Rare decays at LHCb including LFU test and LFV searches

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Rare Decays at LHCb

Muonic B decays

- $\Rightarrow$ Br $B_s^0/B_d^0 \to \mu\mu/\tau\tau$.
- $\Rightarrow$ Br + Ang. $B \to K^* \mu\mu$.
- $\Rightarrow$ Br + Ang. $B_s^0 \to \phi\mu\mu$.
- $\Rightarrow$ Br + Ang. $\Lambda_b \to p\pi\mu\mu$.
- $\Rightarrow$ Isospin $B \to K\mu\mu$.

Charm decays

- $\Rightarrow$ $D \to hh\mu\mu$
- $\Rightarrow$ $D \to e\mu$.

$\Rightarrow$ Enormous Physics program which is constantly expanding.
$\Rightarrow$ Will cover only part of the results.

LFU test

- $\Rightarrow$ $B^+ \to K^+ \ell\ell$
- $\Rightarrow$ $B_d^0 \to K^* \ell\ell$
- $\Rightarrow$ $\Lambda_b \to p\pi\ell\ell$

Strange decays

- $\Rightarrow$ $K_S^0 \to \mu\mu$.

Radiative decays

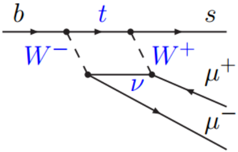
- $\Rightarrow$ $B \to K^*\gamma$, $B_s^0 \to \phi\gamma$
- $\Rightarrow$ $\Xi_b \to \Xi\gamma$
- $\Rightarrow$ $B_s^0/B_d^0 \to J/\psi\gamma$

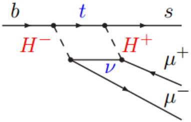
τ decays

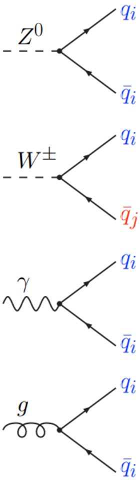
- $\Rightarrow$ $\tau \to \mu\mu\mu$. $\Rightarrow$ $\tau \to p\mu\mu$.

Why rare decays?

- In SM allows only the charged interactions to change flavour.
  - Other interactions are flavour conserving.
- One can escape this constrain and produce $b \to s$ and $b \to d$ at loop level.
  - This kind of processes are suppressed in SM $\to$ Rare decays.
  - New Physics can enter in the loops.







Tools

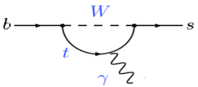
- **Operator Product Expansion and Effective Field Theory**

$$H_{eff} = -\frac{4G_f}{\sqrt{2}} VV'^{*} \sum_i \Big[\underbrace{C_i(\mu)O_i(\mu)}_{\text{left-handed}} + \underbrace{C'_i(\mu)O'_i(\mu)}_{\text{right-handed}} \Big] ,$$

i=1,2	Tree
i=3-6,8	Gluon penguin
i=7	Photon penguin
i=9.10	EW penguin
i=S	Scalar penguin
i=P	Pseudoscalar penguin

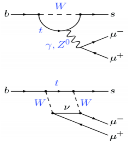
where C_i are the Wilson cœfficients and O_i are the corresponding effective operators.

$b \to s\gamma$



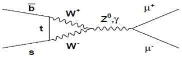
$C_7^{(\prime)}$

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



$C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

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

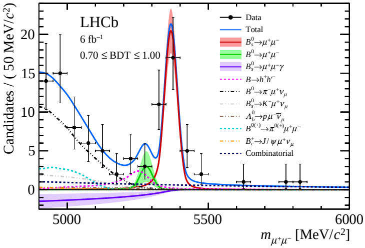


$C_S^{(\prime)}, C_P^{(\prime)}, C_{10}^{(\prime)}$

$B_{s/d} \to \mu\mu$

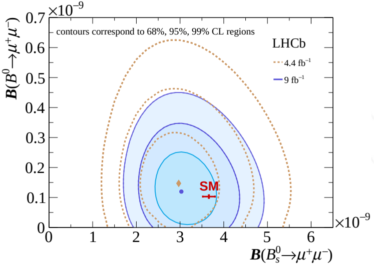
PHYS. REV. LETT. 128, (2022) 041801

$\Rrightarrow$ Golden channel for LHCb.
$\Rrightarrow$ Normalized to the $B \to K\pi$ and $B \to KJ/\psi$.
$\Rrightarrow$ The selection is achived by BDT trained on MC and calibrated on data.

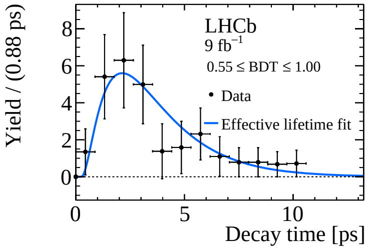


$\Rrightarrow \mathcal{B}(B_s^0 \to \mu\mu) = (3.09^{+0.46+0.15}_{-0.43-0.11})10^{-9}$

$> 10\ \sigma$ significant!



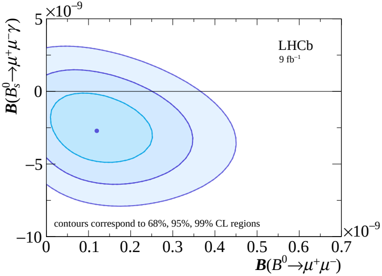
$\Rrightarrow \mathcal{B}(B_d^0 \to \mu\mu) < 2.3 \times 10^{-10}$, 90%CL
$\Rrightarrow \mathcal{B}(B_s^0 \to \mu\mu\gamma) < 1.5 \times 10^{-9}$, 90%CL

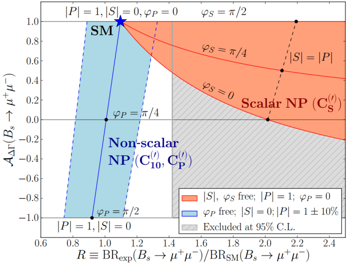


Effective lifetime

⇒ Sensitivity to non-scalar NP.

$\tau(B_s^0 \to \mu\mu) = 2.07 \pm 0.29 \pm 0.03$ ps





$B_{s/d} \to \mu\mu\mu\mu$

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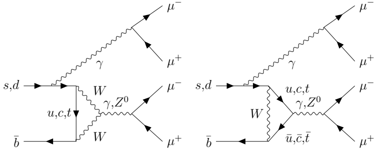
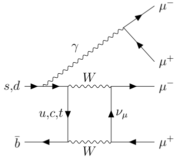
$\Rrightarrow$ ~~Golden~~ Platinum channel for LHCb.

$\Rrightarrow$ Normalized to the $B_s^0 \to J/\psi(\mu\mu)\phi(\mu\mu)$.

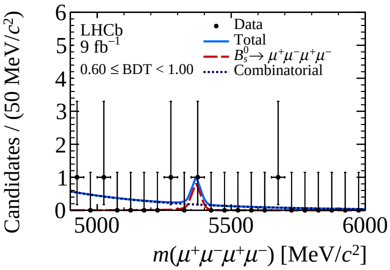


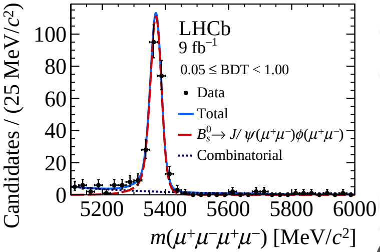


UL at 95 % CL:

$\Rrightarrow \mathcal{B}(B_s^0 \to \mu\mu\mu\mu) < 8.6 \times 10^{-10}$

$\Rrightarrow \mathcal{B}(B_d^0 \to \mu\mu\mu\mu) < 1.8 \times 10^{-10}$





$B_{s/d} \to \tau\tau$

Phys. Rev. Lett. 118, 251802 (2017)

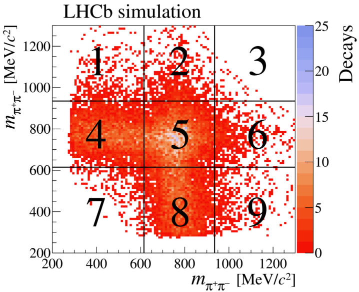
$\Rrightarrow$ NP sensitivity enhanced due to the high τ mass.

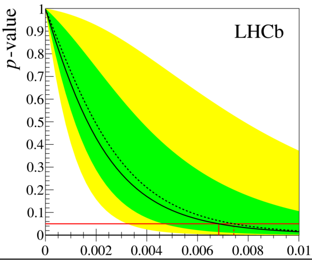
$\Rrightarrow$ More challenging: at least 2ν are escaping.

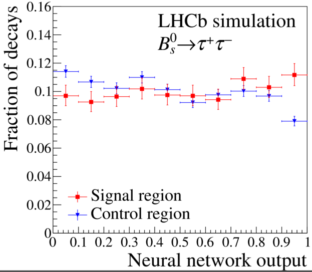
$\Rrightarrow$ Selecting $\tau \to 3\pi\nu$, $\to$ 9.31 %

$\Rrightarrow$ Normalization channel: $B \to D(K\pi\pi)D_s(KK\pi)$.

$\Rrightarrow$ No peak in the B mass window $\to$ fit the NN output.







$B_{s/d} \to ee$

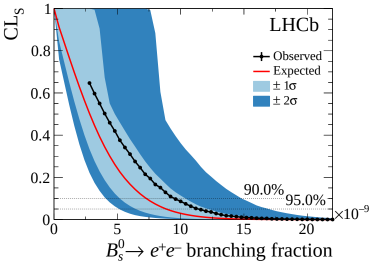
$\Rrightarrow$ Extreamly rare decays!:

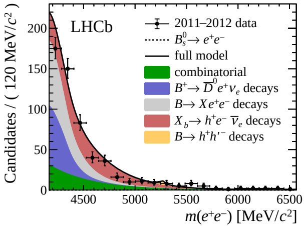
$\mathcal{B}(B_s^0 \to ee) = (8.60 \pm 0.36) \times 10^{-14}$
$\mathcal{B}(B_d^0 \to ee) = (2.41 \pm 0.13) \times 10^{-15}$.

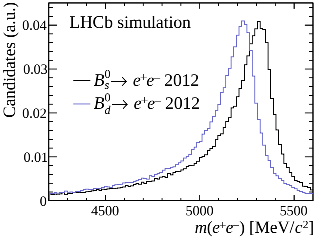
$\Rrightarrow$ Analysed $5\ \text{fb}^{-1}$ of data.

$\Rrightarrow$ Set UL (90% CL):

$\mathcal{B}(B_s^0 \to ee) < 9.4 \times 10^{-9}$
$\mathcal{B}(B_d^0 \to ee) < 2.5 \times 10^{-9}$





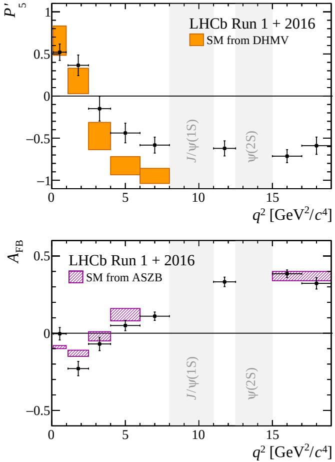


$B^0 \to K^{*}\mu^{-}\mu^{+}$ decay

$\Rrightarrow$ $B^0 \to K^{*}\mu^{-}\mu^{+}$ is a smoking gun for NP hunting!
$\Rrightarrow$ Rich angular observables makes is sensitive to different NP models
$\Rrightarrow$ In addition one can construct less form factor dependent observables:

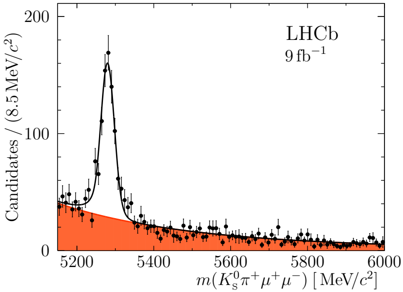
$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

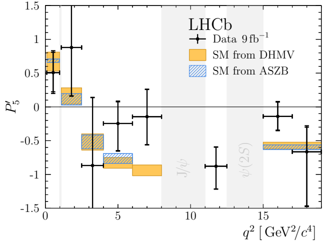
$\Rrightarrow$ Analysed $4.7\ \mathrm{fb}^{-1}$ of data.
$\Rrightarrow$ Results correspond to $3.3\ \sigma$ deviation in $\Re(C_9)$ WC wrt. SM.

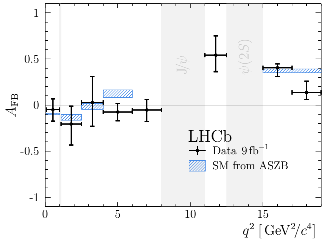


$B^+ \to K^{*+}(K^0_S\pi^+)\mu^-\mu^+$ decay

- ⇛ Isospin partner of previous decay.
- ⇛ Experimentally more chalanging due to the K^0_S presents.
- ⇛ Analysed $9\ \text{fb}^{-1}$ of data.



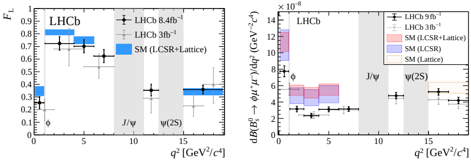




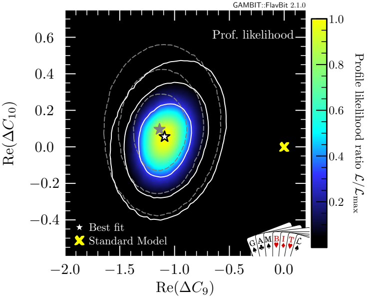
$B_s^0 \to \phi/f_2'(1525)\mu^-\mu^+$ decays

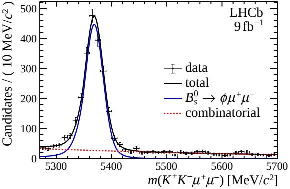
PHYS. REV. LETT.127 (2021) 151801,
JHEP 11 (2021) 043

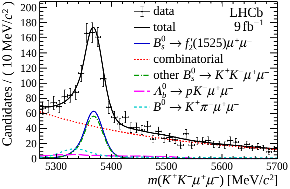
⇛ No self-tagging → not all angular observables accessible.

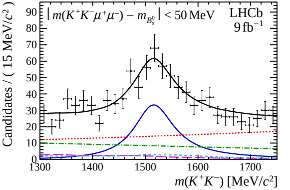


⇛ Tension wrt. the current SM prediction remains.





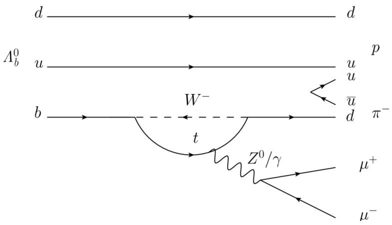




$\Lambda_b \to p\pi\mu\mu$

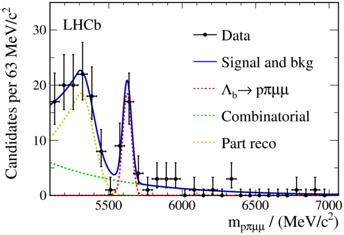
J. High Energy Phys. 04 (2017) 029

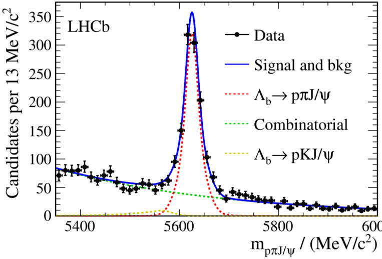
$\Rrightarrow$ First observation of $b \to d$ in baryon system!
$\Rrightarrow$ BDT selection trained on MC
$\Rrightarrow$ Normalized to $\Lambda_b \to p\pi J/\psi$
$\Rrightarrow$ With futher QCD improvements we will be able to to measure $\frac{|V_{ts}|}{|V_{td}|}$.



$\Rrightarrow$ $\frac{\mathcal{B}(\Lambda_b \to p\pi\mu\mu)}{\mathcal{B}(\Lambda_b \to p\pi J/\psi)} = 0.044 \pm 0.012 \pm 0.007$

$\Rrightarrow$ 5.5 σ significance! $\Rrightarrow$ First observation.





$\mathcal{B}(\Lambda_b \to p\pi\mu\mu) =$
$(6.9 \pm 1.9 \pm 1.1^{+1.3}_{-1.0}) \times 10^{-8}$

Search for light scalars

Phys. Rev. D 95, 071101 (2017)

⇛ Hidden sector models are gathering more and more attention.

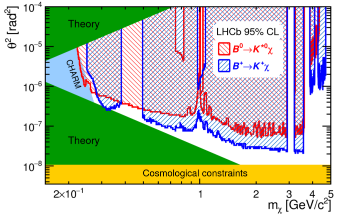
⇛ Inflaton model: new scalar then mixes with the Higgs.

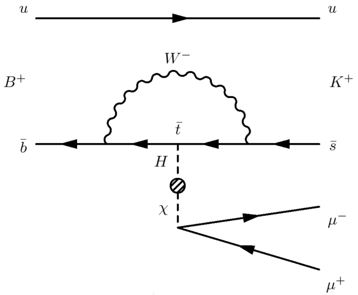
⇛ *B* decays are sensitive as the inflaton might be light.

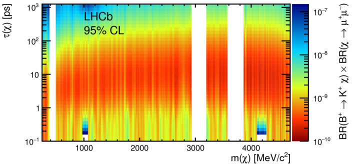
⇛ Searched for long living particle χ produced in: $B \to \chi(\mu\mu)K$.

⇛ Analysis performed blindly as a peak search.

⇛ Light inflaton essentially ruled out:

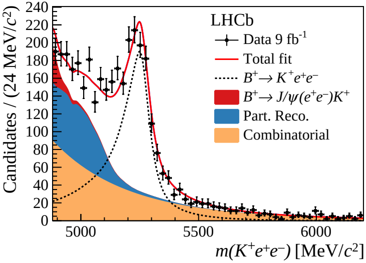


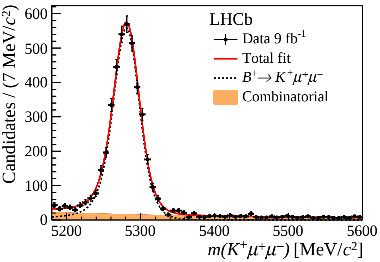




⇛ Most precise measurements performed at LHCb.

⇛ Main challenge is due to electron Bremsstrahlung.





⇛ To protect ourself from electron reconstruction issue we use double ratio:

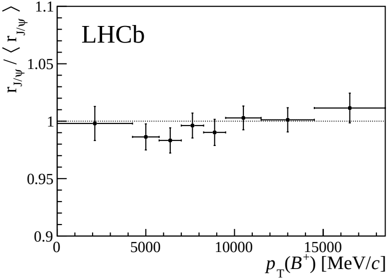
$$R_K = \frac{\mathcal{B}(B \to K\mu\mu) \times \mathcal{B}(B \to KJ/\psi(\to ee))}{\mathcal{B}(B \to Kee) \times \mathcal{B}(B \to KJ/\psi(\to \mu\mu))}$$

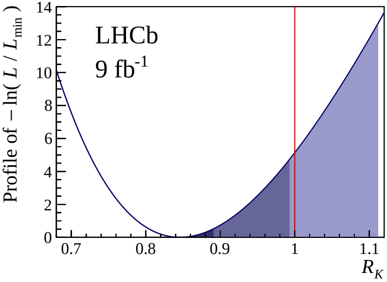
⇛ The efficiency correction was calculated using $B \to J/\psi K$.

⇛ Cross-checked with $B \to \psi(2S) K$.

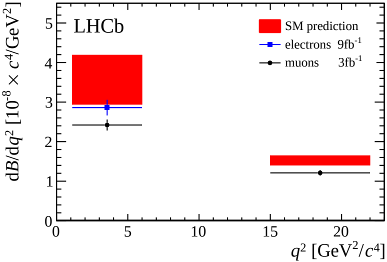
⇛ The result:

$R_K(1.1 < q^2 < 6.0\ \mathrm{GeV}^2/\mathrm{c}^4) = 0.846^{+0.042+0.013}_{-0.039-0.012}$





⇛ Disagrees with SM at $3.1\ \sigma$ level.

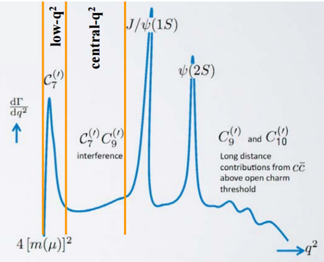


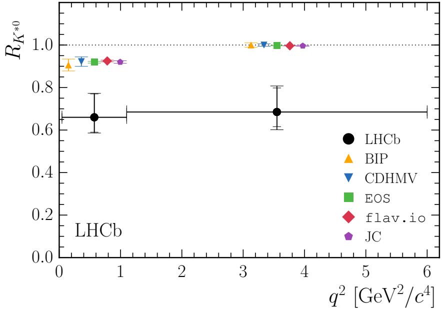
⇛ The neutral continuation of the R_K measurement is to measure its partner:

$$R_{K^*} = \frac{\mathcal{B}(B \to K^* \mu\mu)}{\mathcal{B}(B \to K^* ee)}$$

⇛ Measurement performed in two q^2 bins.

⇛ Normalized in double ratio to $B \to K^* J/\psi$.

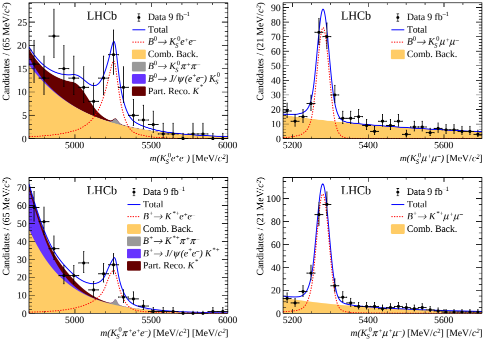




⇛ Over $2\ \sigma$ deviation in each bin.

$B_d^0/B^+ \to K_S^0/K^{*+}e^-e^+$

Phys. Rev. Lett. 128 (2022) 191802



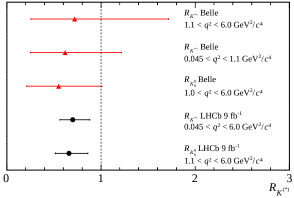
⇛ Same strategy as previous measurements.

Results:

$$R_{K_S^0} = 0.66^{+0.20+0.02}_{-0.14-0.04}$$

$$R_{K^{*+}} = 0.70^{+0.18+0.03}_{-0.13-0.04}$$

⇛ Consistent with SM at 2σ level.



⇛ Measurement performed in the low q^2 regions.

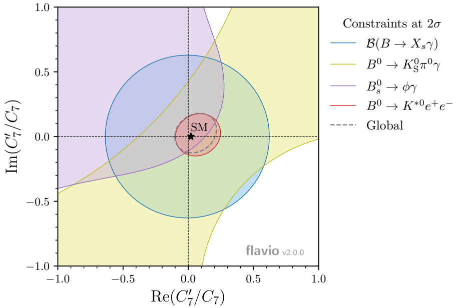
⇛ The electron decays have been observed with significance $> 5\ \sigma$.

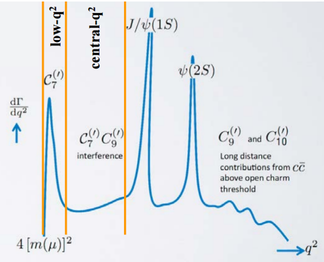
$B^0_d \to K^* e^- e^+$ at low q^2

$\Rightarrow$ Use the electrons to measure the radiative penguing.

$\Rightarrow$ Accessign the kinematic range: $[0.0008, 0.257]\ \mathrm{GeV}^2/\mathrm{c}^4$.

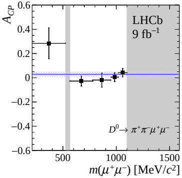
$$F_L = 0.044 \pm 0.026 \pm 0.014$$
$$A_T^{Re} = 0.06 \pm 0.08 \pm 0.02$$
$$A_T^{2} = 0.11 \pm 0.10 \pm 0.02$$
$$A_T^{Im} = 0.02 \pm 0.10 \pm 0.01$$

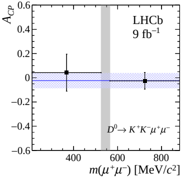


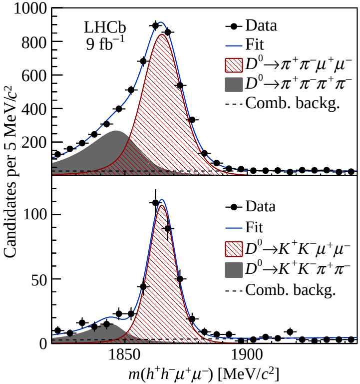


⇛ Extreamly suppressed by GIM mechanism.

⇛ Dominated by long-range iteractions.



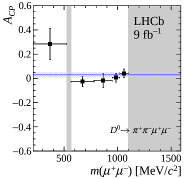


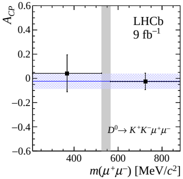


⇛ Because of tagging $(D^* \to D\pi_{\text{slow}})$ one can measure angular observables.

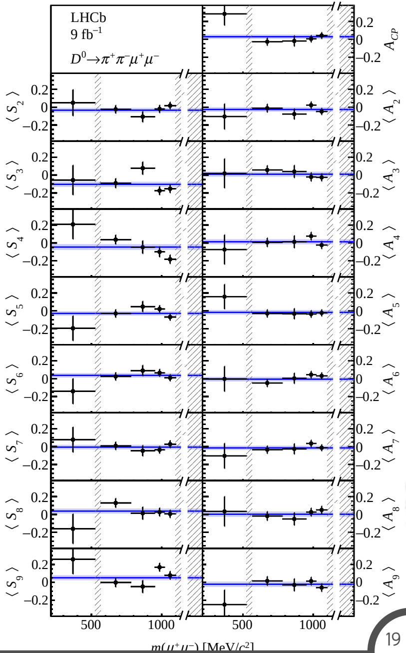
⇛ Extreamly suppressed by GIM mechanism.

⇛ Dominated by long-range iteractions.





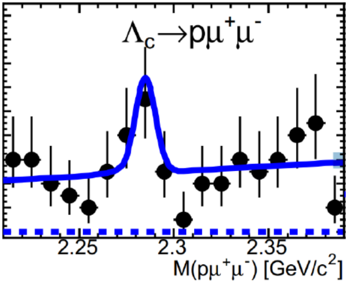
⇛ Because of tagging ($D^* \to D\pi_{\rm slow}$) one can measure angular observables.

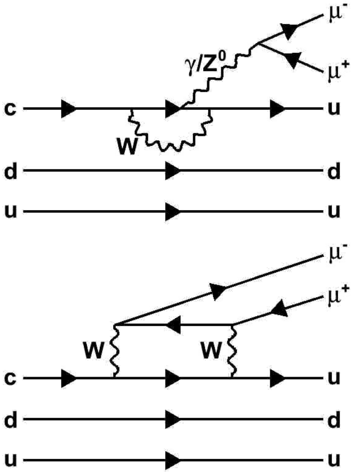


$\Lambda_c \to p\mu\mu$

- ⇛ SM predictions:
  $\mathcal{O}(10^{-8})$
- ⇛ Long distance effects:
  $\mathcal{O}(10^{-6})$

- ⇛ Previous measurement done by Babar:
  $\text{Br}(\Lambda_c^+ \to p\mu^+\mu^-) < 4.4 \cdot 10^{-5}$ at 90% CL



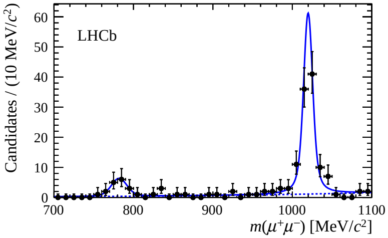


LHCb analysis with $3\ \text{fb}^{-1}$

$\Lambda_c \to p\mu\mu$

$\Rrightarrow$ It's the first observation of $\Lambda_c \to p\mu\mu$ in the ω region, with $5.0\ \sigma$ significance.
$\Rrightarrow$ The corresponding branching fraction reads:

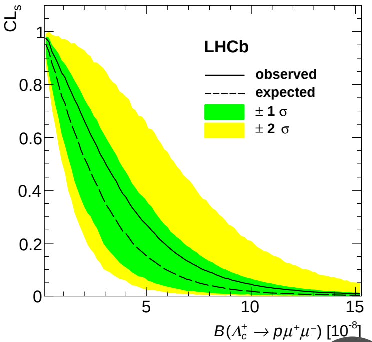
$$\mathcal{B}(\Lambda_c \to p\omega) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0) \cdot 10^{-4}$$



$\Rrightarrow$ No significant excess observed in the nonresonant region:

$$\mathcal{B}(\Lambda_c \to p\mu\mu) < 7.7(9.6) \times 10^{-8}$$

$\Rrightarrow$ Improving BaBar result by 3 orders of magnitude!



$K^0_S \to \mu\mu$

$\Rrightarrow$ pp collisions create enormous amount of strange mesons.

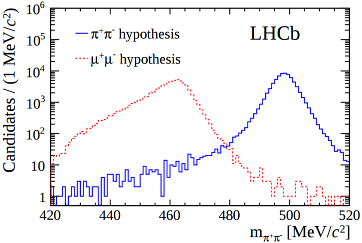
$\Rrightarrow$ Can be used to search for $K^0_S \to \mu\mu$.

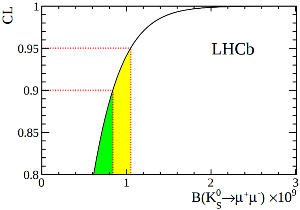
$\Rrightarrow$ SM prediction:

$\mathcal{B}(K^0_S \to \mu\mu) = (5.0 \pm 1.5) \times 10^{-12}$

$\Rrightarrow$ Dominated by the long distance effects.

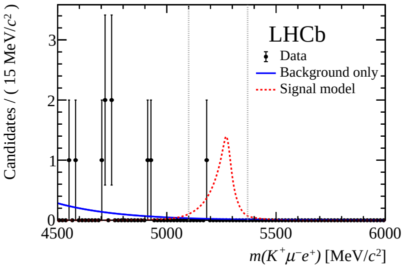
$\Rrightarrow$ Bkg dominated by $K^0_S \to \pi\pi$.





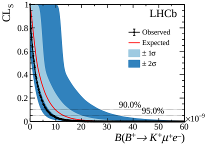
$\Rrightarrow$ No significant enhanced of signal has been observed and UL was set:

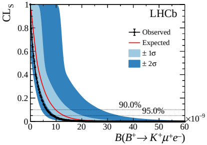
$\mathcal{B}(K^0_S \to \mu\mu) < 0.8(1.0) \times 10^{-9}$ at $90(95)\%$ CL

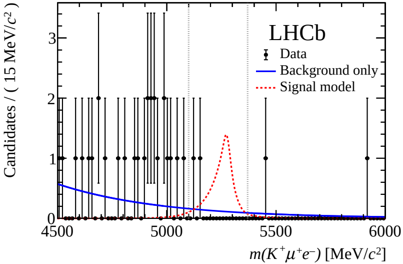


$\Rrightarrow$ Normalized to $B \to KJ/\psi(\mu\mu)$.

$\Rrightarrow$ Both charge sign combinations considered: $B^+ \to K^+\mu^\pm e^\mp$





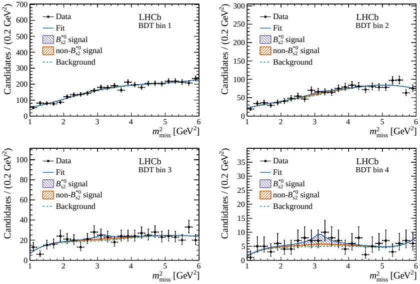


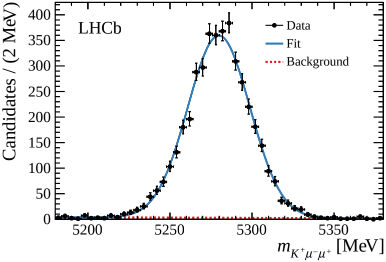
Results at 90 % CL:

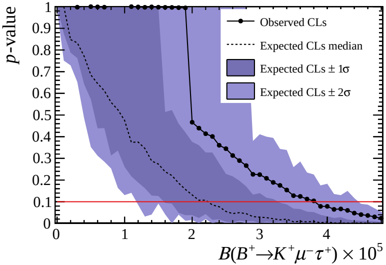
$\Rrightarrow$ $\mathcal{B}(B^+ \to K^+\mu^-e^+ < 7.0\times10^{-9}$

$\Rrightarrow$ $\mathcal{B}(B^+ \to K^+\mu^+e^- < 6.4\times10^{-9}$

⇛ Very challanging due to presents of τ lepton.
⇛ Use the $B_{s2}^{*0} \to B^+ K^-$ to reconstruct the τ momentum.
⇛ Normalized to $B \to KJ/\psi(\mu\mu)$.



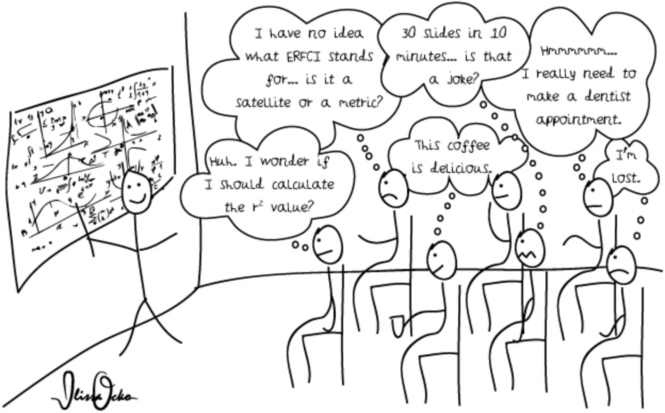




Conclusions

- Lots of rare decays studied at LHCb.
- Observed tensions wrt. to SM in the $b \to s\ell\ell$ transitions.
- LHCb is setting nowadays strongest limits on LFV.
- LUV are the cleanest (wrt. theory errors) of the anomalies.

Thank you for the attention!



Backup

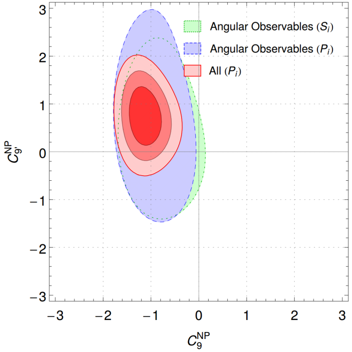
Theory implications

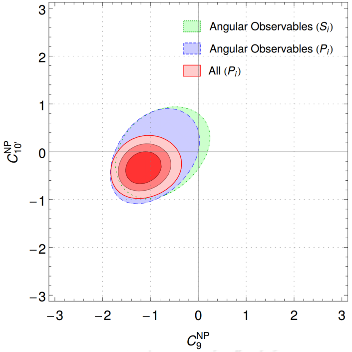
Coefficient	Best fit	1σ	3σ	Pull_{SM}	p-value (%)
$\mathcal{C}_7^{\text{NP}}$	-0.02	$[-0.04, -0.00]$	$[-0.07, 0.04]$	1.1	16.0
$\mathcal{C}_9^{\text{NP}}$	-1.11	$[-1.32, -0.89]$	$[-1.71, -0.40]$	**4.5**	62.0
$\mathcal{C}_{10}^{\text{NP}}$	0.58	$[0.34, 0.84]$	$[-0.11, 1.41]$	2.5	25.0
$\mathcal{C}_{7'}^{\text{NP}}$	0.02	$[-0.01, 0.04]$	$[-0.05, 0.09]$	0.7	15.0
$\mathcal{C}_{9'}^{\text{NP}}$	0.49	$[0.21, 0.77]$	$[-0.33, 1.35]$	1.8	19.0
$\mathcal{C}_{10'}^{\text{NP}}$	-0.27	$[-0.46, -0.08]$	$[-0.84, 0.28]$	1.4	17.0
$\mathcal{C}_9^{\text{NP}} = \mathcal{C}_{10}^{\text{NP}}$	-0.21	$[-0.40, 0.00]$	$[-0.74, 0.55]$	1.0	16.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}$	-0.69	$[-0.88, -0.51]$	$[-1.27, -0.18]$	**4.1**	55.0
$\mathcal{C}_{9'}^{\text{NP}} = \mathcal{C}_{10'}^{\text{NP}}$	-0.09	$[-0.35, 0.17]$	$[-0.88, 0.66]$	0.3	14.0
$\mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$	0.20	$[0.08, 0.32]$	$[-0.15, 0.56]$	1.7	19.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}$	-1.09	$[-1.28, -0.88]$	$[-1.62, -0.42]$	**4.8**	72.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$	-0.68	$[-0.49, -0.49]$	$[-1.36, -0.15]$	3.9	50.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}} = \mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$	-0.17	$[-0.29, -0.06]$	$[-0.54, 0.18]$	1.5	18.0

Table 2: *Best-fit points, confidence intervals, pulls for the SM hypothesis and p-values for different one-dimensional NP scenarios.*

If not NP?

- How about our clean P_i observables?
- The QCD cancel as mentioned only at leading order.
- Comparison to normal observables with the optimised ones.





Transversity amplitudes

⇛ One can link the angular observables to transversity amplitudes

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

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

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

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

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

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

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

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

Link to effective operators

⇛ So here is where the magic happens. At leading order the amplitudes can be written as (soft form factors):

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

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

$$A_{0}^{L,R} = -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + 2\hat{m}_b (\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_{\parallel}(E_{K^*}),$$

where $\hat{s} = q^2/m_B^2$, $\hat{m}_i = m_i/m_B$. The $\xi_{\parallel,\perp}$ are the form factors.

Link to effective operators

$\Rrightarrow$ So here is where the magic happens. At leading order the amplitudes can be written as (soft form factors):

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

$$A_{0}^{L,R} = -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + 2\hat{m}_b (\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_{\parallel}(E_{K^*}),$$

where $\hat{s} = q^2/m_B^2$, $\hat{m}_i = m_i/m_B$. The $\xi_{\parallel,\perp}$ are the form factors.

$\Rrightarrow$ Now we can construct observables that cancel the ξ form factors at leading order:

$$P_5^{\prime} = \frac{J_5 + \bar{J}_5}{2\sqrt{-(J_2^c + \bar{J}_2^c)(J_2^s + \bar{J}_2^s)}}$$

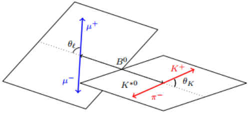
$B^0 \to K^* \mu^- \mu^+$ kinematics

$\Rrightarrow$ The kinematics of $B^0 \to K^* \mu^- \mu^+$ decay is described by three angles θ_l, θ_k, ϕ and invariant mass of the dimuon system (q^2).

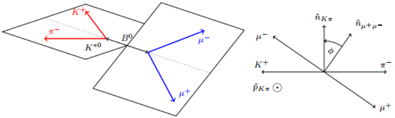
$\Rrightarrow$ $\cos\theta_k$: the angle between the direction of the kaon in the K^* ($\overline{K}^*$) rest frame and the direction of the K^* ($\overline{K}^*$) in the B^0 ($\bar{B}^0$) rest frame.

$\Rrightarrow$ $\cos\theta_l$: the angle between the direction of the μ^- (μ^+) in the dimuon rest frame and the direction of the dimuon in the B^0 ($\bar{B}^0$) rest frame.

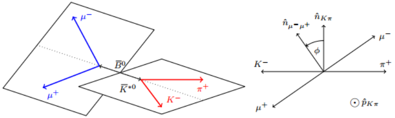
$\Rrightarrow$ ϕ: the angle between the plane containing the μ^- and μ^+ and the plane containing the kaon and pion from the K^*.



(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

$B^0 \to K^* \mu^- \mu^+$ kinematics

⇛ The kinematics of $B^0 \to K^* \mu^- \mu^+$ decay is described by three angles θ_l, θ_k, ϕ and invariant mass of the dimuon system (q^2).

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$

$$+J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi$$

$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi$$

$$+J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big],$$

⇛ This is the most general expression of this kind of decay.

⇛ The CP averaged angular observables are defined:

$$S_i = \frac{J_i + \bar{J}_i}{(d\Gamma + d\bar{\Gamma})/dq^2}$$

Link to effective operators

⇛ The observables J_i are bilinear combinations of transversity amplitudes: $A_{\perp}^{L,R}$, $A_{\|}^{L,R}$, $A_0^{L,R}$.

⇛ So here is where the magic happens. At leading order the amplitudes can be written as:

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

where $\hat{s} = q^2/m_B^2$, $\hat{m}_i = m_i/m_B$. The $\xi_{\|,\perp}$ are the soft form factors.

Link to effective operators

⇛ The observables J_i are bilinear combinations of transversity amplitudes: $A_\perp^{L,R}$, $A_\parallel^{L,R}$, $A_0^{L,R}$.
⇛ So here is where the magic happens. At leading order the amplitudes can be written as:

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

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

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

where $\hat{s} = q^2/m_B^2$, $\hat{m}_i = m_i/m_B$. The $\xi_{\parallel,\perp}$ are the soft form factors.
⇛ Now we can construct observables that cancel the ξ soft form factors at leading order:

$$P_5^\prime = \frac{J_5 + \bar{J}_5}{2\sqrt{-(J_2^c + \bar{J}_2^c)(J_2^s + \bar{J}_2^s)}}$$

Symmetries in $B \to K^* \mu\mu$

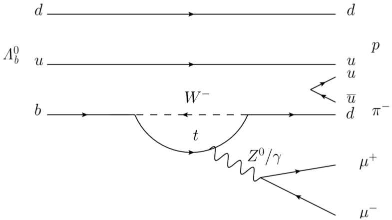
$\Rrightarrow$ We have 12 angular cœfficients (S_i).
$\Rrightarrow$ There exist 4 symmetry transformations that leave the angular distributions unchanged:

$$n_{\|} = \begin{pmatrix} A_{\|}^{L} \\ A_{\|}^{R*} \end{pmatrix}, \quad n_{\perp} = \begin{pmatrix} A_{\perp}^{L} \\ -A_{\perp}^{R*} \end{pmatrix}, \quad n_{0} = \begin{pmatrix} A_{0}^{L} \\ A_{0}^{R*} \end{pmatrix}.$$

$$n_i^{'} = U n_i = \begin{bmatrix} e^{i\phi_L} & 0 \\ 0 & e^{-i\phi_R} \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \cosh i\tilde{\theta} & -\sinh i\tilde{\theta} \\ -\sinh i\tilde{\theta} & \cosh i\tilde{\theta} \end{bmatrix} n_i .$$

$\Rrightarrow$ Using this symmetries one can show that there are 8 independent observables. The pdf can be written as:

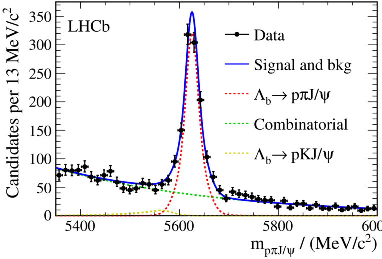
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{dcos}\theta_l\,\mathrm{dcos}\theta_k\,\mathrm{d}\phi}\Big|_{\mathrm{P}} = \frac{9}{32\pi}\big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_k \\ + F_{\mathrm{L}}\cos^2\theta_k + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_k\cos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

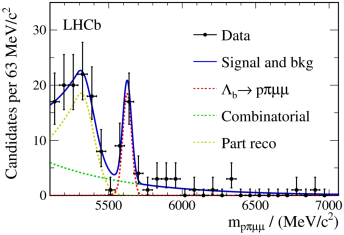


- ⇛ First observation of $b \to d$ in baryon system!
- ⇛ BDT selection trained on MC
- ⇛ Normalized to $\Lambda_b \to p\pi J/\psi$
- ⇛ With futher QCD improvements we will be able to to measure $\frac{|V_{ts}|}{|V_{td}|}$.

⇛ $\frac{\mathcal{B}(\Lambda_b \to p\pi\mu\mu)}{\mathcal{B}(\Lambda_b \to p\pi J/\psi)} = 0.044 \pm 0.012 \pm 0.007$

⇛ 5.5 σ significance! ⇛ First observation.





$\mathcal{B}(\Lambda_b \to p\pi\mu\mu) = (6.9 \pm 1.9 \pm 1.1^{+1.3}_{-1.0}) \times 10^{-8}$

Search for light scalars

Phys. Rev. D 95, 071101 (2017)

⇛ Hidden sector models are gathering more and more attention.

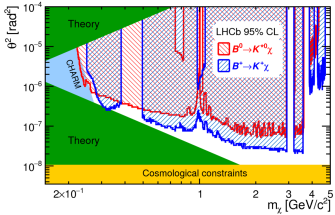
⇛ Inflaton model: new scalar then mixes with the Higgs.

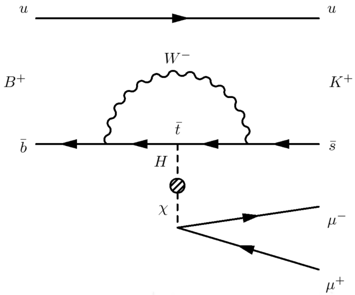
⇛ B decays are sensitive as the inflaton might be light.

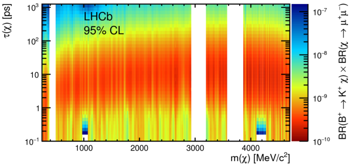
⇛ Searched for long living particle χ produced in: $B \to \chi(\mu\mu)K$.

⇛ Analysis performed blindly as a peak search.

⇛ Light inflaton essentially ruled out:







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

JHEP 02 (2016) 104, CMS-PAS-BPH-15-008, ATLAS-CONF-2017-023, Phys. Rev. Lett. 118 (2017)

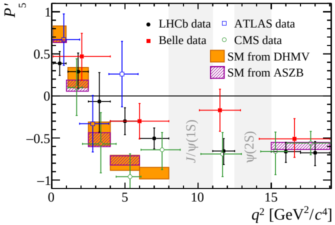
$\Rrightarrow$ $B^0 \to K^* \mu^- \mu^+$ is a smoking gun for NP hunting!

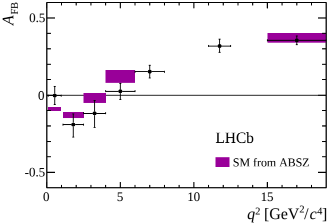
$\Rrightarrow$ Reach angular observables makes is sensitive to different NP models

$\Rrightarrow$ In addition one can construct less form factor dependent observables:

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

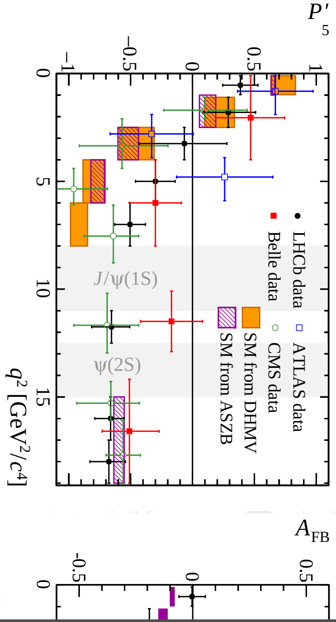
$\Rrightarrow$ In single analysis observed $3.4\,\sigma$ discrepancy in the C_9 WC.





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

JHEP 02 (2016) 104, CMS-PAS-BPH-15-008, ATLAS-CONF-2017-023, Phys. Rev. Lett. 118 (2017)



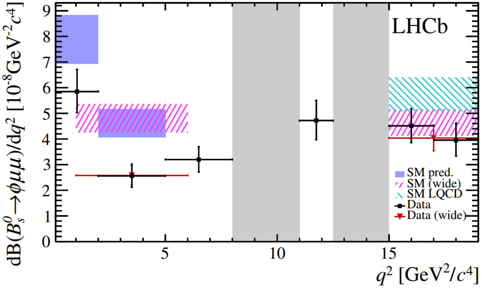
⇛ $B^0 \to K^{*}\mu^-\mu^+$ is a smoking gun for NP hunting!

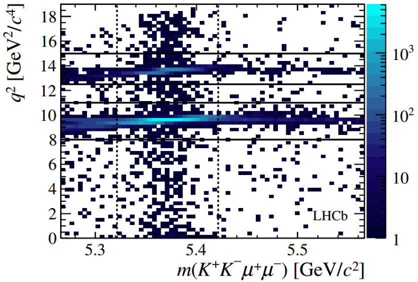
⇛ Reach angular observables makes is sensitive to different NP models

⇛ In addition one can construct less form factor dependent observables:

$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

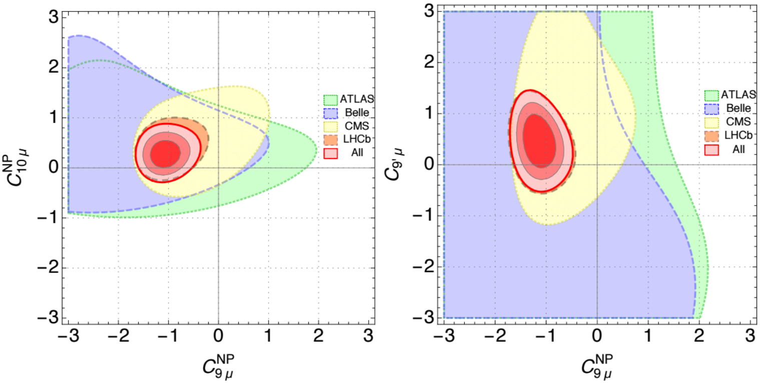
Branching fraction measurements of $B_s^0 \to \phi\mu\mu$





Theory implications of $b \to s\ell\ell$

- A fit prepared by `S. Descotes-Genon, L. Hofer, J. Matias, J. Virto`.
- The data can be explained by modifying the C_9 Wilson cœfficient.
- Overall there is $> 4\ \sigma$ discrepancy wrt. the SM prediction.



Observables in $B \to K^{*}\mu\mu$

$\Rrightarrow$ The kinematics of $B^0 \to K^{*}\mu^-\mu^+$ decay is described by three angles θ_l, θ_k, ϕ and invariant mass of the dimuon system (q^2).

$\Rrightarrow$ The angular distribution can be written as:

$$
\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{dcos}\theta_l\,\mathrm{dcos}\theta_k\,\mathrm{d}\phi}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\big[&\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_k \\
&+F_{\mathrm{L}}\cos^2\theta_k+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_k\cos 2\theta_l \\
&-F_{\mathrm{L}}\cos^2\theta_k\cos 2\theta_l+S_3\sin^2\theta_k\sin^2\theta_l\cos 2\phi \\
&+S_4\sin 2\theta_k\sin 2\theta_l\cos\phi+S_5\sin 2\theta_k\sin\theta_l\cos\phi \\
&+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_k\cos\theta_l+S_7\sin 2\theta_k\sin\theta_l\sin\phi \\
&+S_8\sin 2\theta_k\sin 2\theta_l\sin\phi+S_9\sin^2\theta_k\sin^2\theta_l\sin 2\phi\big].
\end{aligned}
$$

Link to effective operators

⇛ The observables S_i are bilinear combinations of transversity amplitudes: $A_\perp^{L,R}$, $A_\parallel^{L,R}$, $A_0^{L,R}$.
⇛ So here is where the magic happens. At leading order the amplitudes can be written as:

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

where $\hat{s} = q^2/m_B^2$, $\hat{m}_i = m_i/m_B$. The $\xi_{\parallel,\perp}$ are the soft form factors.

Link to effective operators

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$\Rrightarrow$ So here is where the magic happens. At leading order the amplitudes can be written as:

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

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

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

where $\hat{s} = q^2/m_B^2$, $\hat{m}_i = m_i/m_B$. The $\xi_{\parallel,\perp}$ are the soft form factors.
$\Rrightarrow$ Now we can construct observables that cancel the ξ soft form factors at leading order:

$$P_5' = \frac{J_5 + \bar{J}_5}{2\sqrt{-(J_2^c + \bar{J}_2^c)(J_2^s + \bar{J}_2^s)}}$$

Measurement of phase difference

Phys. Rev. D 95, 071101 (2017)

⇛ One could try to measure the phase difference between the resonances and the nonresonant amplitudes to see if the interference is large enough to explain the effects.

⇛ Measured firstly done for the decay $B \to K\mu\mu$.

⇛ The analysis based:

$$C_9^{\text{eff}} = C_9 + Y(q^2) = C_9 + \sum_j \eta_j e^{i\delta_i} A_j^{\text{res}}(q^2)$$

⇛ The amplitudes are modelled Briet-Wigner and Flatte functions.

⇛ Interference cannot explain the observed anomalies.