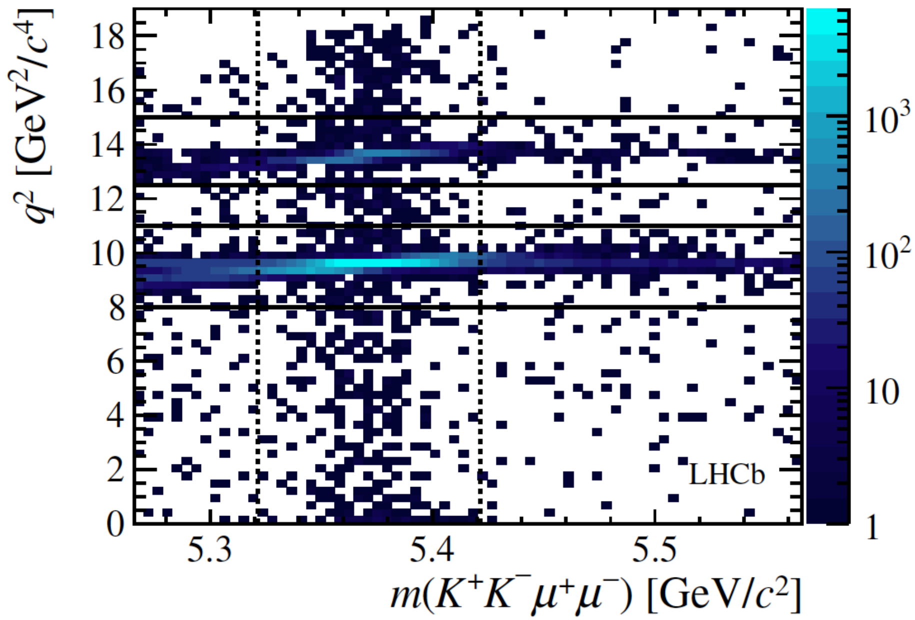
arXiv:1506.08777

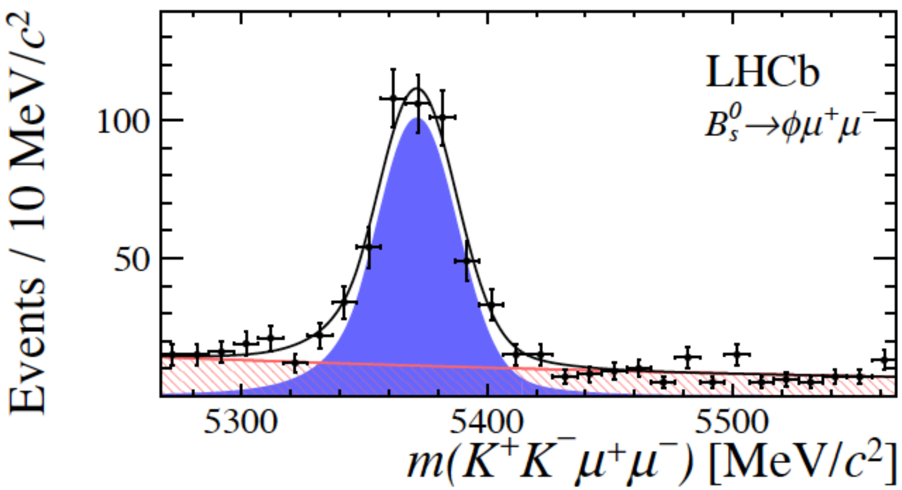
$B_s^0 \to \phi^0 \mu^+ \mu^-$

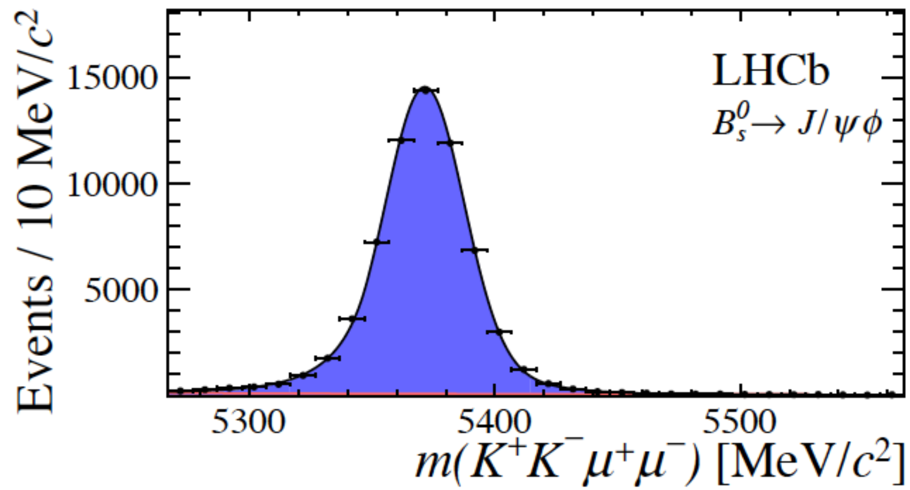
Similar to $B^0 \to K^{*0} \mu^+ \mu^-$:

- Similar selections strategy with BDT
- Lower yield due to $f_s/f_d \sim 0.25$
- B meson flavour not tagged
- Narrow resonance → clean selection
- Negligible S-wave contribution

Angular analysis and BF measurement.







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

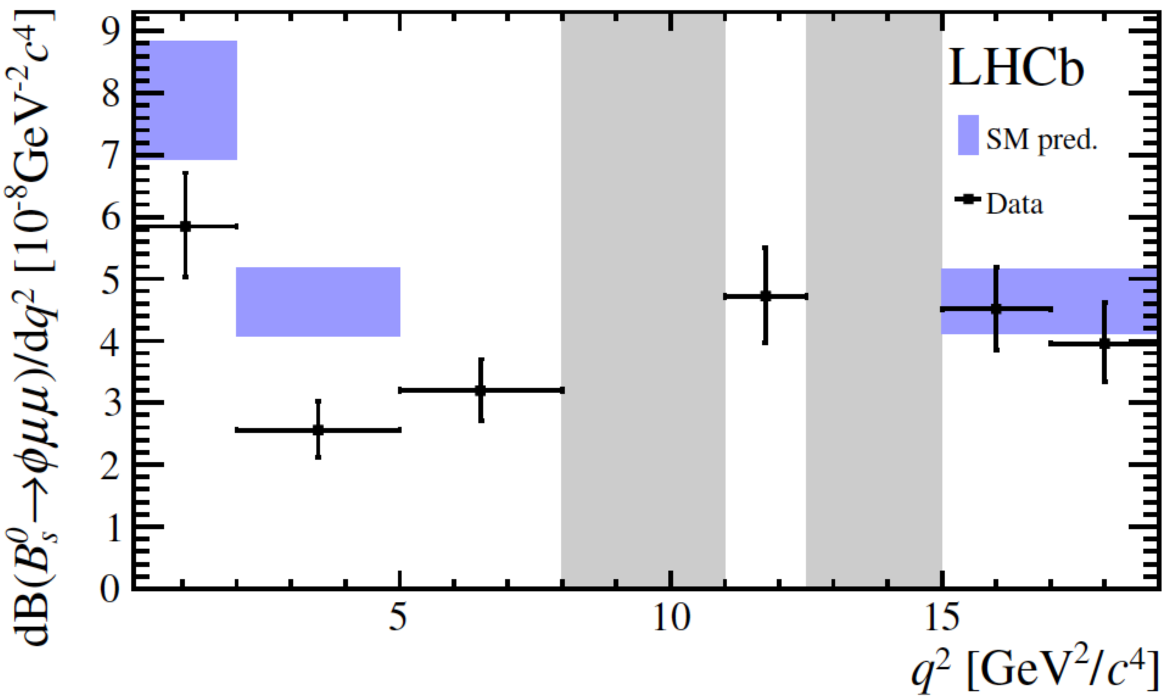
Branching fraction measured using $B_s^0 \to \phi^0 J/\psi$ as normalisation channel.

$$\frac{d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{dq^2} = \frac{1}{q^2_{\rm max} - q^2_{\rm min}} \cdot \frac{N_{\phi\mu\mu}}{N_{J/\psi\phi}} \cdot \frac{\epsilon_{J/\psi\phi}}{\epsilon_{\phi\mu\mu}} \cdot \mathcal{B}(B_s^0 \to J/\psi\,\phi)\mathcal{B}(J/\psi \to \mu^+\mu^-)$$

SM predictions:

- arXiv:1411.3161
- arXiv:1503.05534

Deviation from SM in range [0.0 - 6.0] GeV^2 at 3.5σ



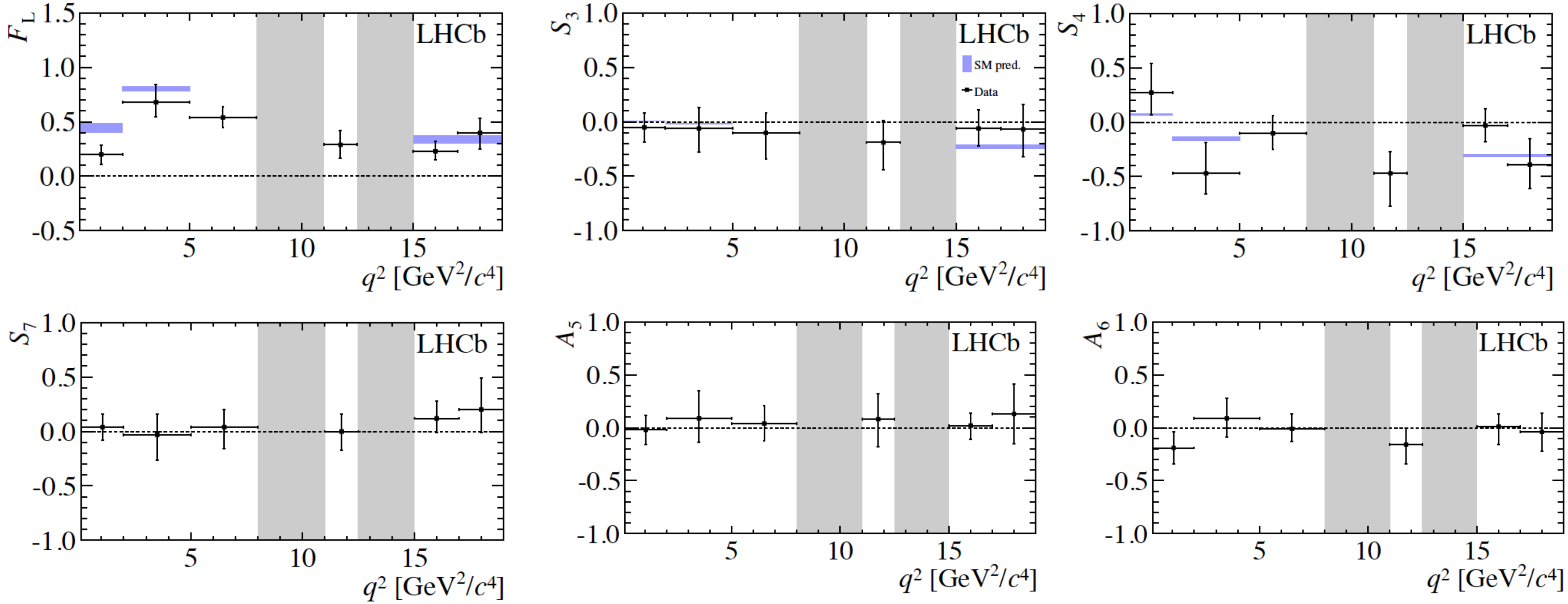
BF across all q^2:

$$\frac{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi\,\phi)} = (7.41^{+0.42}_{-0.40} \pm 0.20 \pm 0.21) \times 10^{-4},$$

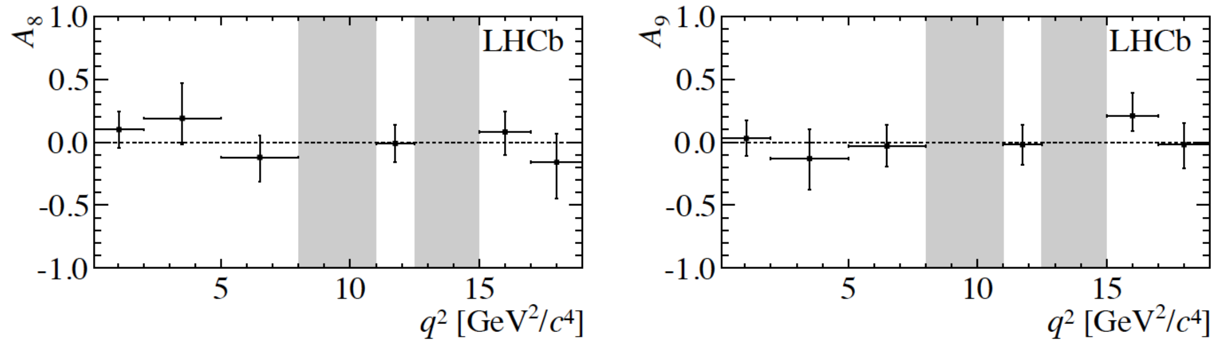
$$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (7.97^{+0.45}_{-0.43} \pm 0.22 \pm 0.23 \pm 0.60) \times 10^{-7}$$

$B_s^0 \rightarrow \phi^0 \mu^+ \mu^-$

Angular fit to m_B, θ_l, θ_k, ϕ. SM predictions arXiv:1411.3161 and arXiv:1503.05534.



All results in agreement with SM.



$$\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-$$

JHEP 06 (2015) 115

$\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-$

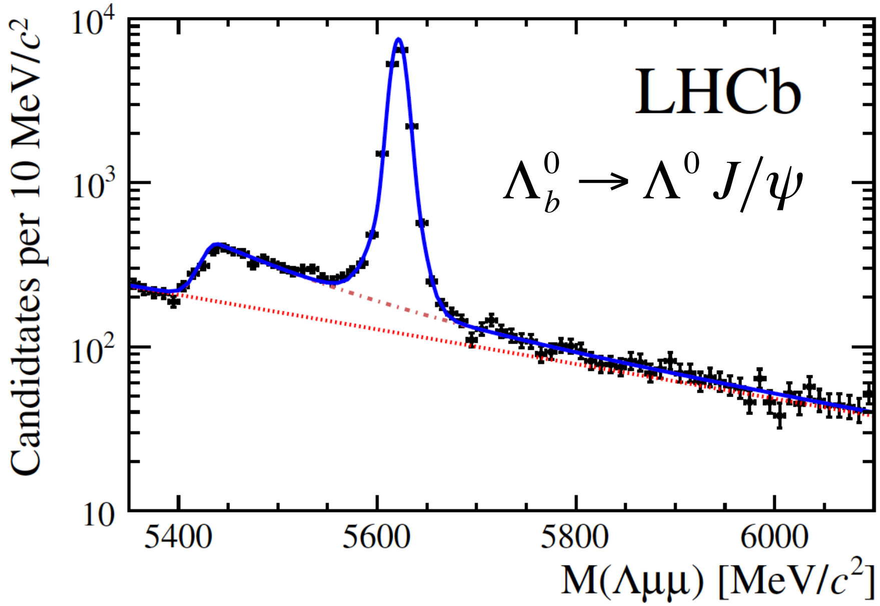
A b→s transition with total spin 1/2:

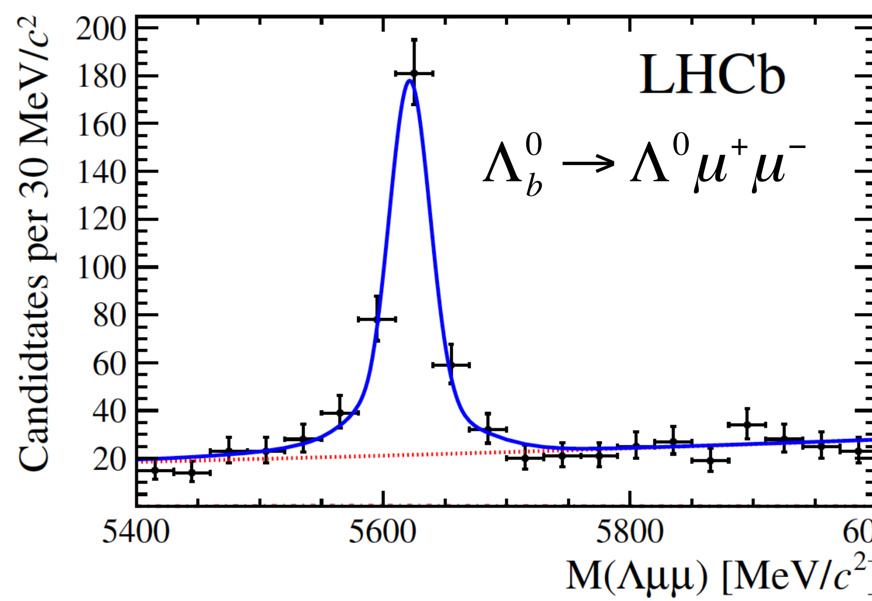
- Additional information on helicity structure
- Polarisation of final state Λ^0 preserved in $\Lambda^0 \to p^+ \pi^-$ decay

Hadronic form factors suffer from large uncertainties.

Neural net selection trained on signal MC and upper mass sideband data.

$\Lambda_b^0 \to \Lambda^0 J/\psi$ normalisation channel.

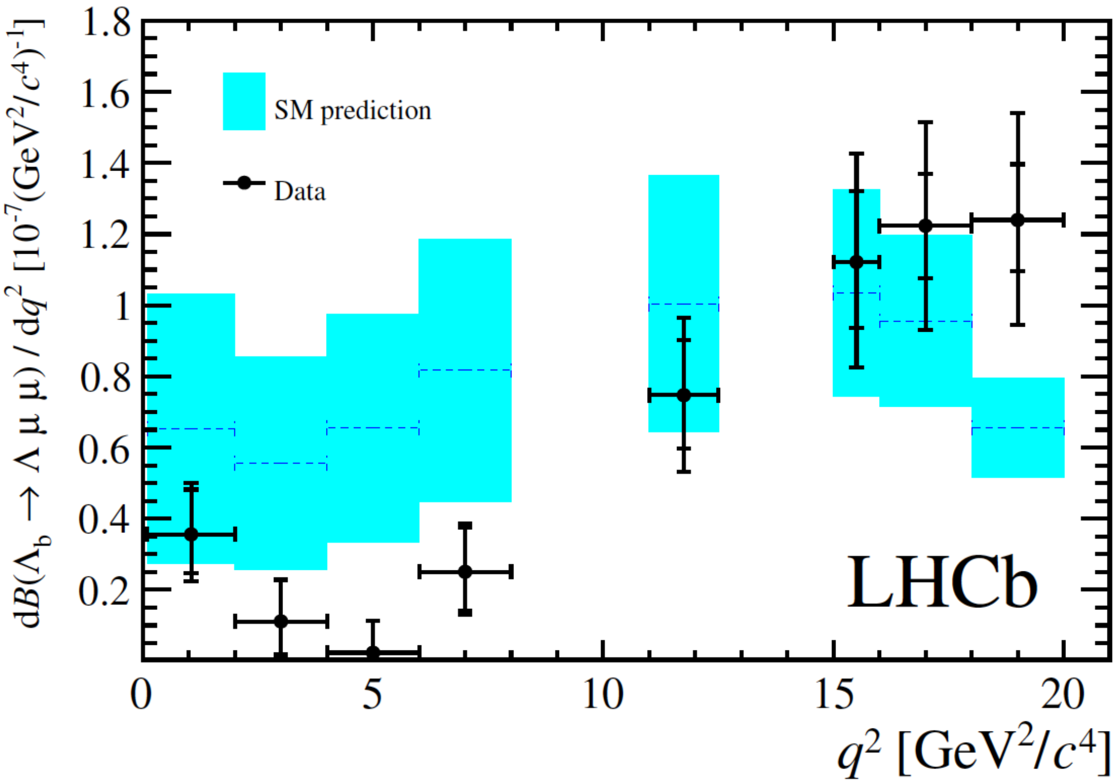




$\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-$

Branching fraction

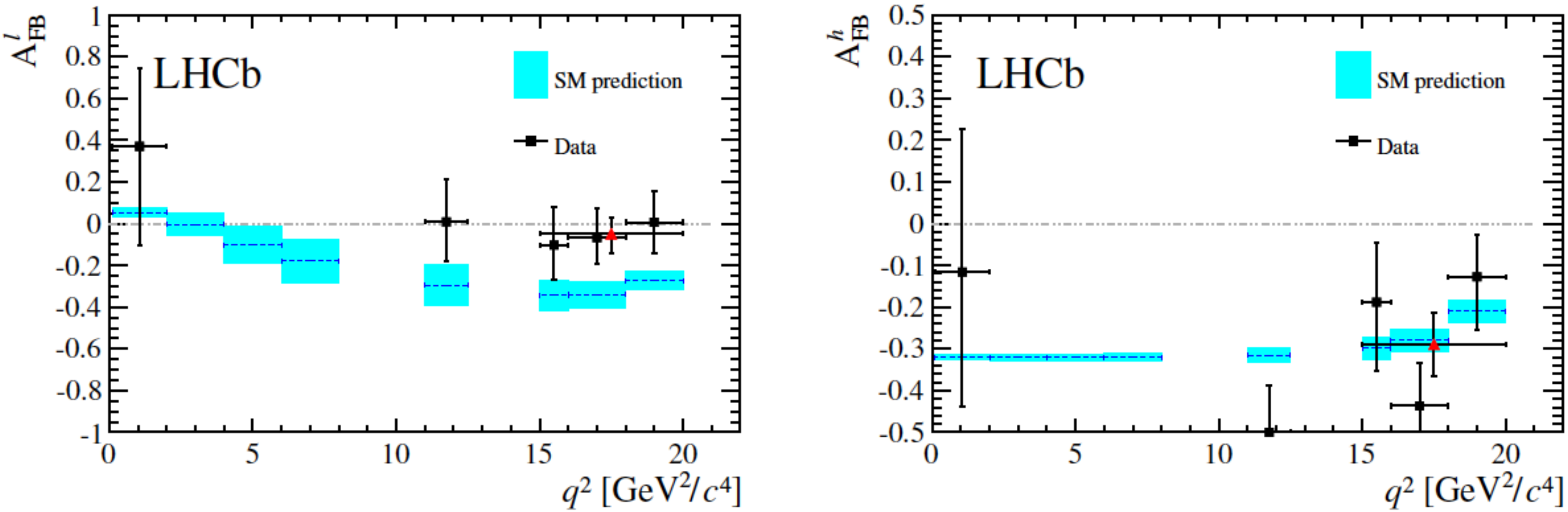
- Measured relative to $\Lambda_b^0 \to \Lambda^0 J/\psi$ in bins of q^2
- In agreement with SM at high q^2
- Lies below SM prediction [PRD 87 (2013) 074502] at high q^2



Angular fit

- Measured forward-backward asymmetry (A_{FB}) for both dimuon and proton-pion systems

$$A^i_{\mathrm{FB}}(q^2) = \frac{\int_0^1 \frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{dcos}\,\theta_i}\mathrm{dcos}\,\theta_i - \int_{-1}^0 \frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{dcos}\,\theta_i}\mathrm{dcos}\,\theta_i}{\mathrm{d}\Gamma/\mathrm{d}q^2}$$



- Agreement with SM in proton-pion system
- Systematic shift in dimuon system
- Predictions from [arXiv:1401.2685]

$$B^+ \to \pi^+ \mu^+ \mu^-$$

Preliminary
LHCb-PAPER-2015-035
in preparation

$B^+ \to \pi^+ \mu^+ \mu^-$

A b→d transition, additionally CKM supressed compared to $B^+ \to K^+ \mu^+ \mu^-$

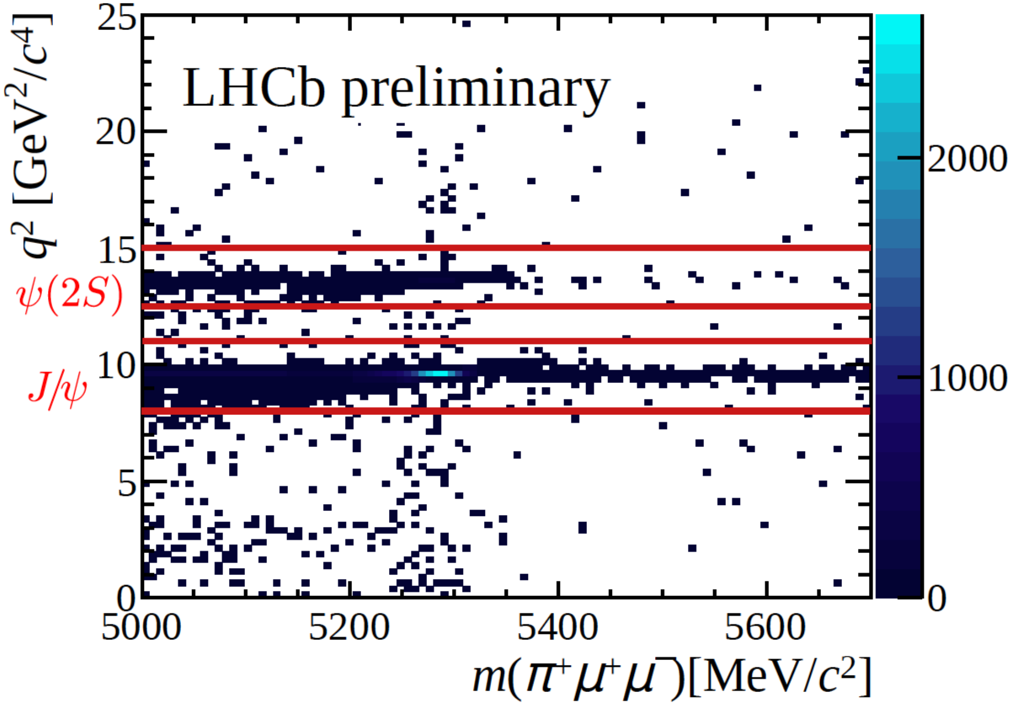
Discovered by LHCb in 2012 using $1 fb^{-1}$. New analysis uses full $3 fb^{-1}$ data set.

Measurement of:

- Differential BF in bins of q^2
- CP asymmetry
- CKM element $|V_{td}|$ and ratio $|V_{td}|/|V_{ts}|$

Selection:

- BDT to reduce combinatorial BG
- Veto on charmonium resonances
- PID supresses peaking BGs



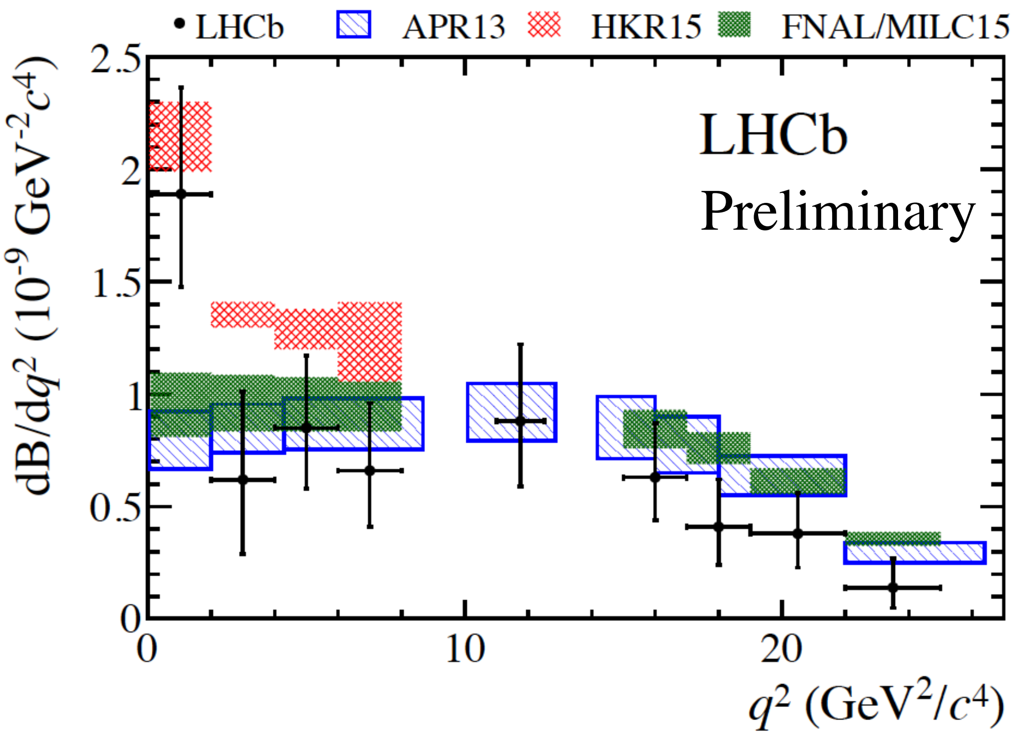
Branching Fraction measured relative to $B^+ \to K^+ J/\psi$

$$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (1.83 \pm 0.24\,(\text{stat}) \pm 0.05\,(\text{syst})) \times 10^{-8}$$

Theoretical predictions from:

- APR13 Phys.Rev.D89,094021(2015)
- HKR15 arXiv:1506.07760,
- FNAL/MILC15 arXiv:1507.01618

Measurement favours FNAL/MILC15 and APR13 in all bins except lowest q^2 bin.



CKM elements from

$$|V_{td}/V_{ts}|^2 = \frac{\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)} \times \frac{\int F_K \mathrm{d}q^2}{\int F_\pi \mathrm{d}q^2}$$

and

$$|V_{td}|^2 = \frac{\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)}{\int F_\pi \mathrm{d}q^2}$$

$$|V_{ts}|^2 = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\int F_K \mathrm{d}q^2}$$

Form factors calculated using EOS [JHEP 1007 098 (2010)] package.

Measurement performed in theoretically favoured q^2 regions, avoiding resonances: [1.0-6.0 GeV^2] and [15.0-22.0 GeV^2].

Preliminary results

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.236^{+0.053}_{-0.038}$$

$$|V_{td}| = 7.15^{+0.85}_{-0.75} \times 10^{-3}$$

Compared to the **PDG**

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.216 \pm 0.011$$

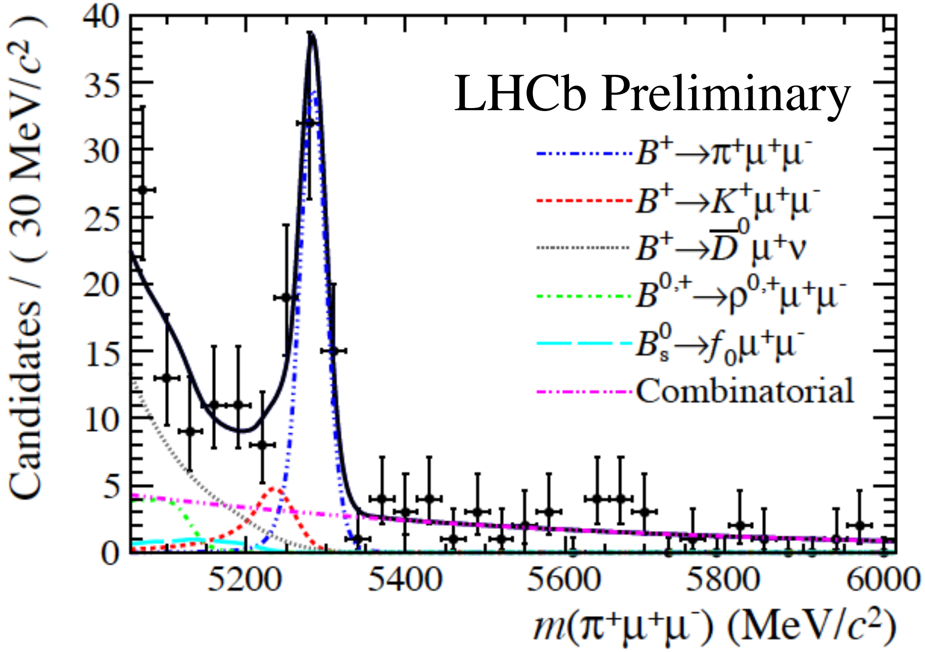
$$|V_{td}| = (8.4 \pm 0.6) \times 10^{-3}$$

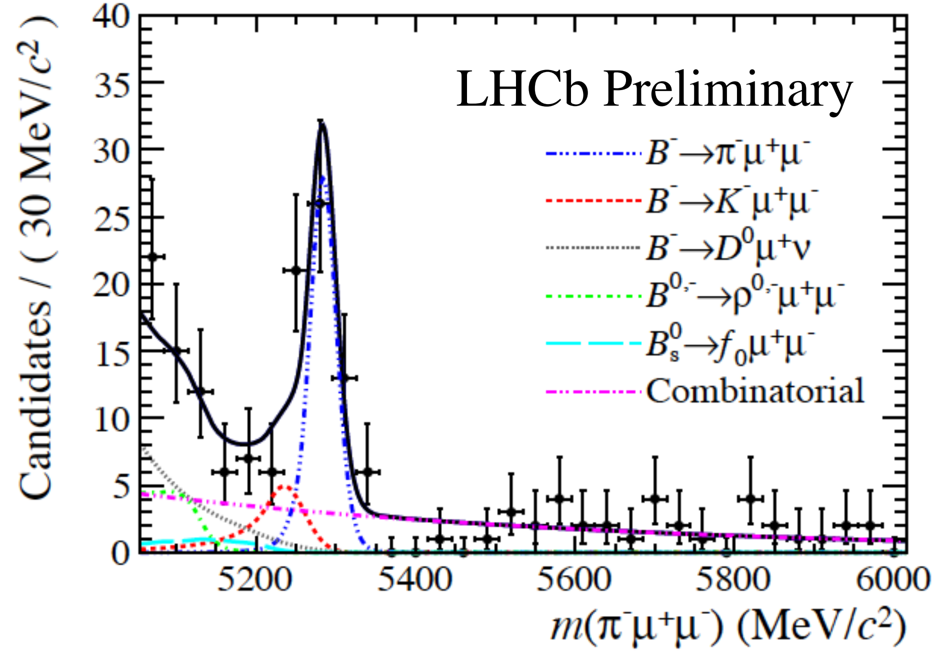
$B^+ \to \pi^+\mu^+\mu^-$

CP asymmetry defined as

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(B^- \to \pi^-\mu^+\mu^-) - \Gamma(B^+ \to \pi^+\mu^+\mu^-)}{\Gamma(B^- \to \pi^-\mu^+\mu^-) + \Gamma(B^+ \to \pi^+\mu^+\mu^-)}$$

Production and detection asymmetries negligible compared to uncertainty.





$$\mathcal{A}_{CP}(B^\pm \to \pi^\pm\mu^+\mu^-) = -0.11 \pm 0.12\,(\mathrm{stat}) \pm 0.01\,(\mathrm{syst})$$

Consistent with SM O(0.1) [arXiv:1506.07760]

$$B^0 \rightarrow K^{*0}\chi^0\left(\rightarrow \mu^+\mu^-\right)$$

arXiv:1508.04094

$B^0 \to K^{*0}\chi^0\left(\to \mu^+\mu^-\right)$

Search for low mass **dark bosons** coupling to SM via mixing with Higgs.

Wide range of possible masses and lifetimes.

Split into two decay time regions defined by detector resolution : σ_t = 0.2 ps

Long lifetime ($t > 3\ \sigma_t$)

- Decay vertex displaced from B decay vertex
- Low backgrounds but lower reconstruction efficiency
- e.g. inflaton [JHEP 1005(2010)010]

Short lifetime ($t < 3\ \sigma_t$)

- Decay vertex at or close to B decay vertex
- SM backgrounds
- e.g. dark matter mediator [Phys.Lett.B727(2013)] or axion(like) [Phys.Rev.D81(2010)034001]

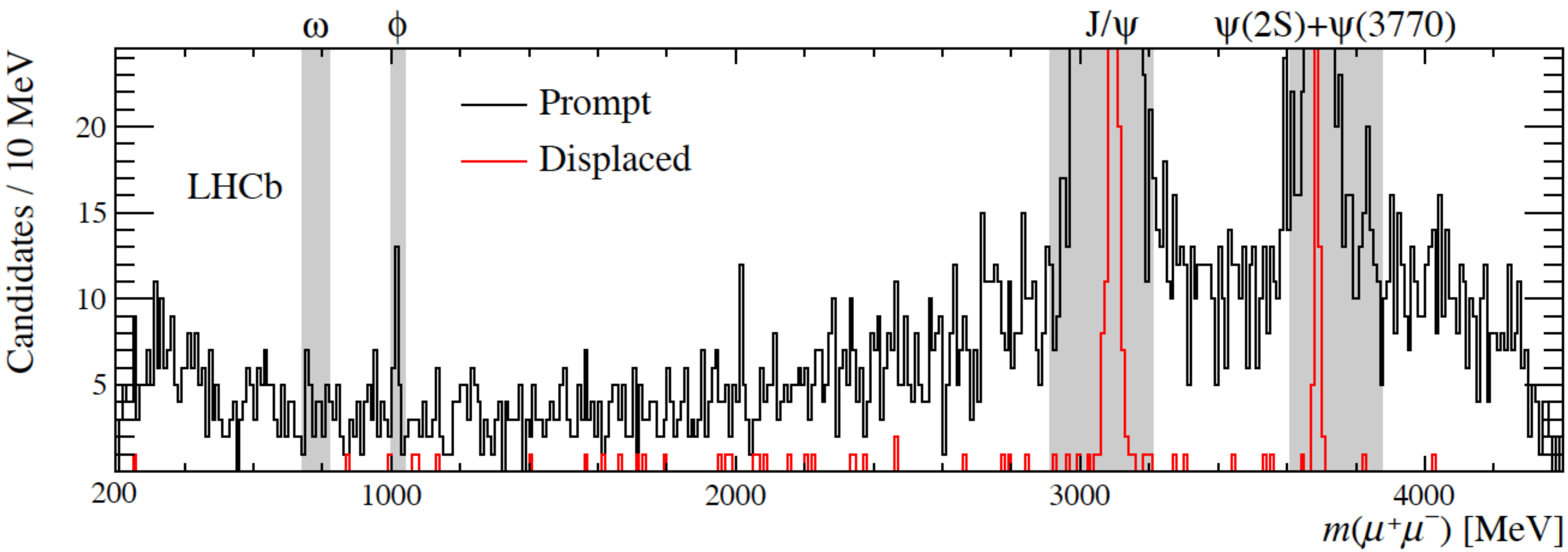
Selection uses multivariate uBDT with performance independent of mass and lifetime.

$B^0 \to K^{*0}\chi^0\left(\to \mu^+\mu^-\right)$

Search made by stepping through mass distribution in steps of 1/2 σ_m (2-8 MeV).

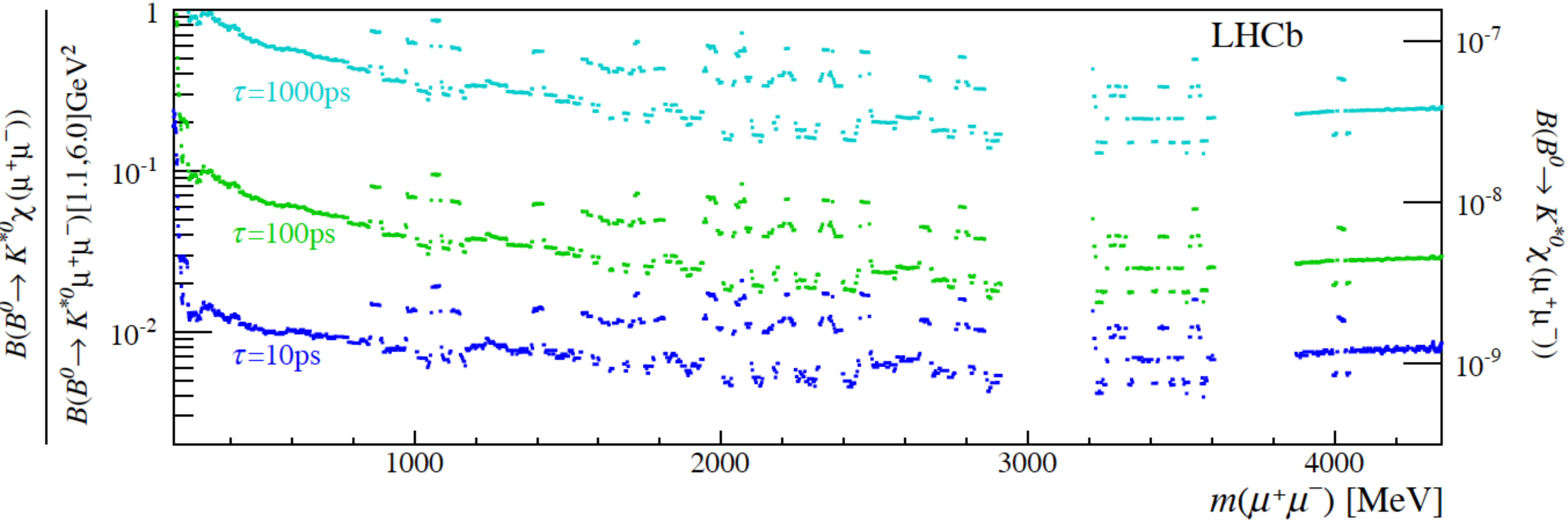
Test statistic formed at each value of m_{test}.

Narrow dimuon resonances vetoed.



$B^0 \to K^{*0}\chi^0\left(\to \mu^+\mu^-\right)$

No significance excesses observed. Limits set on dark bosons:



Limits strongest for short lifetimes.

Stringent constraints placed on models with additional scalar or axial vector fields.

Improvement on limits from B factories.

Conclusions

Large number of rare decay analyses underway at LHCb, only a small sample of the most recent results shown today.

Most results agree with SM but some intriguing hints:

- Low BF measurements at low q^2 in a number of modes
- Deviation from SM in P_5' in $B^0 \to K^{*0}\mu^+\mu^-$

Stay tuned for Run II