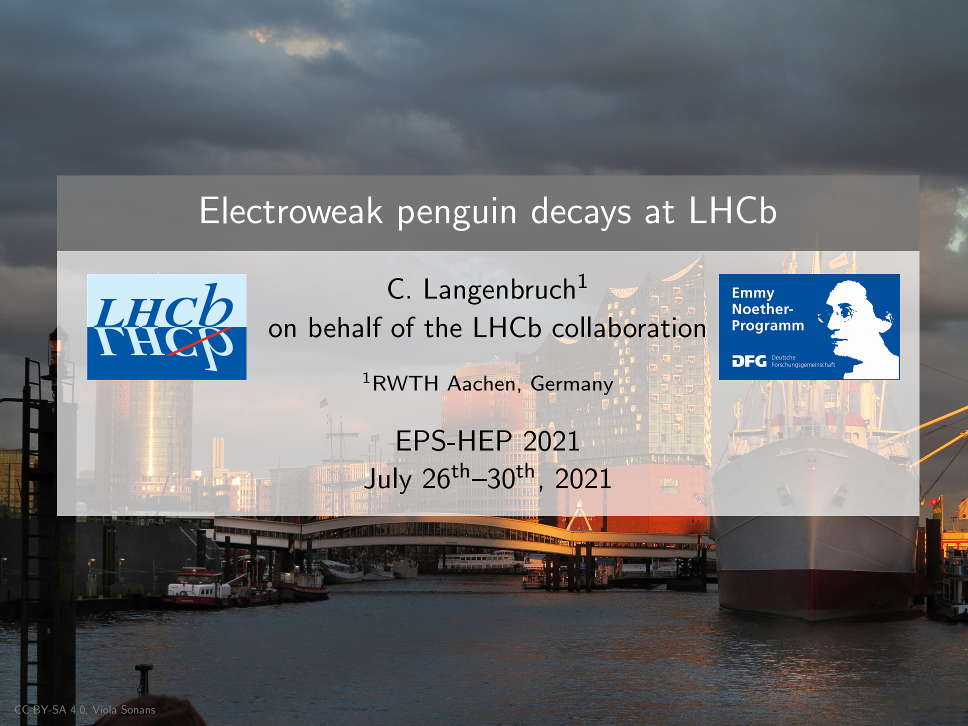

Electroweak penguin decays at LHCb

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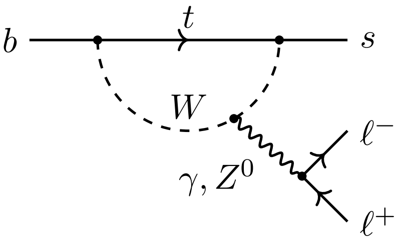
on behalf of the LHCb collaboration

[1]RWTH Aachen, Germany

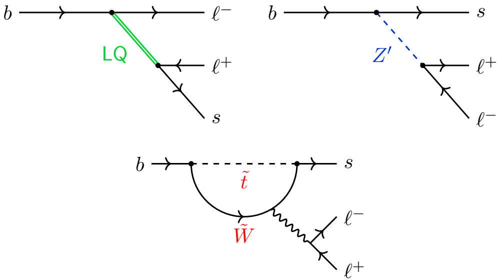
EPS-HEP 2021
July 26th–30th, 2021

Electroweak penguin decays as probes for New Physics

$b \to s\ell\ell$ EWP in the SM

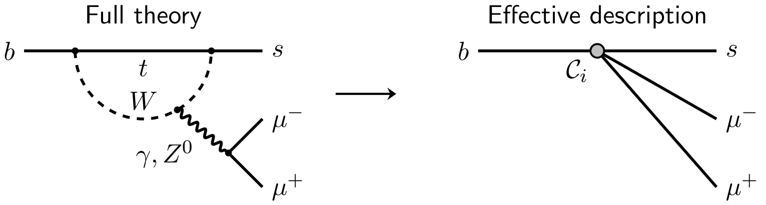


Possible contributions from NP



- Electroweak penguin decays are flavour changing neutral currents, in the SM forbidden at tree-level and only occur as loop-order processes
- New particles can significantly change $\mathcal{B}$ and angular observables
- LHCb ideally suited to perform precision measurements of $b \to s\ell\ell$ decays

EWP decays in effective field theory



Full theory

Effective description

- Rare b decays a multi-scale problem: $\Lambda_{\text{NP}} \gg m_W \gg m_b > \Lambda_{\text{QCD}}$
- Model-independent description in effective field theory

Local operator

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \frac{e^2}{16\pi^2} \sum_i \boxed{\mathcal{C}_i} \boxed{\mathcal{O}_i}$$

Wilson coefficient
("effective coupling")

Flavour-violating coupling

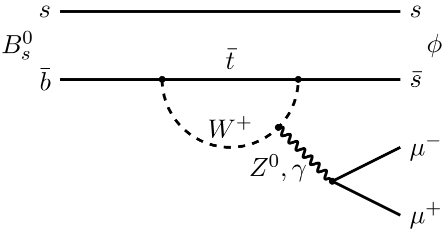
$$\Delta\mathcal{H}_{\text{NP}} = \frac{\boxed{\kappa}}{\boxed{\Lambda^2_{\text{NP}}}} \mathcal{O}_i$$

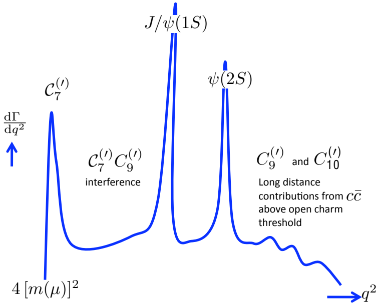
NP scale

- Semileptonic $b \to s\ell\ell$ decays sensitive to several operators $\mathcal{O}_i^{(\text{NP})}$
- Λ_{NP} of $\mathcal{O}(100\,\text{TeV})$ can be probed [JHEP 11 (2014) 121]

Wilson coefficient		Operator
γ-penguin[1]	$\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
ew. penguin	$\mathcal{C}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$
	$\mathcal{C}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$
scalar	$\mathcal{C}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$
pseudoscalar	$\mathcal{C}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$

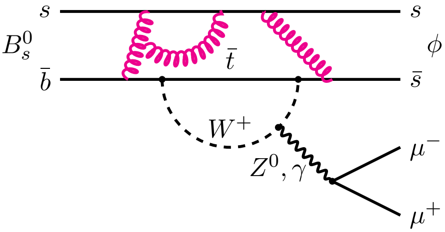
$B_s^0 \to \phi\mu^+\mu^-$ branching fraction

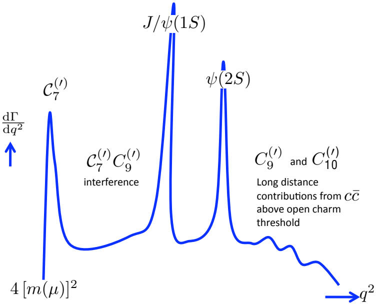




- Decay rates of $b \to s\mu^+\mu^-$ processes sensitive to heavy BSM particles
- Central quantity $q^2 = m_{\mu\mu}^2$, different $\mathcal{O}_i$ contribute depending on q^2
- SM pred. relies on hadronic form factors from non-pert. calculations
  - Low q^2: Light cone sum rules [PRD 71 (2005) 014029] [JHEP 08 (2016) 98] [PRD 75 (2007) 054013] [JHEP 09 (2010) 089] ...
  - High q^2: Lattice calculations [PRD 89 (2014) 094501] [PoS (LATTICE2014) 372] [PRD 88 (2013) 054509] ...
- NEW measurement using full LHCb Run 1+2 data sample [arXiv:2105.14007]

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





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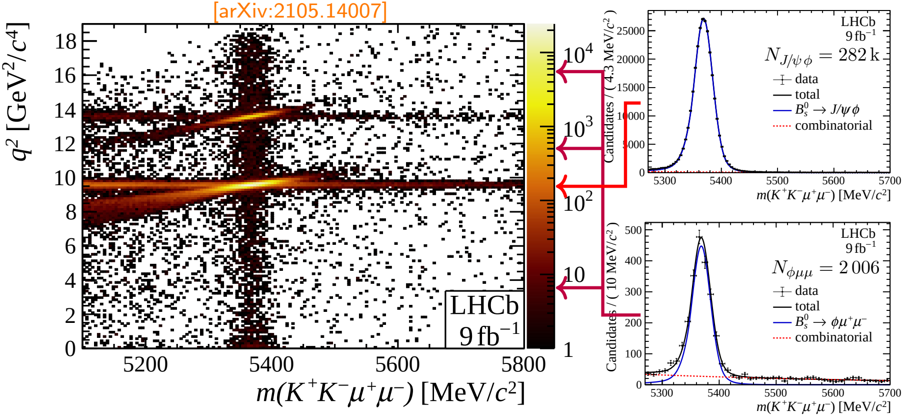
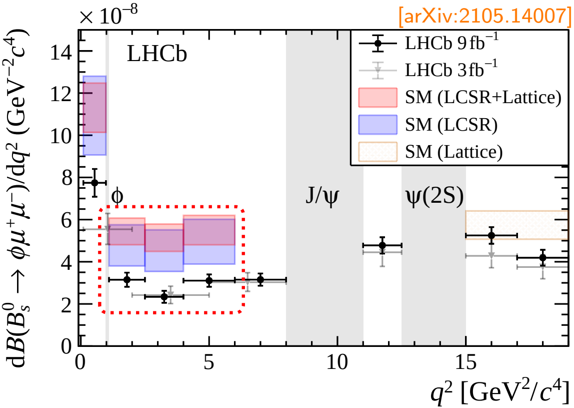
- NEW measurement using full LHCb Run 1+2 data sample [arXiv:2105.14007]

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


[arXiv:2105.14007]

- Narrow cut $\pm 12\,\mathrm{MeV}/c^2$ around known ϕ mass
- BDT to suppress combinatorial background
- Signal clearly visible as vertical band after the full selection
- Veto q^2 range $[8, 11] \cup [12.5, 15]\,\mathrm{GeV}^2/c^4$ containing tree level decays $B_s^0 \to J/\psi\,\phi$ and $B_s^0 \to \psi(2S)\phi$ (used for control and normalisation)

$B_s^0 \to \phi[\to K^+K^-]\mu^+\mu^-$ branching fraction result



SM LCSR
[JHEP 08 (2016) 098]
[EPJC 75 (2015) 8]
SM LCSR+Lattice
[PRL 112 (2014) 212003]
[PoS Lattice 2014 372]

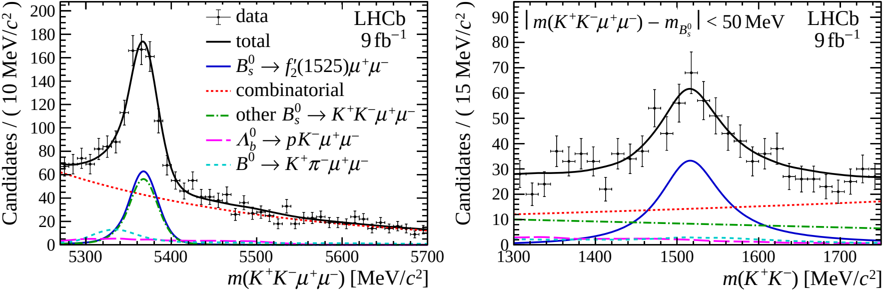
- Measurement relative to normalisation mode $B_s^0 \to J/\psi\,\phi$

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

- $\frac{\epsilon_{\phi\mu\mu}}{\epsilon_{J/\psi\,\phi}}$ from (corrected) simulation, many effects cancel in ratio
- $d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-, 1.1 < q^2 < 6\,\text{GeV}^2/c^4) = (2.88 \pm 0.21)^{-8}\,\text{GeV}^2/c^4$
- Tension with SM at $3.6\,\sigma$ (LCSR+Lattice) and $1.8\,\sigma$ (LCSR only)

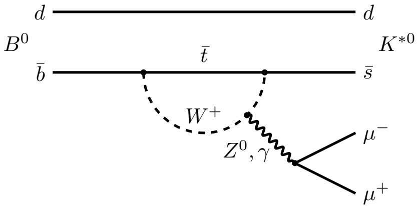
First observation of $B_s^0 \to f_2'(1525)[\to K^+K^-]\mu^+\mu^-$

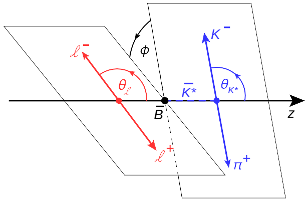
[arXiv:2105.14007]



- $f_2'(1525)$ heavy spin 2 resonance with $\Gamma \sim 86\,\mathrm{MeV}/c^2$
- Fit to $m_{B_s^0}$ and m_{KK} to separate from comb. and $B_s^0 \to K^+K^-\mu^+\mu^-$ bkg.
- $\mathcal{B}(B_s^0 \to f_2'(1525)\mu^+\mu^-) = (1.57 \underbrace{\pm 0.19}_{\text{stat}} \underbrace{\pm 0.06}_{\text{syst}} \underbrace{\pm 0.06}_{q^2\ \text{extr.}} \underbrace{\pm 0.08}_{\text{norm}}) \times 10^{-7}$
- First observation with $9\,\sigma$ significance

Angular analysis of $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$

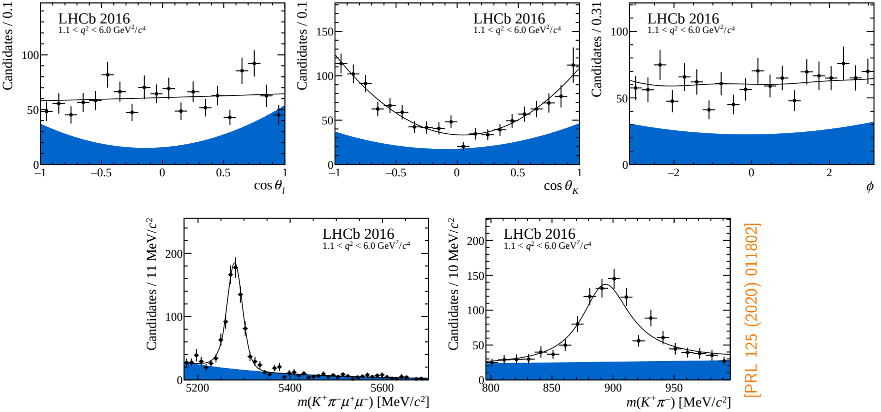




- Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$
- $$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$
- $F_\mathrm{L}, A_\mathrm{FB}, S_i$ combinations of K^{*0} spin amplitudes depending on Wilson coefficients $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$ and form factors
- Perform ratios of observables where form factors cancel at leading order
  Example: $P_5' = \frac{S_5}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}$ [S. Descotes-Genon *et al.*, JHEP, 05 (2013) 137]

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ using Run 1 + 2016

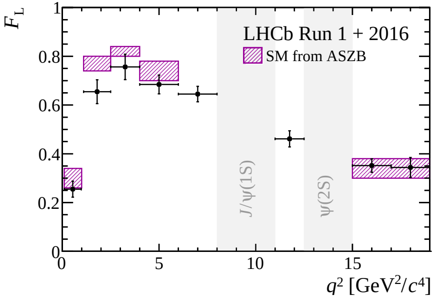
q^2 bin $[1.1, 6.0]\ \mathrm{GeV}^2/c^4$

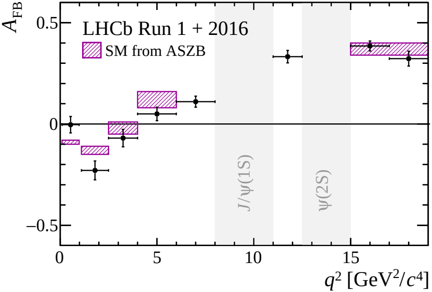


[PRL 125 (2020) 011802]

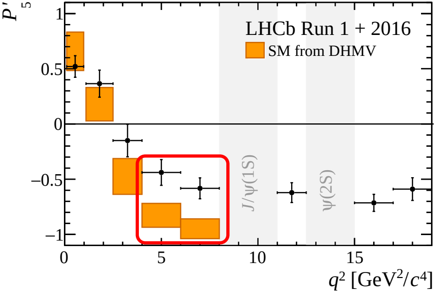
- $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis using Run 1+2016 data [PRL 125 (2020) 011802]
- Determine observables in bins of q^2 using max. likelihood fit of decay angles
- Simultaneously fit of $m_{K\pi\mu\mu}$ and $m_{K\pi}$ to constrain backgrounds (S-wave)

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



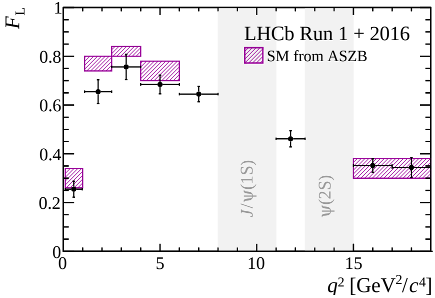


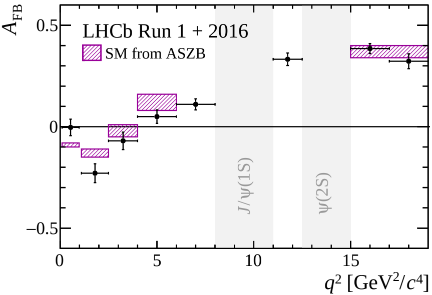
[PRL 125 (2020) 011802]



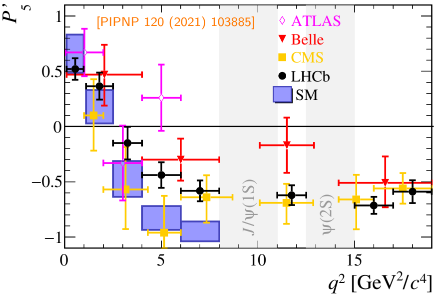
- Generally good agreement with SM, mild tension in F_{L}, A_{FB}
- P_5': local tension of $2.5\,\sigma$ and $2.9\,\sigma$ in q^2 bins $[4.0, 6.0]$ and $[6.0, 8.0]\ \mathrm{GeV}^2/c^4$
- Global $B^0 \to K^{*0}\mu^+\mu^-$ analysis finds deviation corresponding to $3.3\,\sigma$
- Consistent with [PRL 118 (2017) 111801] [PLB 781 (2018) 517] [JHEP 10 (2018) 047]

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





[PRL 125 (2020) 011802]



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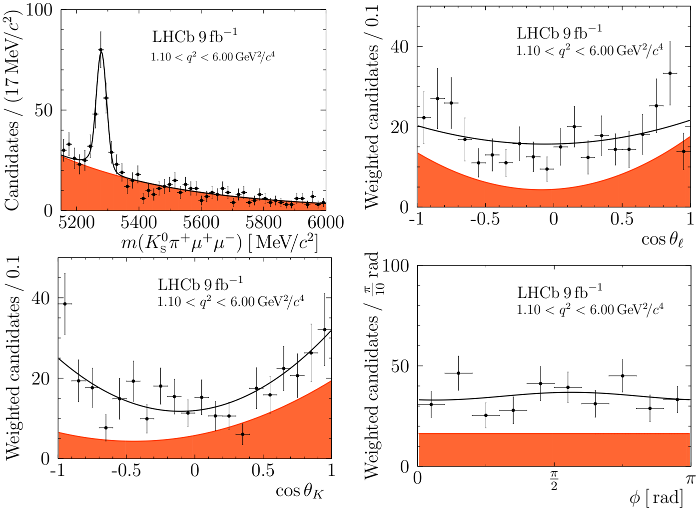
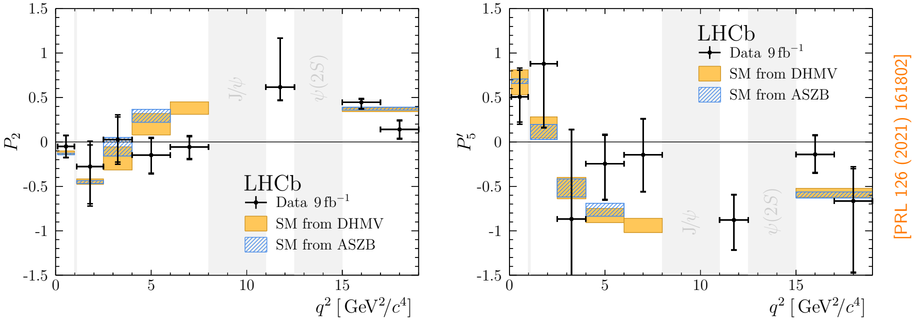
Angular analysis of $B^+ \to K^{*+}(\to K^0_S\pi^+)\mu^+\mu^-$



[PRL 126 (2021) 161802]

- $B^+ \to K^{*+}\mu^+\mu^-$ angular analysis using Run 1+2 data [PRL 126 (2021) 161802]
- First measurement of full set of CP-averaged angular obs.

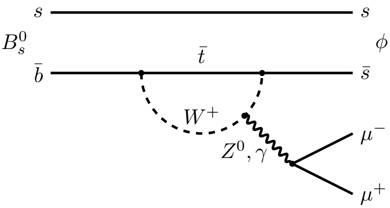
Angular observables for $B^+ \to K^{*+}(\to K^0_S\pi^+)\mu^+\mu^-$

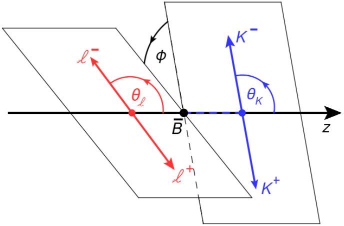


[PRL 126 (2021) 161802]

- Bkg from $K\pi$ system in spin-0 config. determined in fit to m_B and $m_{K\pi}$
- Angular observables determined using folding of decay angles
- Local tension with SM up to $3.0\,\sigma$ for $P_2 = \frac{2}{3}\frac{A_{\rm FB}}{1-F_{\rm L}}$ in $[6,8]\,\mathrm{GeV}^2/c^4$
- Fit of Wilson coeff. $\mathcal{R}e(C_9)$ reveals global tension corresponding to $3.1\,\sigma$

Angular analysis of $B_s^0 \to \phi(\to K^+K^-)\mu^+\mu^-$



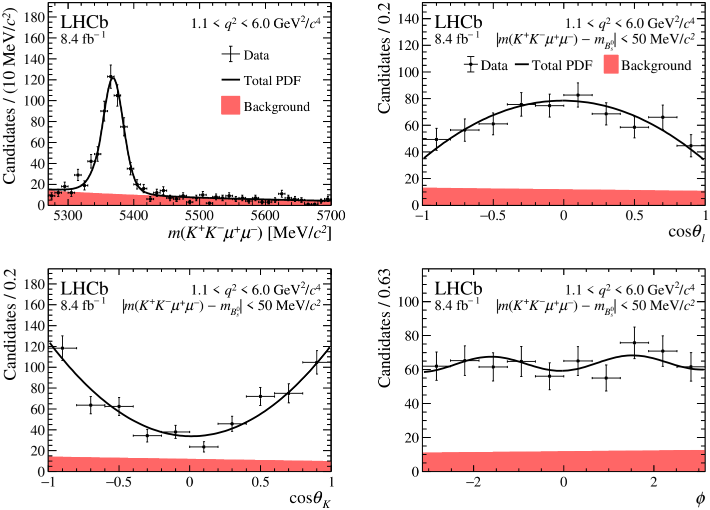


- Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m_{\mu\mu}^2$
- Final state $K^+K^-\mu^+\mu^-$ not flavour specific → untagged decay rate

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + A_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_\mathrm{FB}^\mathrm{CP}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ A_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + A_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

- S_i CP averages, A_i CP asymmetries
- New angular analysis using $8.4\,\mathrm{fb}^{-1}$ LHCb data [arXiv:2107.13428]

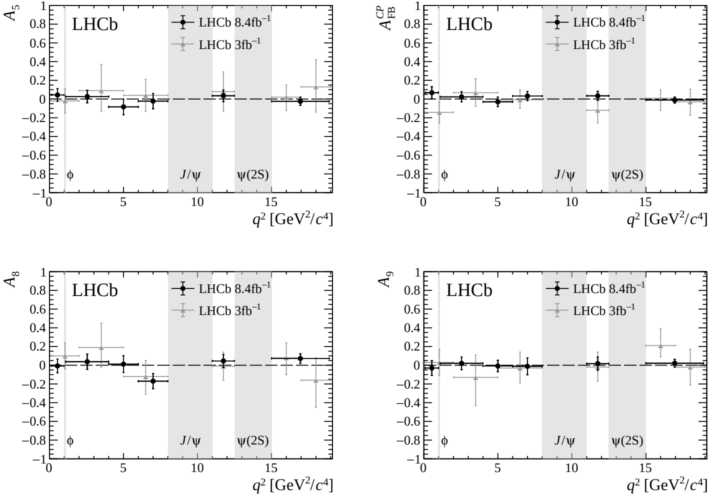
Updated angular analysis of $B_s^0 \to \phi\mu^+\mu^-$



[arXiv:2107.13428]

- Simultaneous fit in three angles and $m(K^+K^-\mu^+\mu^-)$
- Combinatorial background described by first order polynomials

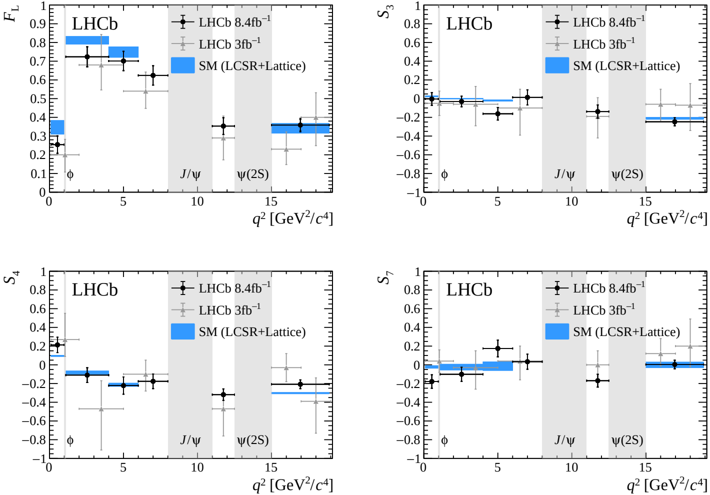
CP asymmetries in $B^0_s \to \phi\mu^+\mu^-$



[arXiv:2107.13428]

- CP asymmetries close to zero
- Consistent with SM prediction

CP symmetries in $B_s^0 \to \phi\mu^+\mu^-$

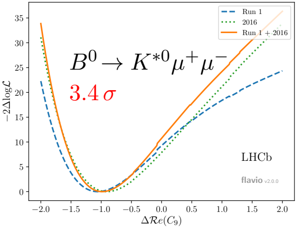


[arXiv:2107.13428]

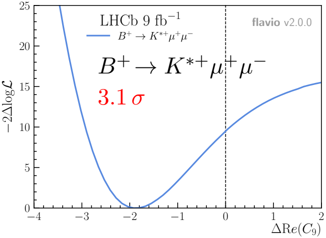
- Overall good agreement of CP symmetries with SM predictions
- Some tension in F_L: Global analysis shows $1.9\,\sigma$ tension
- P_5' not accessible as analysis is untagged

Consistency of $b \to s\mu^+\mu^-$ angular analyses

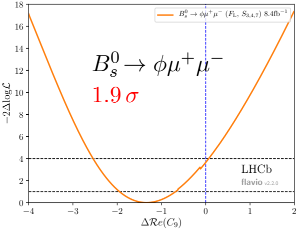
[PRL 125 (2020) 011802]



[PRL 126 (2021) 161802]



[arXiv:2107.13428]



- Use flavio [arXiv:1810.08132] to fit shift of vector coupling $\mathcal{R}e(C_9)$ from SM value using angular observables
- Consistent trends observed for $\Delta\mathcal{R}e(C_9)$ in $B^0 \to K^{*0}\mu^+\mu^-$, $B^+ \to K^{*+}\mu^+\mu^-$ and $B_s^0 \to \phi\mu^+\mu^-$
- Neg. shift of $\mathcal{R}e(C_9)$ preferred over SM hypothesis at level of 2–$3\,\sigma$

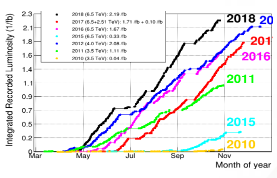
Conclusions

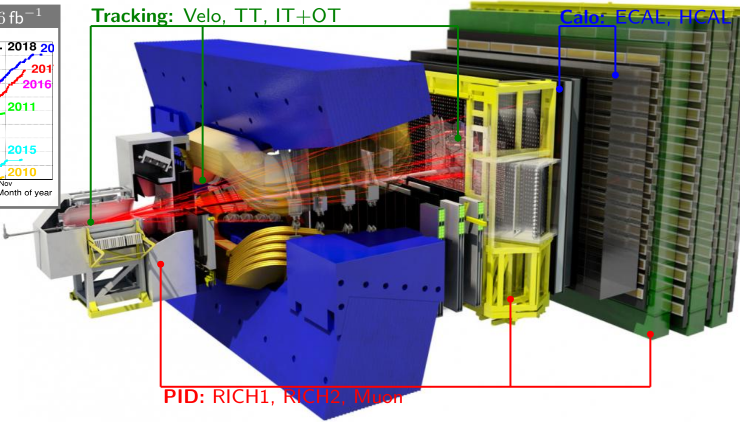
- EW penguin decays an excellent laboratory to search for NP effects, that can significantly affect branching fractions and angular obs.
- Branching fractions of $b \to s\mu^+\mu^-$ decays
  - New measurement of $\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$ [arXiv:2105.14007]
    $3.6\,\sigma$ below SM prediction, consistent with other $b \to s\mu^+\mu^-$ decays
  - First observation of $B_s^0 \to f_2'(1525)\mu^+\mu^-$ with $9\,\sigma$ [arXiv:2105.14007]
- Angular analyses of $b \to s\mu^+\mu^-$ decays show consistent picture, between 2–$3\,\sigma$ tension with SM prediction
  - New angular analysis of $B_s^0 \to \phi\mu^+\mu^-$ [arXiv:2107.13428]
  - Angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$ [PRL 126 (2021) 161802]
  - Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 (2020) 011802]
- Exciting time for EW penguins
- Extensive program to clarify the anomalies at LHCb

Backup

LHCb: Optimally suited for rare B decays

Run 1: $3\,\mathrm{fb}^{-1}$, 2015–2018: $6\,\mathrm{fb}^{-1}$





Tracking: Velo, TT, IT+OT

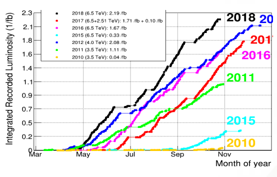
Calo: ECAL, HCAL

PID: RICH1, RICH2, Muon

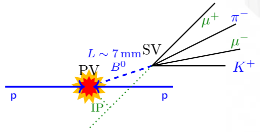
- Large $\sigma_{b\bar{b}}$: $(284 \pm 53)\,\mu\mathrm{b}$ at $7\,\mathrm{TeV}$ and $(495 \pm 52)\,\mu\mathrm{b}$ at $13\,\mathrm{TeV}$ [PLB 694 (2010) 209-216] [JHEP 10 (2015) 172]
- Excellent IP resolution $\sim 20\,\mu\mathrm{m}$ to identify B decay vertices, $\Delta p/p = 0.5 - 1\%$
- Particle identification: $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\pi\to K} \sim 5\%$ and $\epsilon_{\mu\to\mu} \sim 97\%$, $\epsilon_{\pi\to\mu} \sim 1 - 3\%$
- Low trigger thresholds: $p_{\mathrm{T}}(\mu) > 1.8\,\mathrm{GeV}$, $E_{\mathrm{T}}(e) > 3.0\,\mathrm{GeV}$

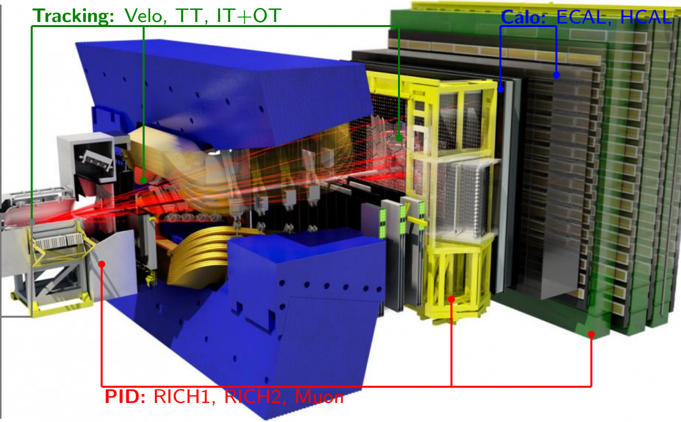
LHCb: Optimally suited for rare B decays

Run 1: $3\,\text{fb}^{-1}$, 2015–2018: $6\,\text{fb}^{-1}$



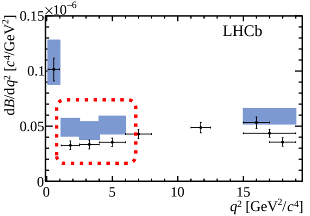
Heavy flavour signature

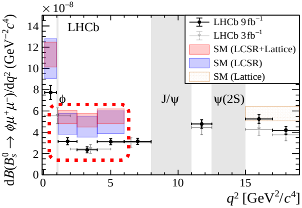


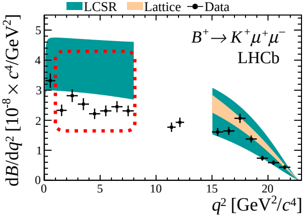


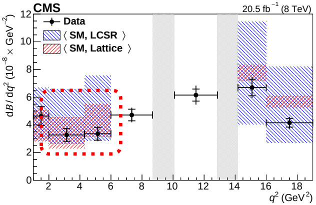
- Large $\sigma_{b\bar{b}}$: $(284\pm 53)\,\mu\text{b}$ at $7\,\text{TeV}$ and $(495\pm 52)\,\mu\text{b}$ at $13\,\text{TeV}$ [PLB 694 (2010) 209-216] [JHEP 10 (2015) 172]
- Excellent IP resolution $\sim 20\,\mu\text{m}$ to identify B decay vertices, $\Delta p/p = 0.5-1\%$
- Particle identification: $\epsilon_{K\to K}\sim 95\%$, $\epsilon_{\pi\to K}\sim 5\%$ and $\epsilon_{\mu\to\mu}\sim 97\%$, $\epsilon_{\pi\to\mu}\sim 1-3\%$
- Low trigger thresholds: $p_{\text{T}}(\mu) > 1.8\,\text{GeV}$, $E_{\text{T}}(e) > 3.0\,\text{GeV}$

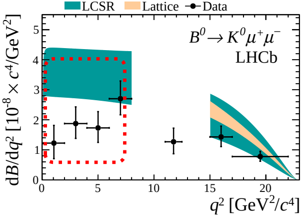
Similar to the rates of many other $b\to s\mu^+\mu^-$ decays!

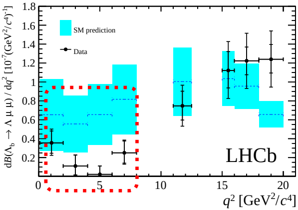

LHCb $B^0\to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]


LHCb $B_s^0\to\phi\mu^+\mu^-$ [arXiv:2105.14007]


LHCb $B^+\to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]


CMS $B^0\to K^{*0}\mu^+\mu^-$ [PLB 753 (2016) 424]


LHCb $B^0\to K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]


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

- Data consistently below SM predictions (particularly at low q^2)
- Tensions at $1-3\sigma$ level, sizeable hadronic theory uncertainties