Measurements of $b \to s(d)\ \mu^+\mu^-$ at LHCb

J. Alexander Ward
(University of Warwick, Monash University)
On behalf of the LHCb collaboration

31st International Symposium on Lepton Photon Interactions at High Energies
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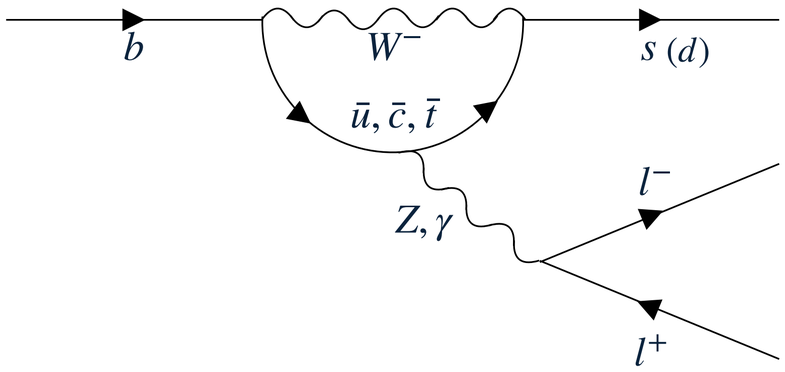
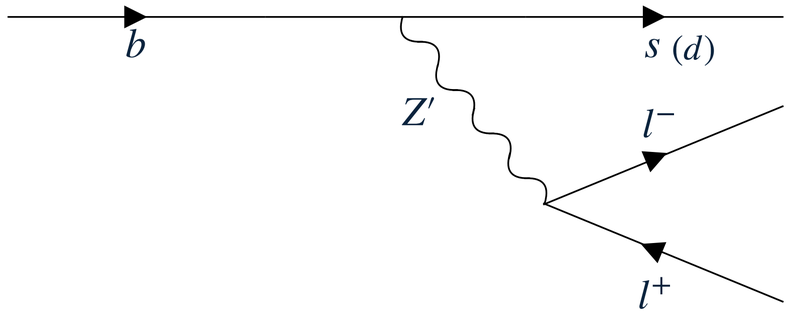
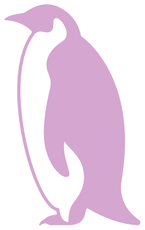
- $b \to s(d)\ ll$ quark transitions are flavour-changing neutral currents (FCNC)
  - Suppressed in the SM, occurring via loops or box diagrams
  - Small BR prediction ~ $10^{-6} - 10^{-7}$
  - Sensitive to New Physics (NP) contributions

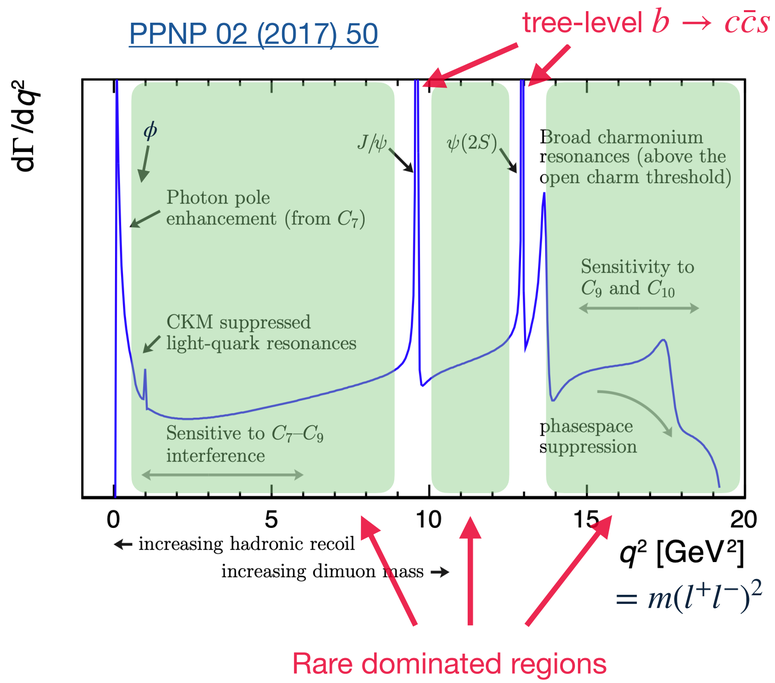


NP mediator



- NP particles could:
  - Enhance or suppress decay rates
  - Modify angular distributions in final state
  - Introduce CP violation source





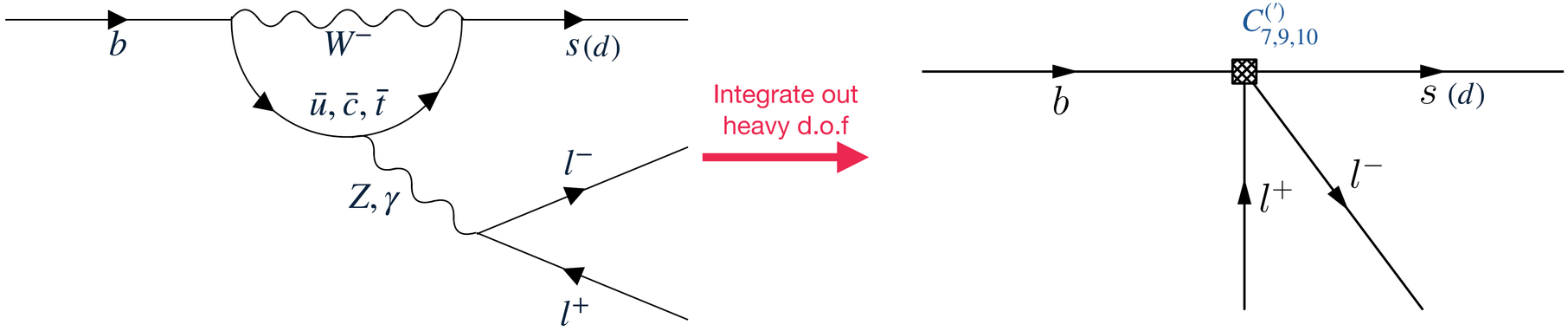
- At heavy hadron scale, FCNC described by Weak Effective Hamiltonian

Effective coupling
Wilson Coefficients (WCs)

$$\mathrm{H}_{eff} = \frac{-4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i \mathrm{C}_i \mathrm{O}_i$$

Local Operators

- NP can modify the WCs : $\mathrm{C}_i = \mathrm{C}_i^{SM} + \mathrm{C}_i^{NP}$
- Probing different $q^2 = m(l^+l^-)^2$ regions provides access to different WCs
- $C_7^{(\prime)}$ related to photon pole
- $C_{9,10}^{(\prime)}$ corresponding to vector and axial respectively



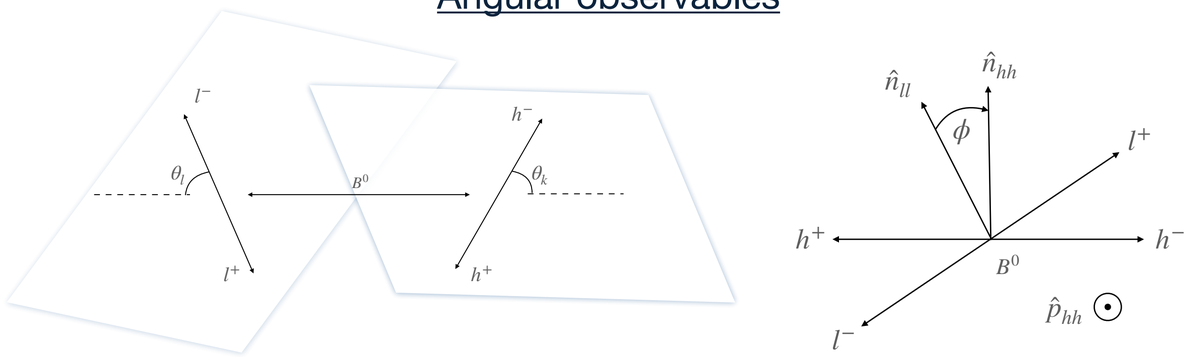
Uncertainty of SM predictions

Experimental challenge

Branching fractions

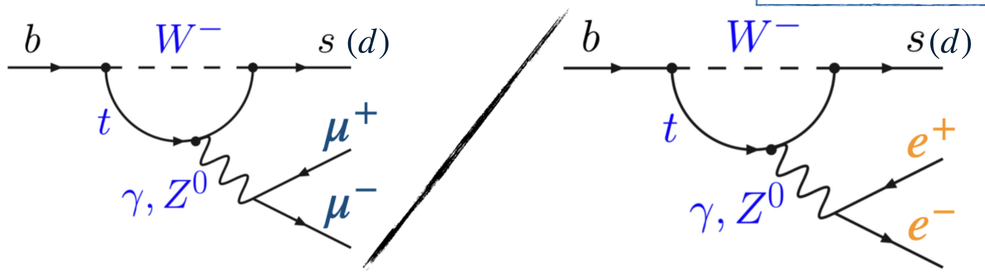
$$\frac{dB(b \to Vll)/dq^2}{B(b \to VJ/\psi)}$$

Angular observables



Lepton Flavour Universality

B. Mitreska : Tests of LFU and searches for LFU at LHCb

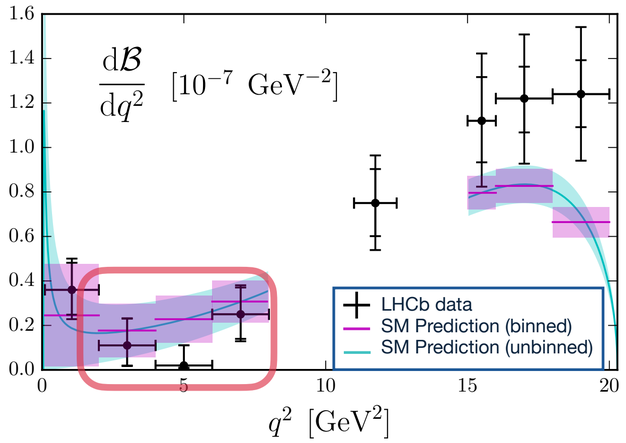


Differential branching fractions: $b \to s\ \mu^+\mu^-$

$b \to s\ \mu^+\mu^-$ Differential branching fractions

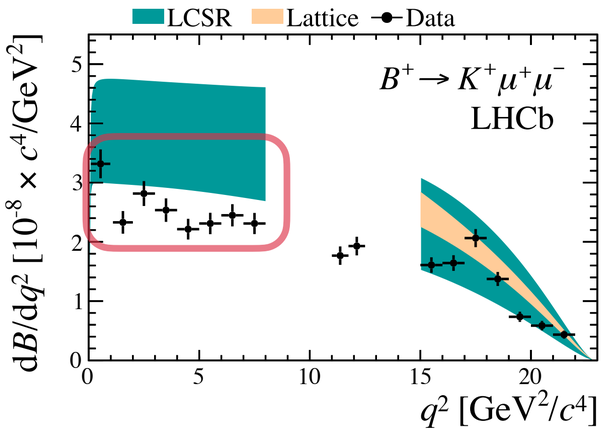
$\Lambda_b^0 \to \Lambda^0\ \mu^+\mu^-$

[JHEP 06 (2015) 115] [PRD 93 074501 (2016)]



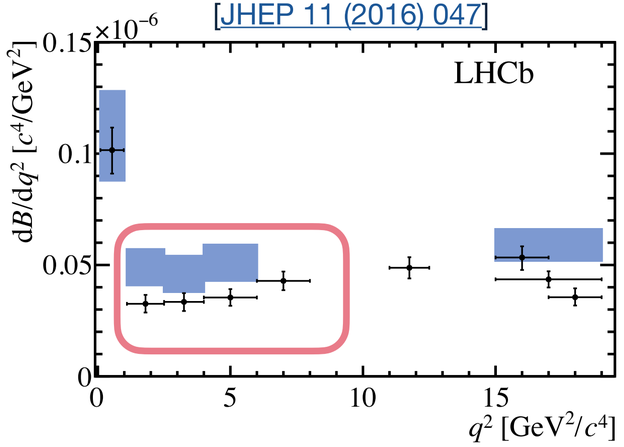
$B^{(+)} \to K^{(+)}\mu^+\mu^-$

[JHEP 06 (2014) 133]



$B^0 \to K^*(892)^0\ \mu^+\mu^-$

[JHEP 11 (2016) 047]

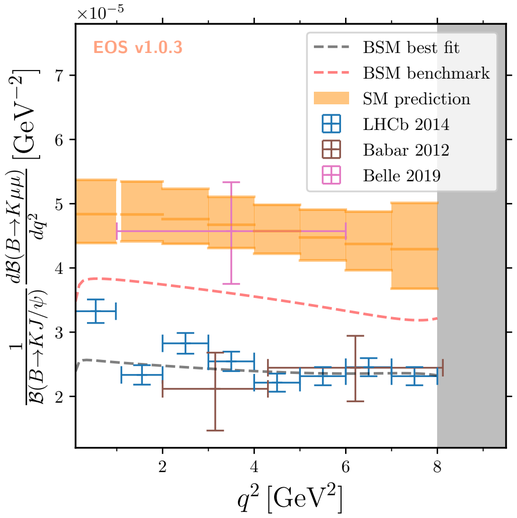


Run 1 SM Tensions:

- Reported measurements below SM by 1-3σ in low q^2 bins
- Non-local hadronic uncertainties difficult to estimate
- Recently updated SM predictions, tensions persist

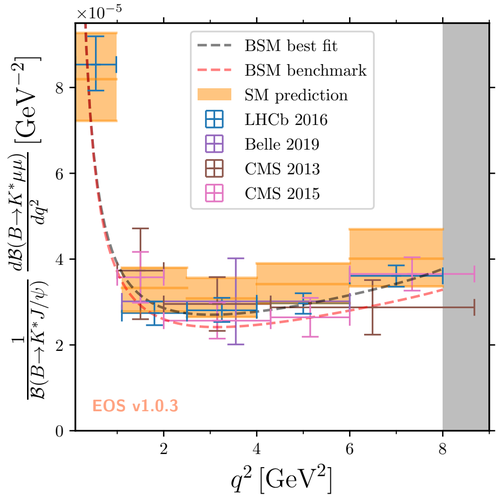
Run 1 : 2011-2012 $\approx 3\ fb^{-1}$
Run 2 : 2015-2018 $\approx 6\ fb^{-1}$

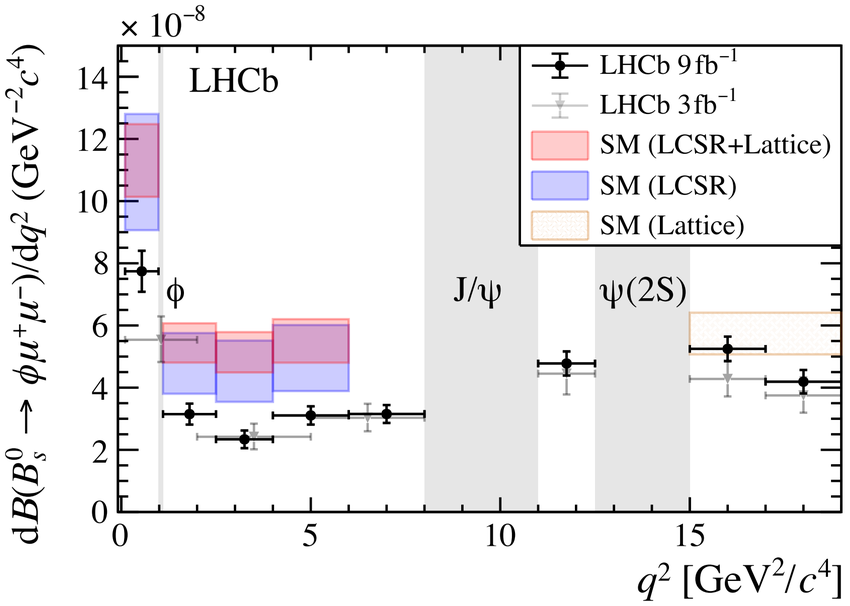
[JHEP 09 (2022) 133]



As mentioned in talk by B. Allanach

[JHEP 09 (2022) 133]



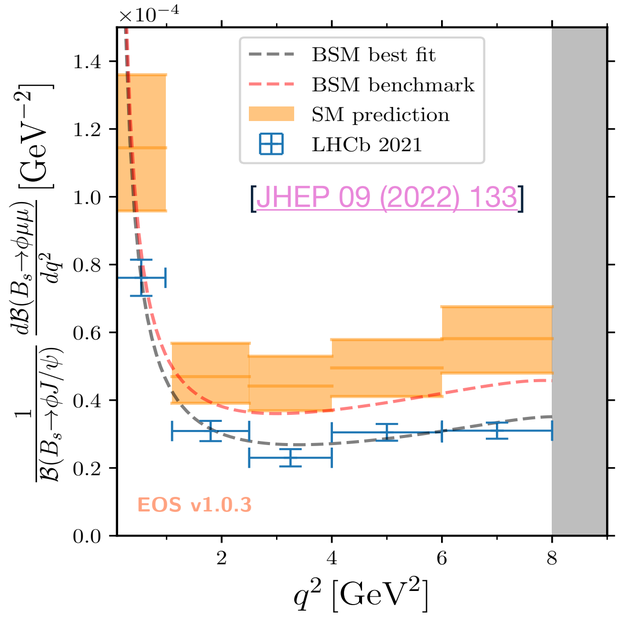


SM tension

In low q^2 [1.1,6.0] GeV^2/c^4

3.6σ (LCSR + Lattice)

1.8σ (LCSR)



- Update of *JHEP* 1307 (2013) 084 / *JHEP* 09 (2015) 179 - factor four increase in number of B_s^0 from 2015 paper
- Reconstructed in the $K^+K^-\mu^+\mu^-$ final state
- Veto q^2 regions :
  - Dominated by tree-level $b \to c\bar{c}s$ modes
  - Contributions from $B_s^0 \to \phi(\to \mu^+\mu^-)\ \phi$ at [0.98,1.1] GeV^2/c^4
- $B_s^0 \to J/\psi\ \phi$ used as normalisation
- Differential BF determined via simultaneous fit to rare q^2 bins, via extended ML fit

Most precise $B_s^0 \to \phi\ \mu^+\mu^-$ BF measurement

$$\mathrm{B}(B_s^0 \to \phi\mu^+\mu^-) = (\ 8.14 \pm 0.22 \pm 0.16 \pm 0.39 \pm 0.03) \times 10^{-7}$$

stat, syst, absolute BF, extrapolation to full q^2 range

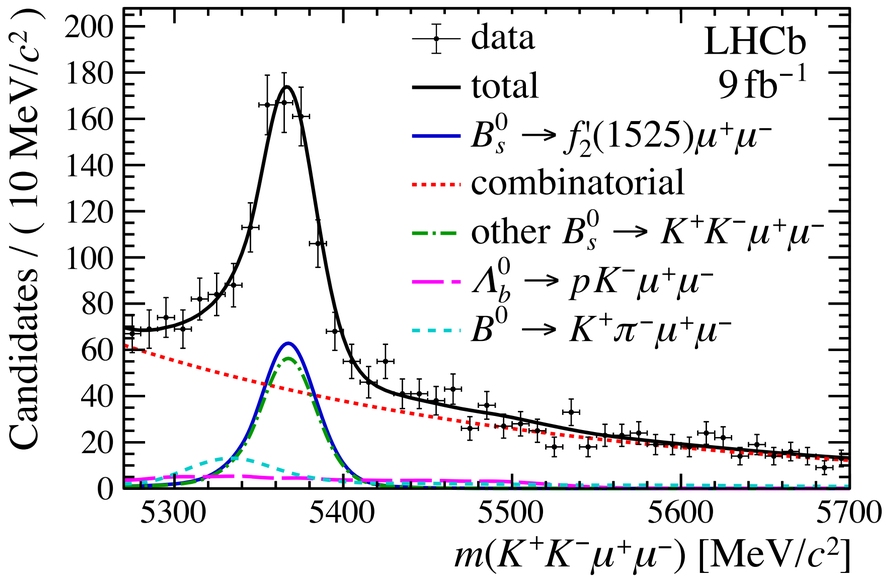
$B_s^0 \to f_2'(1525)\ \mu^+\mu^-$ [PRL 127 (2021) 151801]

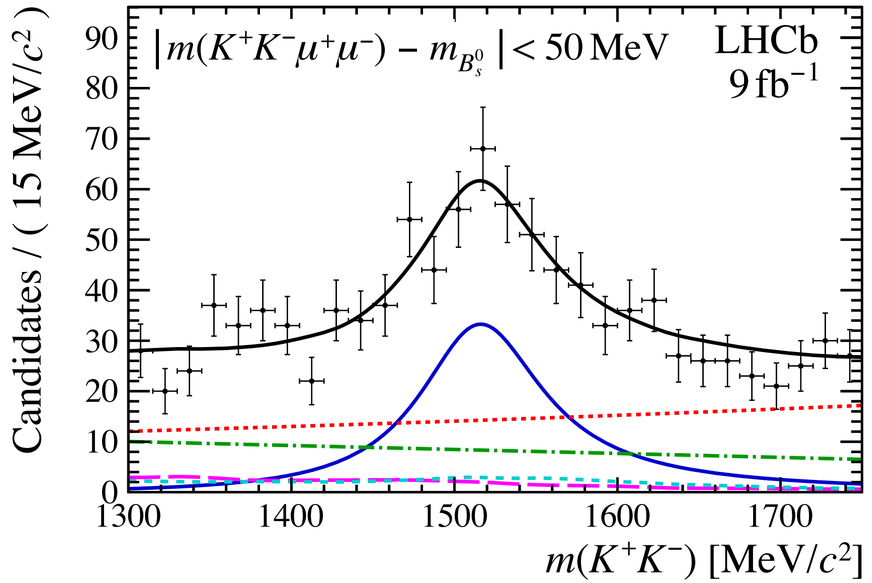
- First observation of a rare semi-leptonic decay involving a spin-2 meson in the final state
- Similar selection to $B_s^0 \to \phi\ \mu^+\mu^-$ from same paper
- Combined fit to q^2 regions [0.1, 0.98] ∪ [1.1,8.0] ∪ [11.0,12.5] GeV^2/c^4
- 2D fit to $m(K^+K^-\mu^+\mu^-)$ and $m(K^+K^-)$
- S- and P-wave resonance contributions from e.g. ϕ and $\phi(1680)$ combined in fit
- BF in agreement with SM

stat, syst, absolute BF, extrapolation to full q^2 range

$$\mathrm{B}(B_s^0 \to f_2'\mu^+\mu^-) = (1.57 \pm 0.19 \pm 0.06 \pm 0.08 \pm 0.06) \times 10^{-7}$$

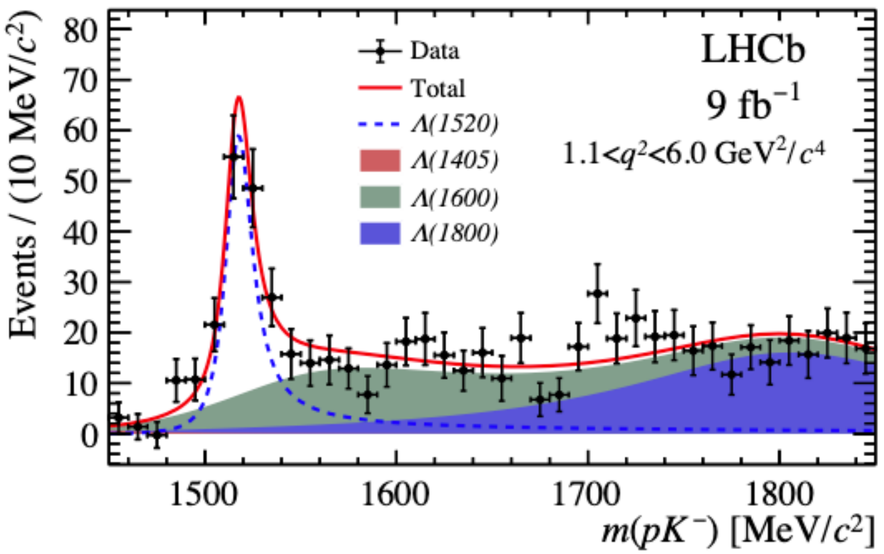
9σ observation





$\Lambda_b^0 \to \Lambda(1520)\ \mu^+\mu^-$ [arXiv:2302.08262]

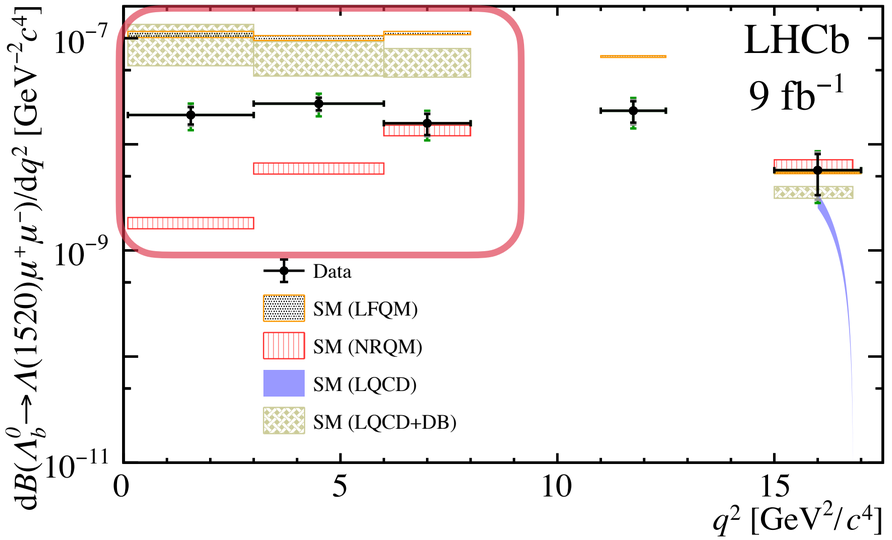
New result! Feb 2023



- Reconstructed as $\Lambda(1520) \to pK^-$
- Normalised to more abundant $\Lambda_b^0 \to pK^- J/\psi$
- Narrow $\Lambda(1520)$ width of ~16 MeV
- Spin parity of $J^P = (3/2)^-$ provides info. on potential NP in $b \to sll$

high q^2 (>15.0 GeV^2/c^4)
SM consistent with data

low q^2 (<8.0 GeV^2/c^4)
Discrepancy but cannot make statement on agreement
Large variation in SM predictions

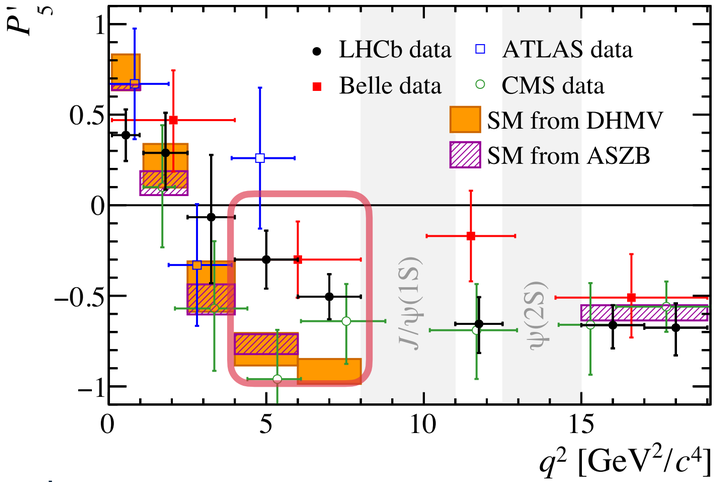


Angular observables

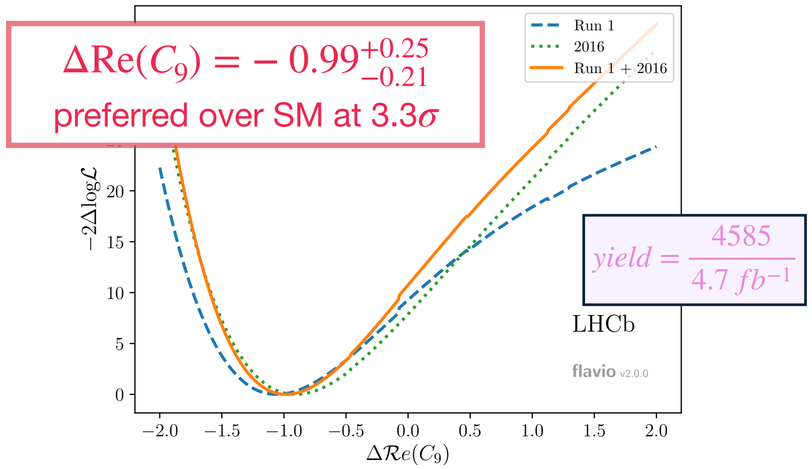
Angular analysis: $B \to Vll$

- Extract more information, complementary to branching fraction measurements
- Kinematics of $B \to Vll$ decays described entirely by q^2 and helicity angles, $\overrightarrow{\Omega} = (\theta_h, \theta_l, \phi)$
- **Complex angular structures** gives access to different operators in H_{eff}
- Self-conjugated decays access CP averaged (S_i) and CP asymmetry (A_i) observables, **sensitive to NP** in WCs $\mathrm{C}_{7,9,10}$
- Observables with reduced form-factors uncertainties: $P_i^{'} = \frac{S_i}{\sqrt{F_L(1-F_L)}}$, eg: the $P_5^{'}$ tension

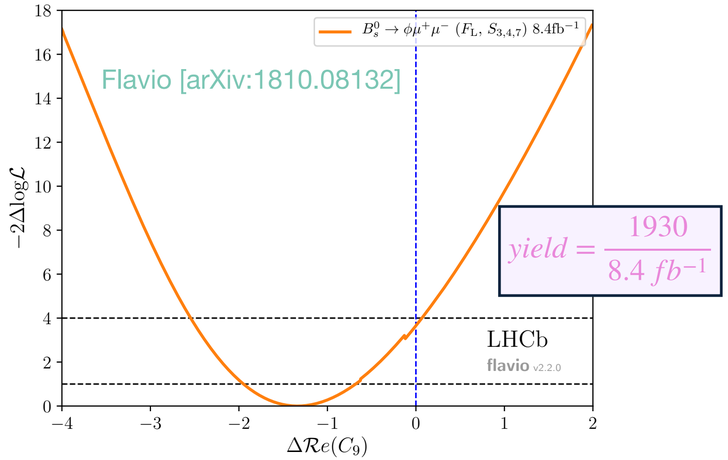
$B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 (2020) 011802]



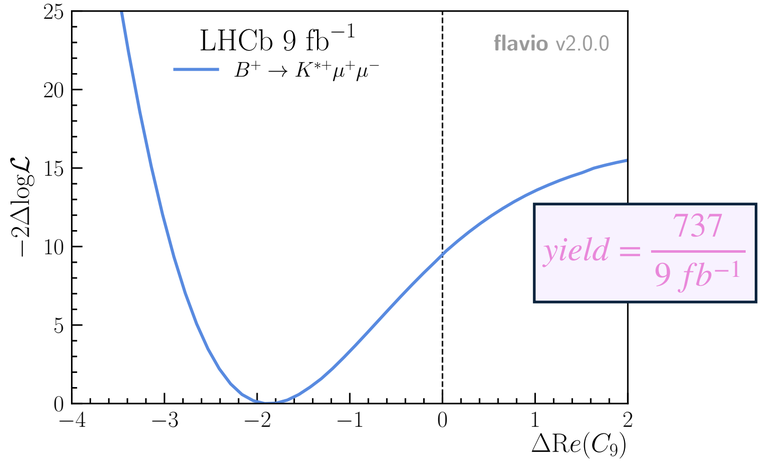
Covered by M. Rama



$B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 (2020) 011802]



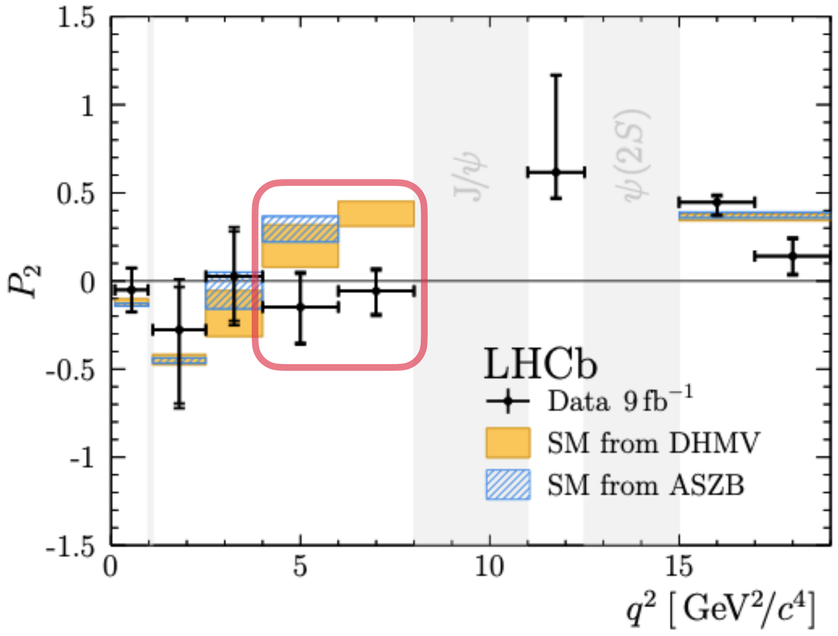
$B_s^0 \to \phi\ \mu^+\mu^-$ [JHEP 11 (2021) 043]

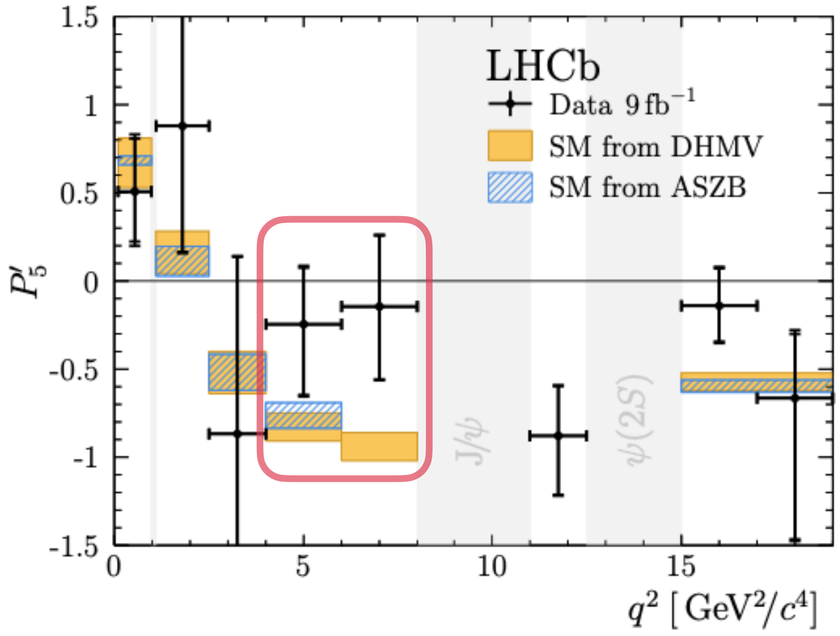


$B^+ \to K^{*+}\mu^+\mu^-$ [PRL 126 (2021) 161802]

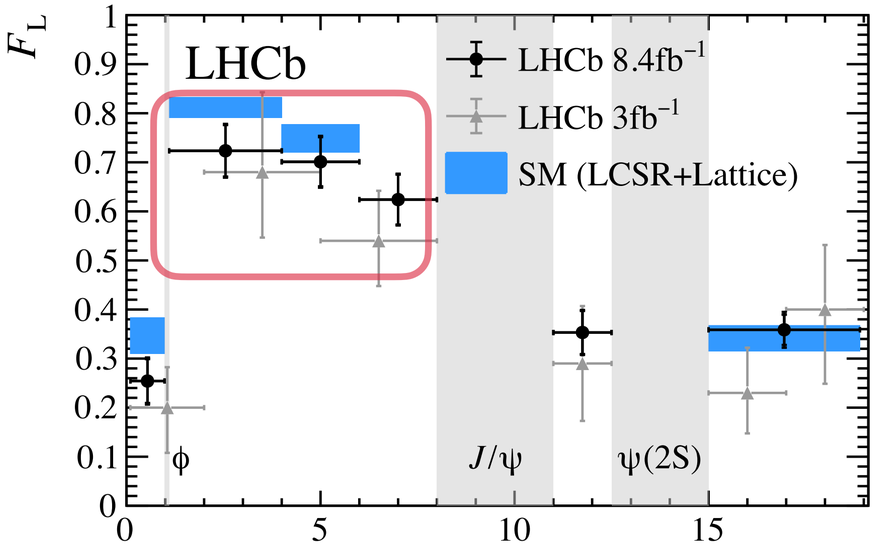
- $B^0 \to (K^{*+} \to K^0_S\pi^+)\ \mu^+\mu^-, K^0_S \to \pi^+\pi^-$
- First measurement of full set of P-wave observables
- S-wave treated as nusiance parameters
- Optimised observables ($P_i^{(\prime)}$) used
- The majority of observables show good agreement with the SM predictions
- Deviations in $P_5^{'}$ (S_5) and P_2 (A_{FB}) in the low q^2 bins confirm the global tension observed in $B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 (2020) 011802]

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

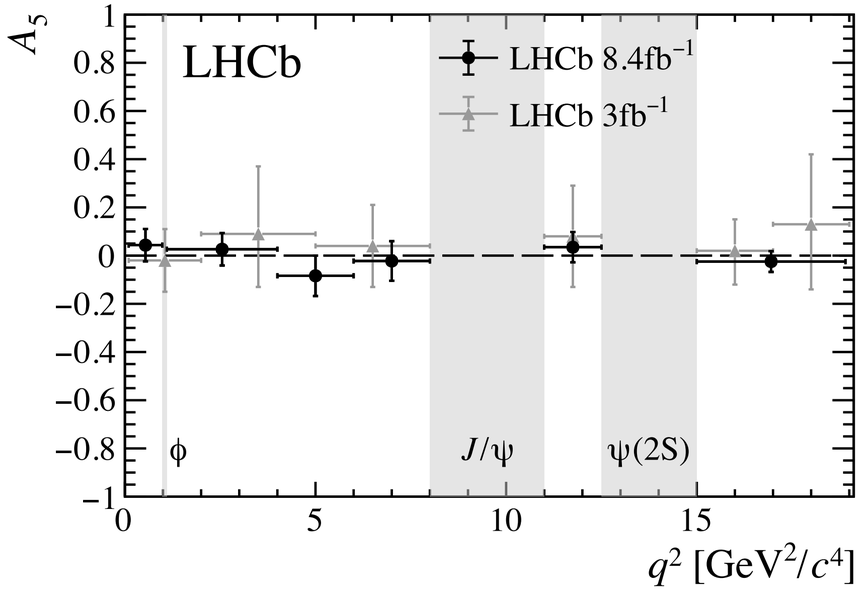




$B_s^0 \to \phi\ \mu^+\mu^-$ [JHEP 11 (2021) 043]

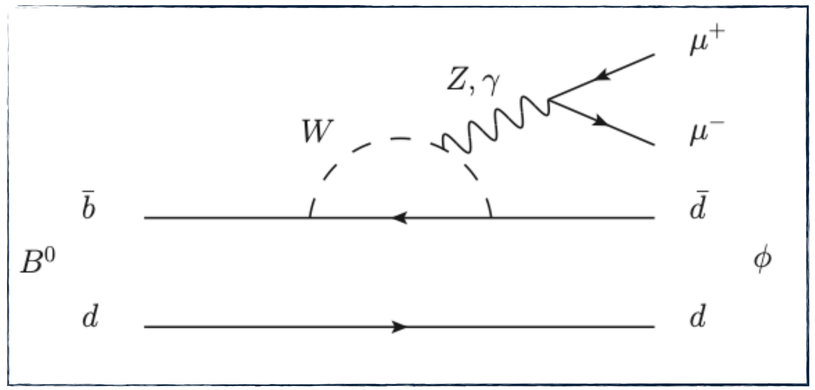


$F_L = S_{1c}$: fraction of longitudinal polarisation of the hadronic meson



- Complementary to BF measurement — same selection criteria
- Update of JHEP 09 (2015) 179
- Simultaneous fit to $\overrightarrow{\Omega}$, $m(K\pi\mu\mu)$
- S-wave not constrained (treated as systematic uncertainty)
- Agreement between SM predictions and data — CP asymmetries ~0
- Mild tension seen in FL

$b \to d\mu\mu$



- At tree-level, decays via $s\bar{s}$ colour-suppressed annihilation penguins, BF ~$\mathcal{O}(10^{-12})$
- Dominated by EWP contributions from $\omega - \phi$ mixing with larger BF ~$\mathcal{O}(10^{-10})$, with potential NP effects

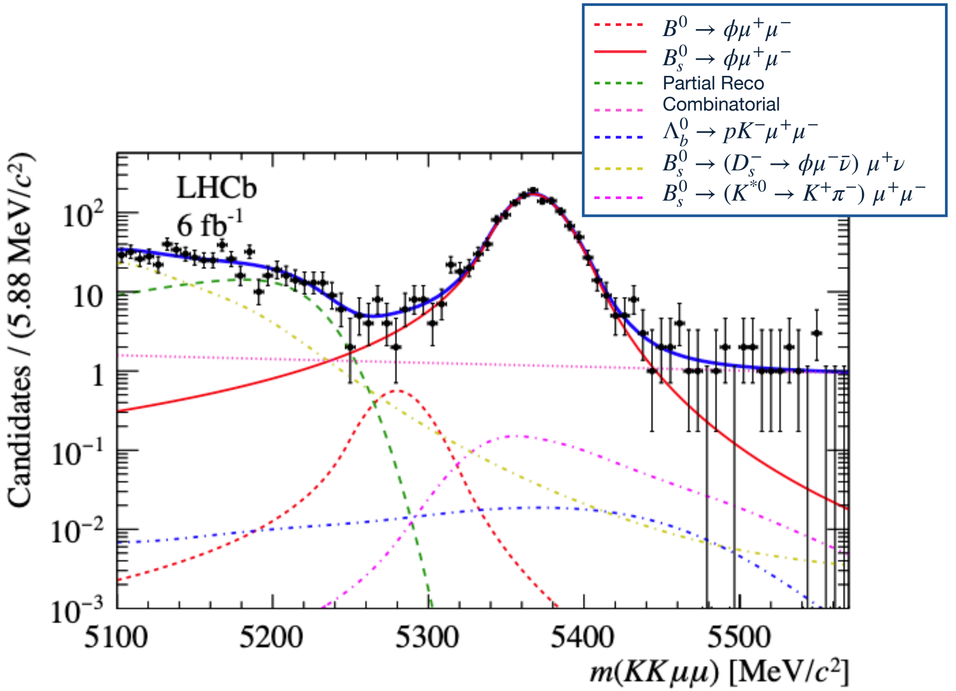
- Searched in rare q^2 regions
- Normalised to $B_s^0 \to \phi\ \mu^+\mu^-$, with existing LHCb measurement
- BF ratio,

$$R = \frac{\mathrm{B}(B^0 \to \phi\mu^+\mu^-)}{\mathrm{B}(B_s^0 \to \phi\mu^+\mu^-)} < 4.4 \times 10^{-3} \text{ at 90\% CL}$$

- Upper limit, accounting for full q^2 range:

$$B(B^0 \to \phi\mu^+\mu^-) < 3.2 \times 10^{-9} \text{ at 90\% CL}$$

- Compatible with SM predictions



No statistically significant signal observed above the background

Summary

New results:

- Several results in semi-leptonic $b \to s\mu\mu$ sector
- Steps into measuring $b \to d\mu\mu$ observables
- Constraints on NP models
- **Tensions with SM persist**

Run 1 & 2:

- **More results to come**:
  - Updates of Run 1 measurements
  - Analysing new channels/observables
  - Eg: Can perform unbinned angular analyses

Stay tuned for many more LHCb results in the future!

Upgraded detector:

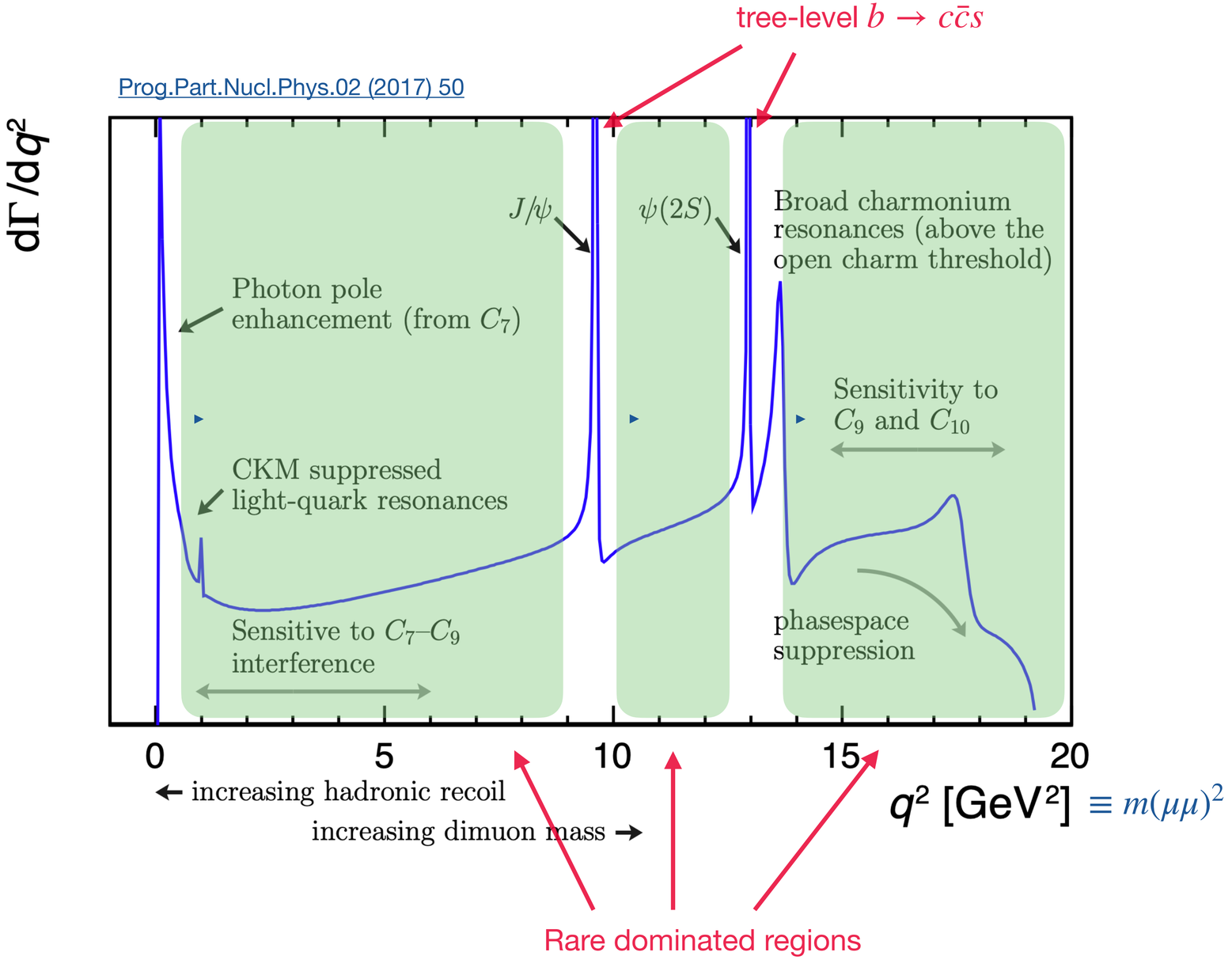
- 5x luminosity, aim to collect $50\ fb^{-1}$ **in Runs 3 & 4**
- Large step in sensitivity of EWP measurements
- Opportunity for precise measurements in $b \to dl^+l^-$

Thanks for listening

LHC Run3 First collisions
LHCb control room July 5 2022

Backup

- *Branching fractions*:
  - $B \to K^{(*)}\ \mu^+\mu^-$ (Run 1) [JHEP 06 (2014) 133]
  - $\Lambda_b^0 \to \Lambda^0\ \mu^+\mu^-$ (Run 1) [JHEP 06 (2015) 115 + erratum JHEP 09 (2018) 145]
  - $B^0 \to K^*(892)^0\ \mu^+\mu^-$ (Run 1) [JHEP 11 (2016) 047+ erratum JHEP 04 (2017) 142]
  - $B_s^0 \to \phi\ \mu^+\mu^-$ and $B_s^0 \to f_2'(1525)\ \mu^+\mu^-$ (Run 1+2) [PRL 127 (2021) 151801]
  - $\Lambda_b^0 \to \Lambda(1520)\ \mu^+\mu^-$ (Run 1) [arXiv:2302.08262]
- *Angular observables*:
  - $B^{(+)} \to K^{(+)}\mu^+\mu^-$ (Run 1) [JHEP 05 (2014) 082]
  - $\Lambda_b^0 \to \Lambda^0\ \mu^+\mu^-$ (Run 1) [JHEP 06 (2015) 115]
  - $B_s^0 \to \phi\ \mu^+\mu^-$ (Run 1) [JHEP 09 (2015) 179]
  - $B_s^0 \to \phi\ \mu^+\mu^-$ (Run1+2) [JHEP 11 (2021) 043]
  - $B^0 \to K^{*0}\mu^+\mu^-$ (Run 1+ 2016) [PRL 125 (2020) 011802]
  - $B^+ \to K^{*+}\mu^+\mu^-$ (Run 1+2) [PRL 126 (2021) 161802]
- *Searches*:
  - $B^0 \to \phi\ \mu^+\mu^-$ (Run 1+2) [JHEP 05 (2022) 067]


tree-level $b \to c\bar{c}s$
Prog.Part.Nucl.Phys.02 (2017) 50
$d\Gamma/dq^2$
J/ψ
$\psi(2S)$
Broad charmonium resonances (above the open charm threshold)
Photon pole enhancement (from C_7)
Sensitivity to C_9 and C_{10}
CKM suppressed light-quark resonances
Sensitive to C_7–C_9 interference
phasespace suppression
0
5
10
15
20
← increasing hadronic recoil
increasing dimuon mass →
q^2 [GeV^2] $\equiv m(\mu\mu)^2$
Rare dominated regions

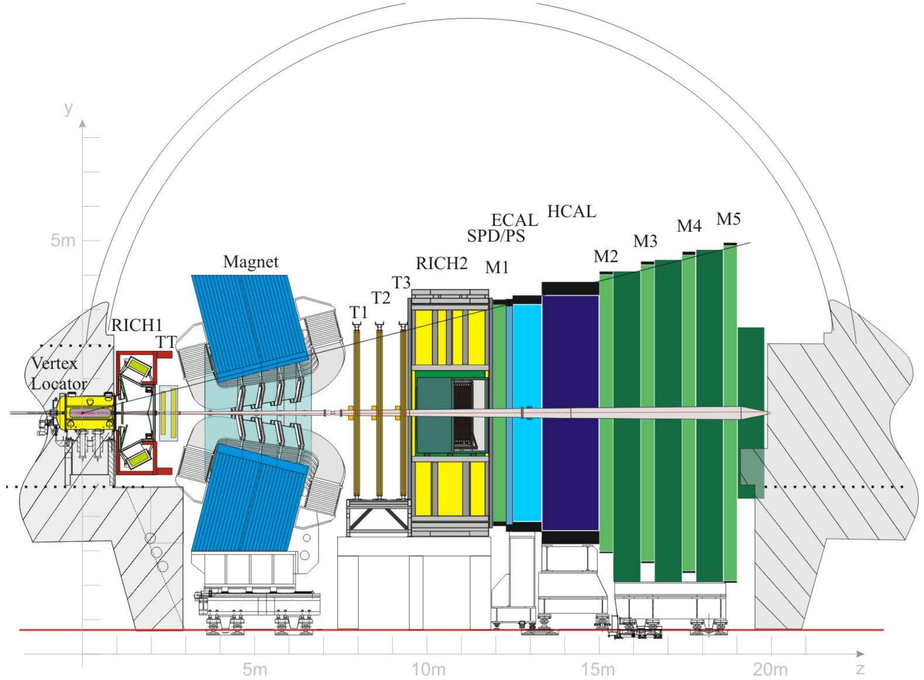


Figure: LHCb detector during Run 1 &

- *Forward detector*:

  27% of b hadrons from pp collisions within acceptance

- *Vertex locator*:

  Precise reconstructions of b and c hadronic decays

- *Tracking:*

  ~96% efficiency, $\Delta_p/p \approx 0.5 - 1\,\%$

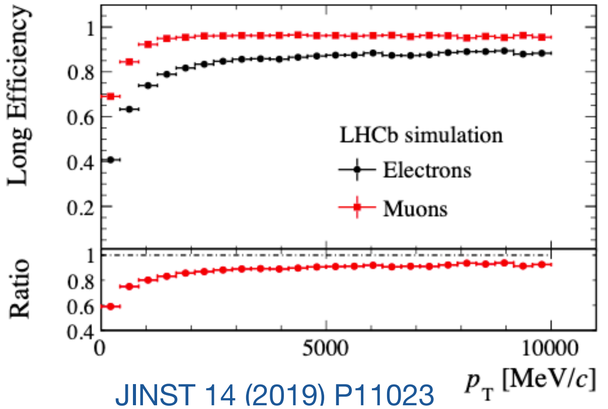
- *Charged particle ID*:

  Efficient identification [$\epsilon_{\mu\to\mu} \approx 97\,\%$,
  $\epsilon_{\pi\to\mu} \approx 1 - 3\,\%$]

- *Trigger*:

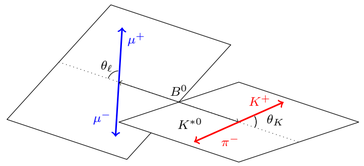
  ~90% efficiency on di-μ channel

- Why $b \to s\mu\mu$? :
  - Dedicated μ tracking stations
  - Low $e^{\pm}$ Bremsstrahlung reconstruction efficiency
  - $\tau^{\pm} \to \mu^{\pm}\nu_{\mu}\nu_{\tau}$ low resolution from missing $\nu_{\mu}\nu_{\tau}$
- ∴ most $b \to sll$ results at LHCb currently $l = \mu$

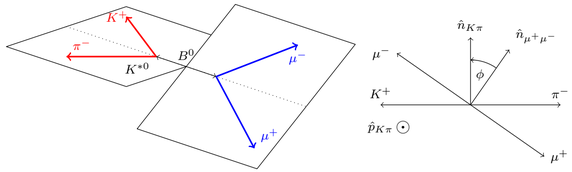


JINST 14 (2019) P11023

- Kinematics of $B \to Vll$ decays described entirely by q^2 and helicity angles, $\overrightarrow{\Omega} = (\cos\theta_h, \cos\theta_l, \phi)$
- Complex angular structures gives access to different operators in H_{eff}
- Self-tagging decays access CP averaged observables



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



(b) ϕ definition for the B^0 decay

- Self-conjugated decays access CP averaged (S_i) and CP asymmetry (A_i) observables, sensitive to NP in WCs $\mathrm{C}_{7,9,10}$
- Observables with reduced form-factors observed, eg:

$$P_i^{'} = \frac{S_i}{\sqrt{F_L(1-F_L)}}$$

- $P_5^{'}$ best known discrepancy

$$\begin{aligned}
\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d(\Gamma+\bar{\Gamma})}{dq^2 d\cos\theta_l d\cos\theta_h d\phi}\bigg|_P = \frac{9}{32\pi}\Big[&\frac{3}{4}(1-F_L)(\sin^2\theta_h) + F_L(\cos^2\theta_h) \\
&+ \frac{1}{4}(1-F_L)(\sin^2\theta_h)(\cos 2\theta_l) \\
&- F_L(\cos^2\theta_h)(\cos 2\theta_l) \\
&+ A_3(\sin^2\theta_h)(\sin^2\theta_l)(\cos 2\phi) \\
&+ S_4(\sin 2\theta_h)(\sin 2\theta_l)(\cos\phi) \\
&+ A_5(\sin 2\theta_h)(\sin\theta_l)(\cos\phi) \\
&+ A_6(\sin^2\theta_h)\cos\theta_l \\
&+ S_7(\sin 2\theta_h)(\sin\theta_l)(\sin\phi) \\
&+ A_8(\sin 2\theta_h)(\sin 2\theta_l)(\sin\phi) \\
&+ A_9(\sin^2\theta_h)(\sin^2\theta_l)(\sin 2\phi)\Big]
\end{aligned}$$

- 5D simultaneous fit to $\vec{\Omega}$, $m(K\pi\mu\mu)$, $m(K\pi)$
- $m(K\pi)$ fit used to constraint S-wave interference
- P_5' tension reduced to 2.8σ and 3.0σ wrt. Run 1 (3 fb^{-1}) analysis [JHEP 02 (2016) 104]
- Reduced tension in q^2 bins [4.0,6.0] and [6.0,8.0]GeV^2/c^4
- $\Delta\mathrm{Re}(C_9) = -0.99^{+0.25}_{-0.21}$ preferred over SM at 3.3σ