LHCb: Experimental overview on measurements with Rare Decays

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on behalf of the LHCb collaboration

IMPLICATIONS OF LHCB MEASUREMENTS AND FUTURE PROSPECTS

CERN, 17-19 October 2018

Outline

- Rare decays of heavy hadrons
- Experimental results at LHCb:
  - Radiative *b*-decays
  - Leptonic *b*-decays
  - Semi-leptonic *b*-decays
  - LFV in *b*-decays
  - Charm and strange rare decays
- Future prospects

Rare decays of heavy hadrons

Rare Decays (RD) are Flavour Changing Neutral Currents (FCNC) forbidden at tree-level in the Standard Model (SM)

- Sensitive to new particles entering the loop diagrams
- Allow to probe New Physics (NP) at much larger scales (compared to direct searches)

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Model-independent description through effective field theory approach:

$$H_{eff} \propto V_{tb} V_{ts}^* \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

- $\mathcal{O}_i$: complete basis of 4-body operators allowed by Lorentz invariance
- C_i: Wilson coefficients absorb effect of heavy dof and are computed pertubatively matching to full SM theory

→ Deviations from SM calculations are a clear sign of NP effects!

Dominant operators in the SM:

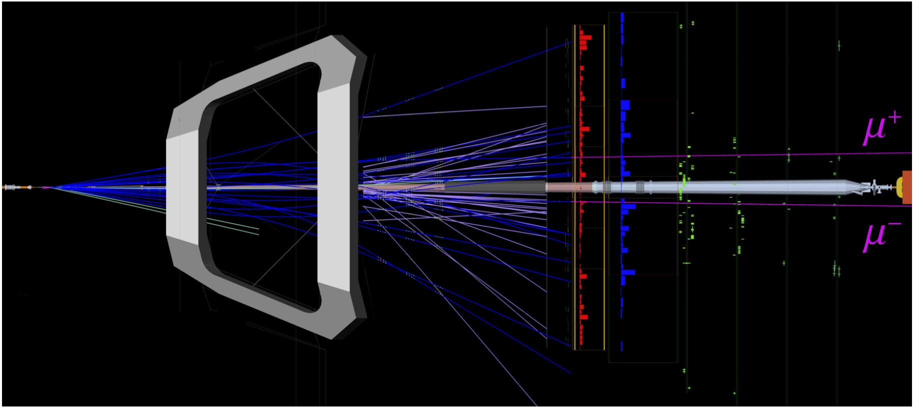
$$C_7^{(\prime)} \propto (\bar{s}\sigma_{\mu\nu}P_{L(R)}b)F^{\mu\nu}$$
$$C_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma_\mu\ell)$$
$$C_{10}^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma_\mu\gamma_5\ell)$$
$$C_S^{(\prime)} \propto (\bar{s}P_{L(R)}b)(\bar{\ell}\ell)$$
$$C_P^{(\prime)} \propto (\bar{s}P_{L(R)}b)(\bar{\ell}\gamma_5\ell)$$

can be probed with different RD transitions:

Transition	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$b \to s\gamma$	X			
$b \to \ell^+\ell^-$			X	X
$b \to s\ell^+\ell^-$	X	X	X	

Global fits allow to compare SM predictions to large number of observables

Experimental results

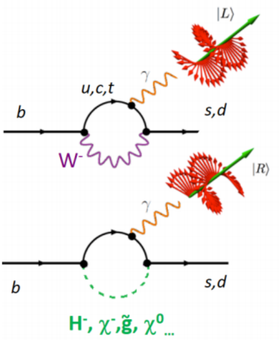


Radiative $b \rightarrow s\gamma$ decays

Studied in detail at B-factories

- BR and CPV measurements in good agreement with the SM [PDG]
- constrain $|C_7|^2 + |C_7'|^2$ only $\rightarrow$ room for NP in C_7'
- C_7' accessible experimentally through photon polarisation:
  - dominantly left-handed in SM due to absence of right-handed currents
  - up to 50% right-handed polarisation in SM extensions
    [Atwood et al., Phys.Rev.Lett.79:185-188,1997]

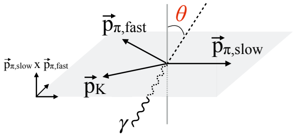
$$\alpha_\gamma^{SM} = \frac{P(\gamma_L) - P(\gamma_R)}{P(\gamma_L) + P(\gamma_R)} = 1 + \mathcal{O}\left(\frac{m_s}{m_b}\right)$$

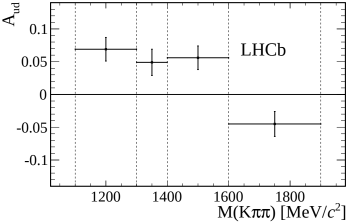


Photon polarisation at LHCb

- First observation in $B^+ \to K^+\pi^+\pi^-\gamma$ with $3\,\text{fb}^{-1}$ (2011-2012):

PHYS. REV. LETT. 112, 161801 (2014)





Full amplitude analysis ongoing

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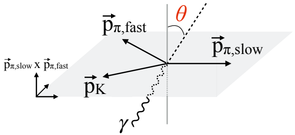
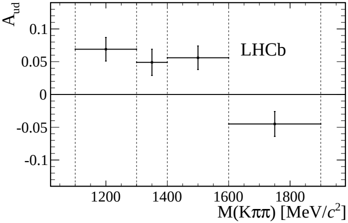
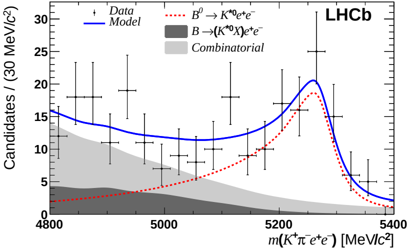




Full amplitude analysis ongoing

- First measurement in $B^0 \to K^{*0} e^+ e^-$ low q^2 with $3\,\mathrm{fb}^{-1}$:



JHEP04(2015)064

$$A_{\mathrm{T}}^{(2)} = -0.23 \pm 0.23 \pm 0.05$$
$$A_{\mathrm{T}}^{\mathrm{Im}} = +0.14 \pm 0.22 \pm 0.05$$

Update with full dataset ongoing

$B_s^0 \to \phi\gamma$ [PHYS. REV. LETT. 118, 021801 (2017)]

Time-dependent decay rate is sensitive to photon polarisation:

$$\Gamma(t) \propto e^{-\Gamma_s t}\left[cosh(\frac{\Delta\Gamma_s t}{2}) - \mathcal{A}^{\Delta} sinh(\frac{\Delta\Gamma_s t}{2}) \pm \mathcal{C} cos(\Delta m_s t) \mp \mathcal{S} sin(\Delta m_s t)\right]$$

- SM prediction: $\mathcal{A}^{\Delta} \simeq \frac{2\mathrm{Re}(e^{-i\phi_s} C_7 C_7')}{|C_7|^2+|C_7'|^2} = 0.047^{+0.029}_{-0.025}$ [PLB 664 (2008) 174]

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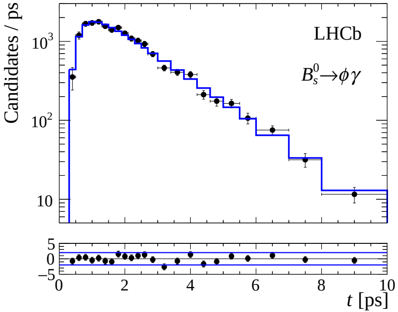
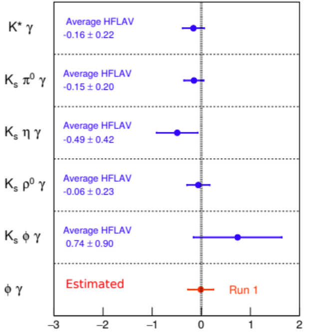
Untagged measurement with $3\,\mathrm{fb}^{-1}$:

$$\mathcal{A}^{\Delta} = -0.98\,^{+0.46}_{-0.52}\,^{+0.23}_{-0.20}$$



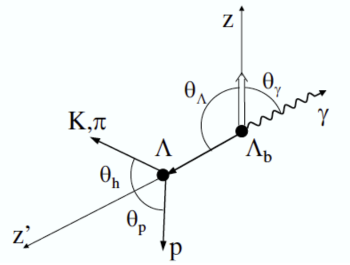
Tagged measurement ongoing:



Radiative baryon decays

Baryon $b \to s\gamma$ decays are also accessible at LHCb and provide complementary measurement of the photon polarisation:

- Angular analysis of $\Lambda_b^0 \to \Lambda\gamma$:



$$\frac{d\Gamma}{dcos\theta_p} \propto 1 - \alpha_\gamma \alpha_{p,1/2} cos\theta_p$$

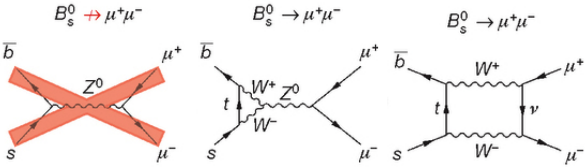
$$\alpha_{p,1/2} = (0.642 \pm 0.013) \text{ [PDG]}$$

- Other decays with richer angular distributions: $\Xi_b^- \to \Xi^-\gamma$ and $\Omega_b^- \to \Omega^-\gamma$

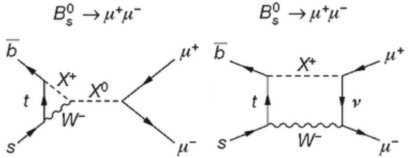
- Experimentally very challenging but results expected soon!

Leptonic $b \to \ell^+\ell^-$ decays

Helicity suppression in the SM $\to$ extremely sensitive to NP effects

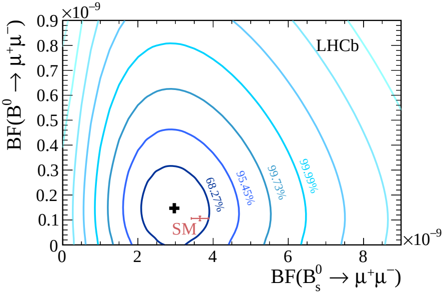


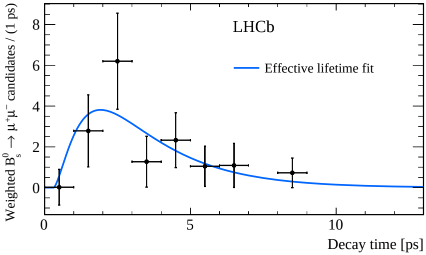
- theoretically clean due to fully leptonic final state
- probe new scalars in the loops



$B^0_{(s)} \to \mu^+\mu^-$ [PHYS. REV. LETT. 118, 191801 (2017)]

First observation by single experiment exploiting $4.4\,\text{fb}^{-1}$ (2011-2016):





- $B^0_s \to \mu^+\mu^-$ observed with 7.6σ, no significant excess for $B^0 \to \mu^+\mu^-$
- ATLAS limit below SM: $\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ at 95% C.L.
- First measurement of $B^0_s \to \mu^+\mu^-$ lifetime:

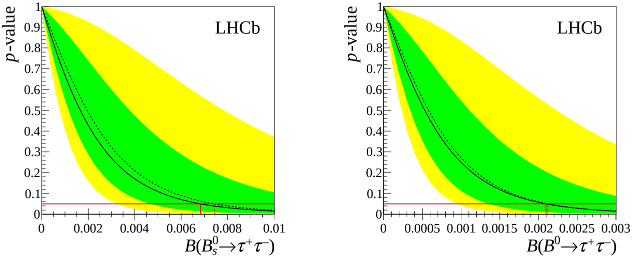
$$\tau(B^0_s \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05\,\text{ps}$$

$B^0{}_{(s)} \to \tau^+\tau^-$ [PHYS. REV. LETT. 118, 251802 (2017)]

τ decays very challenging at LHCb due to missing neutrinos

- $\to$ Exploit hadronic decay of τ and excellent vertex resolution
- $\to$ Exploit kinematic constraints on the system

Search with $3\,\text{fb}^{-1}$ (2011-2012) compatible with background only:

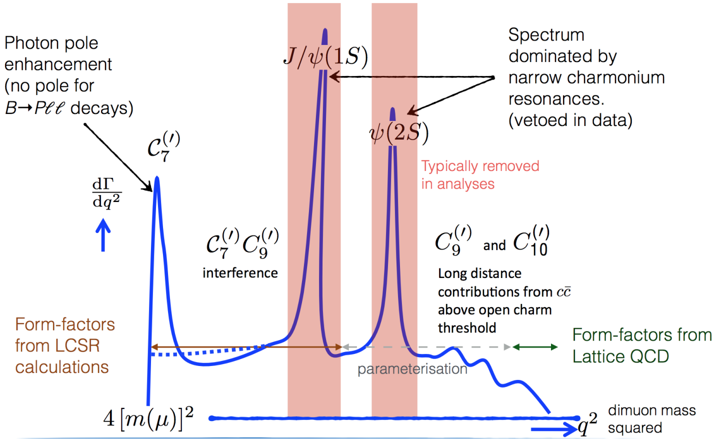


First direct limit on $B_s^0 \to \tau^+\tau^-$ and world best limit on $B^0 \to \tau^+\tau^-$:

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ at 95\% C.L.}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ at 95\% C.L.}$$

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

Contributions from both $C_7^{(\prime)}$, $C_9^{(\prime)}$ and $C_{10}^{(\prime)}$ in different q^2 regions

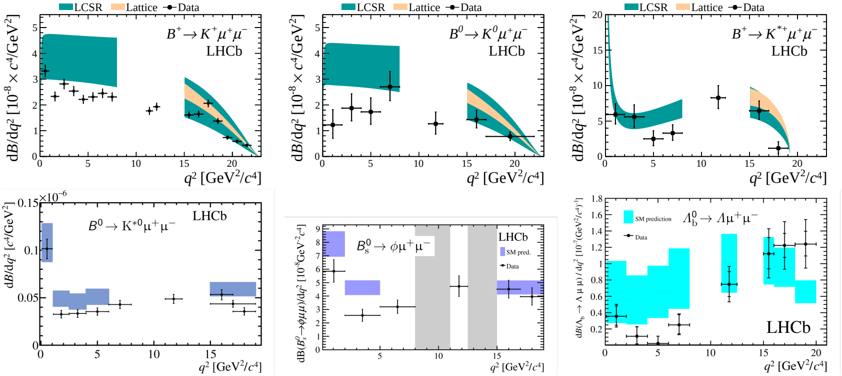


Give access to differential branching ratios and angular distributions

Differential branching ratios in $b \to s\ell^+\ell^-$ decays

Several measurements systematically below the SM at low q^2:

JHEP 06 (2014) 133

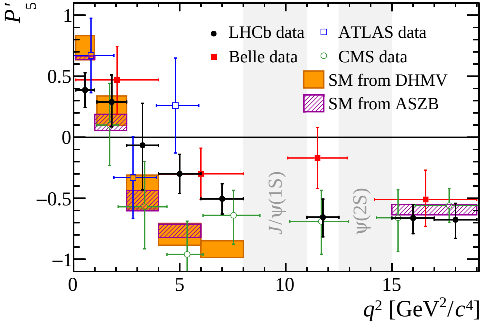


JHEP 04 (2017) 142 , JHEP 09 (2015) 179, JHEP 06 (2015) 115

- Interesting to check in $b \to d\ell^+\ell^-$ decays.

Angular observables in $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 02 (2016) 104]

Form factor "free" observables: $P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$ [JHEP 05 (2013) 137]



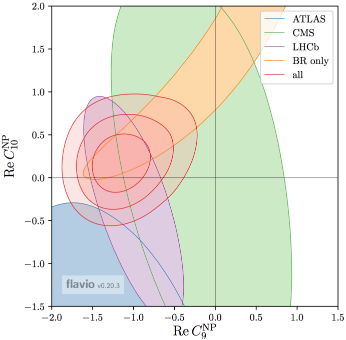
Phys.Rev.Lett.118(2017)11,111801, JHEP10(2018)047, PHYS.LETT.B781(2018)517-541,

Descotes-Genon et al., Altmannshofer and Straub

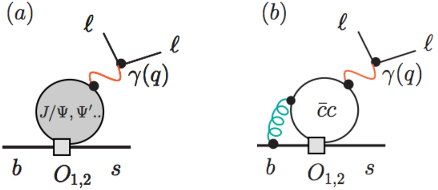
- Update with Run 2 data ongoing.
- Interesting also to study other modes.

A sign of New Physics?

- Global fits point to additional contributions to C_9 or C_9 and C_{10}



Eur.Phys.J.C(2017)77:377

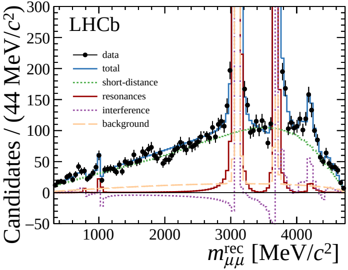


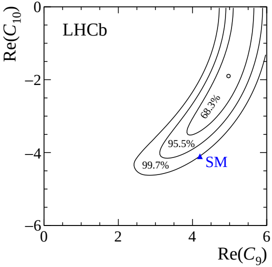
arXiv:1406.0566

- Could the effect on C_9 be explained by hadronic effects?
  - See talk by R. Zwicky on how to eliminate hadronic uncertainties

Phase difference in $B^+ \to K^+\mu^+\mu^-$ [EUR.PHYS.J.C(2017)77:161]

Fit to full dimuon mass spectrum including:
$\rho, \omega, \phi, J/\psi, \psi(2S), \psi(3770), \psi(4040), \psi(4160), \psi(4415)$



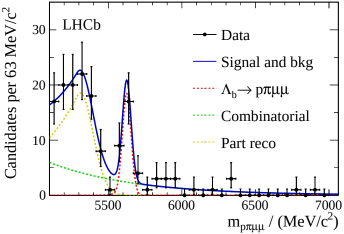


$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37 \pm 0.15 \pm 0.23) \times 10^{-7}$$

→ Interference is small, 3σ deviation in C_9-C_{10} plane wrt SM

- Repeating analysis for $B^0 \to K^{*0}\mu^+\mu^-$
- New methods to probe large-distance effects by Blake et al., Bobeth et al.

- **First observation** of $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$ [JHEP 04 (2017) 029]:



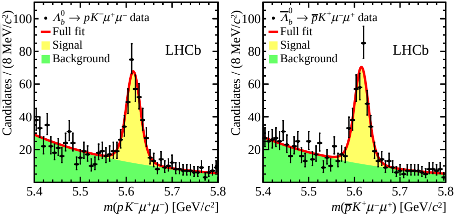
First observation of $b \to d$ transition in baryons!

$$\mathcal{B}(\Lambda_b^0 \to p\pi^-\mu^+\mu^-) = (6.9 \pm 1.9 \pm 1.1^{+1.3}_{-1.0}) \times 10^{-8}$$

- **CP asymmetry** in $\Lambda_b^0 \to pK^-\mu^+\mu^-$ [JHEP 06 (2017) 108]:

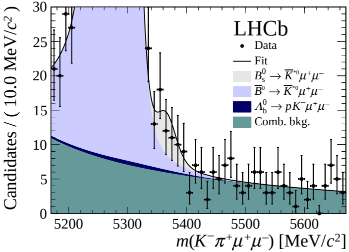
$$\Delta\mathcal{A}_{CP} = (-3.5 \pm 5.0 \pm 0.2) \times 10^{-2}$$
$$a_{CP}^{\hat{T}-odd} = (1.2 \pm 5.0 \pm 0.7) \times 10^{-2}$$

$$\Delta\mathcal{A}_{CP} = \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to pK^- J/\psi)$$



Exploring new modes: $b \to d\ell^+\ell^-$

- First evidence for the decay $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$ [JHEP 07 (2018) 020]:
  - Extremely challenging due to $B^0 \to K^{*0}\mu^+\mu^-$ contamination
  - Distinguishable thanks to LHCb high momentum resolution



- Using $4.6\,\text{fb}^{-1}$ data (2011-2016): 3.4σ significance

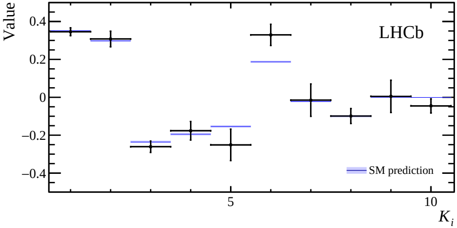
$$\mathcal{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-) = (2.9 \pm 1.0(\text{stat}) \pm 0.2(\text{syst}) \pm 0.3(\text{norm})) \times 10^{-8}$$

Opens the door to differential BR and angular analyses in $b \to d\ell^+\ell^-$!

Exploring new modes: angular analyses

- Angular moments of the decay $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 09 (2018) 146]:
  - Complementary test of SM to understand nature of anomalies
  - Focus on high q^2 region: $15 < q^2 < 20\ (\mathrm{GeV}/c^2)^2$
  - Measure full basis of 34 observables for first time
  - Use angular moments method due to available statistics
  - Using $5\,\mathrm{fb}^{-1}$ data (2011-2016): results compatible with SM

$$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2}\sum_i^{34} K_i f_i(\vec{\Omega})$$



$$A_{FB}^{l} = -0.39 \pm 0.04(\mathrm{stat}) \pm 0.01(\mathrm{syst})$$
$$A_{FB}^{h} = -0.30 \pm 0.05(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$
$$A_{FB}^{lh} = +0.25 \pm 0.04(\mathrm{stat}) \pm 0.01(\mathrm{syst})$$

Lepton Flavour Universality

Discrepancies in $b \to s\ell^+\ell^-$ measurements could be explained by large hadronic effects $\to$ ratio of branching fractions with different lepton flavours, i.e., Lepton flavour universality (LFU) tests:

- Ratios accurately predicted in the SM ($O(1\%)$)
  - LFU violation from Yukawa couplings only
  - No observable effect in b-decays
  - Lepton mass effects only relevant in the kinematic limit

- Experimentally challenging due to different interaction of e and μ with matter
  - Important bremsstrahlung emission from e
  - Large pile-up in calorimeters leads to tighter thresholds

  $\to$ Double ratios to cancel these effects and stringent cross-checks

R_K and R_{K^*}

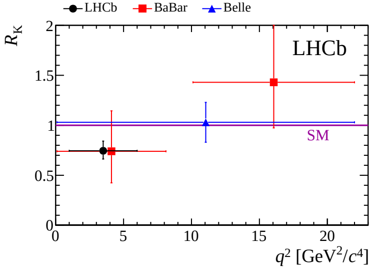
Ratios of branching fractions measured as double ratios:

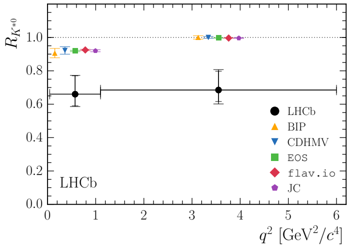
$$R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)} =$$
$$= \frac{N(B^0 \to K^{*0}\mu^+\mu^-)}{N(B^0 \to K^{*0}J/\psi(\mu^+\mu^-))} \cdot \frac{N(B^0 \to K^{*0}J/\psi(e^+e^-))}{N(B^0 \to K^{*0}e^+e^-)} \cdot$$
$$\cdot \frac{\epsilon(B^0 \to K^{*0}J/\psi(\mu^+\mu^-))}{\epsilon(B^0 \to K^{*0}\mu^+\mu^-)} \cdot \frac{\epsilon(B^0 \to K^{*0}J/\psi(e^+e^-))}{\epsilon(B^0 \to K^{*0}e^+e^-)}$$

- efficiencies from MC with data corrections
- very strong cross-check with $r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0}J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0}J/\psi(e^+e^-))}$

R_K and R_{K^*}

Results with $3\,\text{fb}^{-1}$ (2011-2012): 2.6σ and $2.1 - 2.5\sigma$ from the SM





PHYS.REV.LETT.113,151601(2014), JHEP08(2017)055

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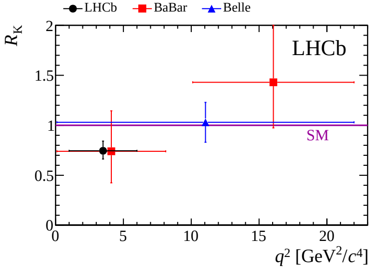
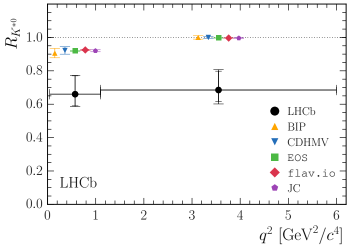




PHYS.REV.LETT.113,151601(2014), JHEP08(2017)055

Working on:

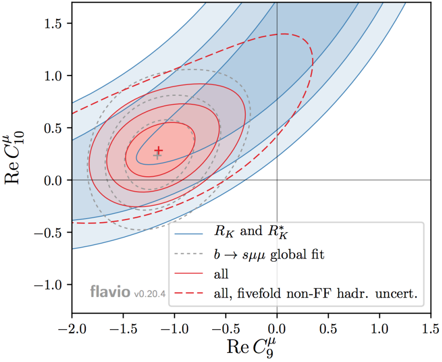
- updated measurements with more data and reduced systematics
- tests of LFU in other modes: $B_s^0 \to \phi\ell^+\ell^-$, $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$, $\Lambda_b^0 \to pK^-\ell^+\ell^-$, etc.

If confirmed $\to$ clear sign of NP!

Global fits with all $b \to s\ell^+\ell^-$ observables

LFU observables point in the same direction as differential BR and angular measurements in global fits!

Phys. Rev. D 96, 055008 (2017)



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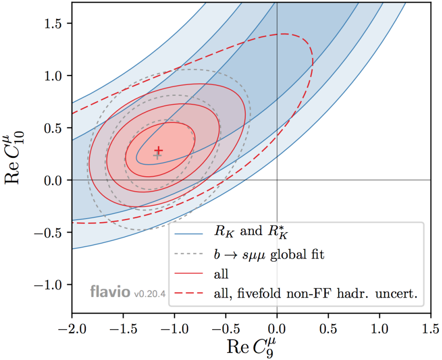


Specific physics models proposed, some explaining also tensions in $b \to d\ell\nu$ (see talk by S. Klaver):

- Lepto-quarks
- Pati-Salam models
- Massive vector bosons
- `Insert new ideas`
- See talks by D. Guadagnoli and M. Blanke

$\rightarrow$ important to check other RD that might be affected

Lepton Flavour Violation (LFV)

Some models predict LFV to explain LFU violation

- LFV effectively forbidden in the SM $\rightarrow$ null test
- Large heavy-hadron samples allow to put stringent limits

LHCb results with Run 1 data: in short, all compatible with SM so far

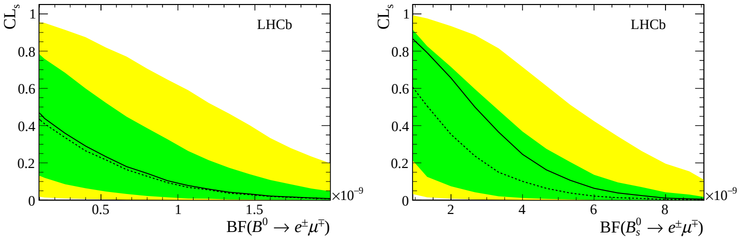
Decay	Branching ratio limit	Reference
$\tau^- \rightarrow p\mu^+\mu^+$	4.4×10^{-7}	PHYSICS LETTERS B 724 (2013)
$\tau^+ \rightarrow \overline{p}\mu^+\mu^-$	4.4×10^{-7}	PHYSICS LETTERS B 724 (2013)
$B_s^0 \rightarrow e^+\mu^-$	1.1×10^{-8}	PHYS.REV.LETT. 111 (2013) 141801
$B^0 \rightarrow e^+\mu^-$	2.8×10^{-9}	PHYS.REV.LETT. 111 (2013) 141801
$\tau \rightarrow \mu\mu\mu$	4.7×10^{-8}	JHEP 02 (2015) 121
$D^0 \rightarrow e^+\mu^-$	1.3×10^{-8}	PHYS. LETT. B754 (2016) 167

Searches for $b \rightarrow X\ell^+\ell^-$ LFV decays ongoing

LFV: $B^0_{(s)} \to e^+\mu^-$ [JHEP 1803 (2018) 078]

New results using $3\,\text{fb}^{-1}$ (2011-2012) and improved selection:

- Enhanced in NP models up to $\mathcal{O}(10^{-11})$
- Search in bins of output classifier to enhance sensitivity
- Results compatible with background only hypothesis



Most stringent limits on these decays:

$$\mathcal{B}(B^0_s \to e^+\mu^-) < 5.4 \times 10^{-9} \text{ at } 90\% \text{ C.L.}$$
$$\mathcal{B}(B^0 \to e^+\mu^-) < 1.0 \times 10^{-9} \text{ at } 90\% \text{ C.L.}$$

Rare charm decays

- Angular and CP asymmetries in $D^0 \to hh\mu^+\mu^-$ [Phys.Rev.Lett.121(2018)091801]:

$D^0 \to \pi^+\pi^-\mu^+\mu^-$

$$A_{FB} = (3.3 \pm 3.7 \pm 0.6)\%$$
$$A_{2\phi} = (-0.6 \pm 3.7 \pm 0.6)\%$$
$$A_{CP} = (4.9 \pm 3.8 \pm 0.7)\%$$

$D^0 \to K^+K^-\mu^+\mu^-$

$$A_{FB} = (0 \pm 11 \pm 2)\%$$
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  - No signal outside the ϕ and ω regions

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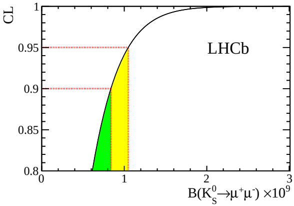
- Update of $D^0 \to \mu^+\mu^-$ search ongoing
- See talk by G. Hiller for SM predictions and NP effects

Rare strange decays

- Search for $K^0_S \to \mu^+\mu^-$ with $3\,\text{fb}^{-1}$ [EUR. PHYS. J. C, 77 10 (2017) 678]:

Compatible with background only:

$$\mathcal{B}(K^0_S \to \mu^+\mu^-) < 0.8 \times 10^{-9} \text{ at } 90\% \text{ C.L.}$$



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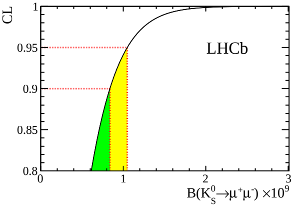
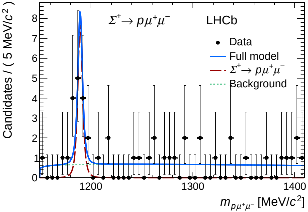


- Evidence for $\Sigma \to p\mu^+\mu^-$ with 3 fb^{-1} [PHYS.REV.LETT.120, 221803 (2018)]:

Excess with 4.1σ significance:

$$\mathcal{B}(\Sigma \to p\mu^+\mu^-) = (2.2^{1.8}_{-1.3}) \times 10^{-8}$$

HyperCP excess [PRL(94)021801] not confirmed



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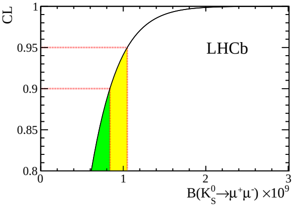

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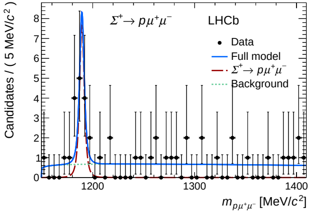

Exploring also other modes: $K_S^0 \to \ell^+\ell^-\ell^+\ell^-$, $K_S^0 \to \pi^0\mu^+\mu^-$, Λ decays...

Future prospects [Physics case for an LHCb Upgrade II]

LHCb major upgrade for Run 3, could go to 300 fb^{-1} in HL-LHC!

$b \to s\gamma$

$\sigma_{\text{stat}}(\mathcal{A}^{\Delta}, \alpha_{\gamma}, A_{\text{T}}^{\text{Im},2}) < 1\%$
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$\sigma(\mathcal{B}) \sim 1.8\%(\text{stat}),\ \sim 4\%(\text{syst})$
$\sigma(\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0 \to \mu^+\mu^-)}) \sim 10\%$ stat. limited
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$b \to s\ell^+\ell^-$

Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to K^+e^+e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0}e^+e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B_s^0 \to \phi e^+e^-$	–	80	230	530	3 300
$\Lambda_b^0 \to pKe^+e^-$	–	120	360	820	5 000
$B^+ \to \pi^+e^+e^-$	–	20	70	150	900

Summary

Rare FCNC decays provide clean observables to test the SM

- C_7 well constrained but still NP possible in C_7' $\rightarrow$ photon polarisation
- Scalar contributions constrained by $B_s^0 \rightarrow \mu^+\mu^-$ but room for NP
- Tensions wrt SM in both $b \rightarrow s\ell^+\ell^-$ differential BR and angular observables possibly pointing to NP in C_9 or C_9 and C_{10}
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Exciting times in front of us

- Updating results and exploring new modes to confirm the anomalies: b-baryons, $b \rightarrow d\ell^+\ell^-$, charm, strange...
- Theory community input most welcome!
- Squeezing recorded data and promising Upgrade 1 and 2 ahead

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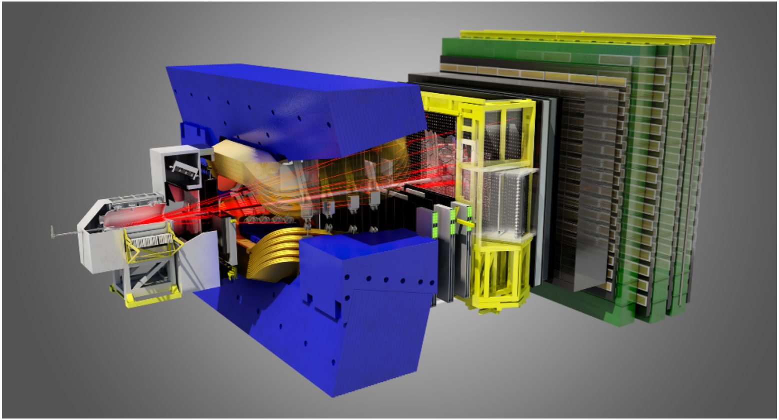
Stay tuned!

BACK-UP

The LHCb detector [JINST3 (2008) S08005]



Huge production of heavy flavour hadrons (all of them!)

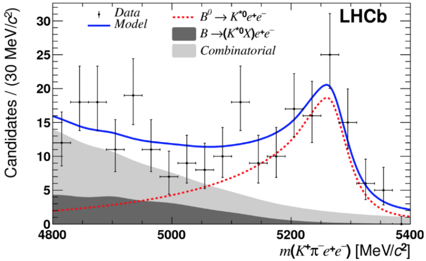
Very good momentum and vertex resolution

Excellent μ identification

Neutral particle identification and energy measurement

Photon polarisation in $B^0 \to K^{*0} e^+ e^-$ at low q^2

$B^0 \to K^{*0} e^+ e^-$ dominated by photon pole at low q^2 $\to$ sensitivity to photon polarisation



$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\tilde{\phi}} = \frac{9}{16\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \left(\frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K - F_{\mathrm{L}}\cos^2\theta_K\right)\cos 2\theta_\ell + \frac{1}{2}(1-F_{\mathrm{L}})\boxed{A_{\mathrm{T}}^{(2)}}\sin^2\theta_K\sin^2\theta_\ell\cos 2\tilde{\phi} + (1-F_{\mathrm{L}})A_{\mathrm{T}}^{\mathrm{Re}}\sin^2\theta_K\cos\theta_\ell + \frac{1}{2}(1-F_{\mathrm{L}})\boxed{A_{\mathrm{T}}^{\mathrm{Im}}}\sin^2\theta_K\sin^2\theta_\ell\sin 2\tilde{\phi}\Big].$$

$$A_{\mathrm{T}}^{(2)}(q^2 \to 0) = \frac{2\mathcal{R}e(\mathcal{C}_7\mathcal{C}_7^{\prime *})}{|\mathcal{C}_7|^2 + |\mathcal{C}_7^{\prime}|^2} \qquad A_{\mathrm{T}}^{\mathrm{Im}}(q^2 \to 0) = \frac{2\mathcal{I}m(\mathcal{C}_7\mathcal{C}_7^{\prime *})}{|\mathcal{C}_7|^2 + |\mathcal{C}_7^{\prime}|^2}$$

analysis uses $q^2 \in [0.002, 1.120]$ GeV^2/c^4

$$A_{\mathrm{T}}^{(2)} = -0.23 \pm 0.23 \pm 0.05$$
$$A_{\mathrm{T}}^{\mathrm{Im}} = +0.14 \pm 0.22 \pm 0.05$$

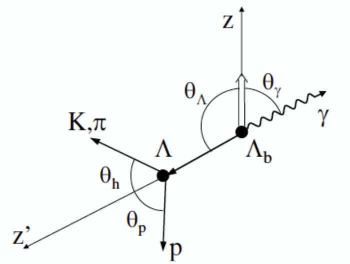
Compatible with $C_7'/C_7 = 0$ but room for improvement

Photon polarisation in radiative baryon decays

- Angular analysis of $\Lambda_b^0 \to \Lambda\gamma$:

$$\frac{d\Gamma}{dcos\theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b^0} cos\theta_\gamma$$

$$\frac{d\Gamma}{dcos\theta_p} \propto 1 - \alpha_\gamma \alpha_{p,1/2} cos\theta_p$$

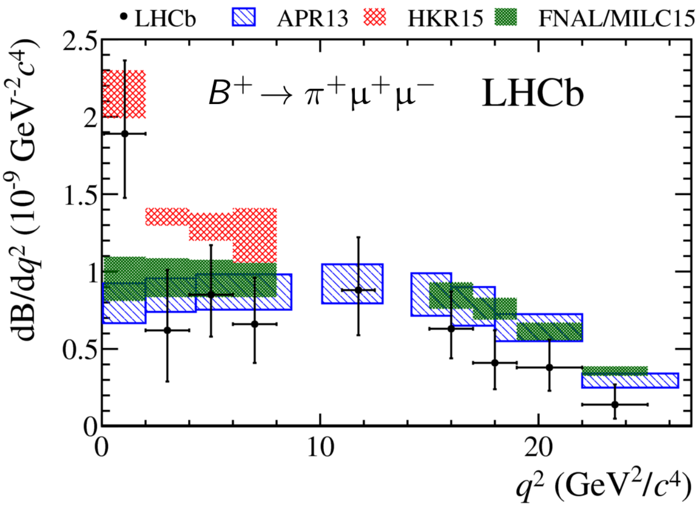


  - $P_{\Lambda_b^0} = (0.06 \pm 0.07)$ [Phys. Lett. B 724 (2013) 27]
  - $\alpha_{p,1/2} = (0.642 \pm 0.013)$ [PDG]

Differential Branching Ratios in $b \to s\ell^+\ell^-$ decays

JHEP 10 (2015) 034

- Trend not observed so far in $b \to d\ell^+\ell^-$ but precision is lower:



Angular observables in $b \to s\ell^+\ell^-$

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

Angular moments of the decay $\Lambda_b^0 \to \Lambda \mu^+ \mu^-$ [JHEP 09 (2018) 146]

$$
\begin{aligned}
\frac{\mathrm{d}^5\Gamma}{\mathrm{d}\vec{\Omega}} = \frac{3}{32\pi^2}\Big(& \left(K_1 \sin^2\theta_\ell + K_2 \cos^2\theta_\ell + K_3 \cos\theta_\ell\right) + \\
& \left(K_4 \sin^2\theta_\ell + K_5 \cos^2\theta_\ell + K_6 \cos\theta_\ell\right) \cos\theta_b + \\
& \left(K_7 \sin\theta_\ell \cos\theta_\ell + K_8 \sin\theta_\ell\right) \sin\theta_b \cos\left(\phi_b + \phi_\ell\right) + \\
& \left(K_9 \sin\theta_\ell \cos\theta_\ell + K_{10} \sin\theta_\ell\right) \sin\theta_b \sin\left(\phi_b + \phi_\ell\right) + \\
& \left(K_{11} \sin^2\theta_\ell + K_{12} \cos^2\theta_\ell + K_{13} \cos\theta_\ell\right) \cos\theta + \\
& \left(K_{14} \sin^2\theta_\ell + K_{15} \cos^2\theta_\ell + K_{16} \cos\theta_\ell\right) \cos\theta_b \cos\theta + \\
& \left(K_{17} \sin\theta_\ell \cos\theta_\ell + K_{18} \sin\theta_\ell\right) \sin\theta_b \cos\left(\phi_b + \phi_\ell\right) \cos\theta + \\
& \left(K_{19} \sin\theta_\ell \cos\theta_\ell + K_{20} \sin\theta_\ell\right) \sin\theta_b \sin\left(\phi_b + \phi_\ell\right) \cos\theta + \\
& \left(K_{21} \cos\theta_\ell \sin\theta_\ell + K_{22} \sin\theta_\ell\right) \sin\phi_\ell \sin\theta + \\
& \left(K_{23} \cos\theta_\ell \sin\theta_\ell + K_{24} \sin\theta_\ell\right) \cos\phi_\ell \sin\theta + \\
& \left(K_{25} \cos\theta_\ell \sin\theta_\ell + K_{26} \sin\theta_\ell\right) \sin\phi_\ell \cos\theta_b \sin\theta + \\
& \left(K_{27} \cos\theta_\ell \sin\theta_\ell + K_{28} \sin\theta_\ell\right) \cos\phi_\ell \cos\theta_b \sin\theta + \\
& \left(K_{29} \cos^2\theta_\ell + K_{30} \sin^2\theta_\ell\right) \sin\theta_b \sin\phi_b \sin\theta + \\
& \left(K_{31} \cos^2\theta_\ell + K_{32} \sin^2\theta_\ell\right) \sin\theta_b \cos\phi_b \sin\theta + \\
& \left(K_{33} \sin^2\theta_\ell\right) \sin\theta_b \cos\left(2\phi_\ell + \phi_b\right) \sin\theta + \\
& \left(K_{34} \sin^2\theta_\ell\right) \sin\theta_b \sin\left(2\phi_\ell + \phi_b\right) \sin\theta \Big) .
\end{aligned}
$$

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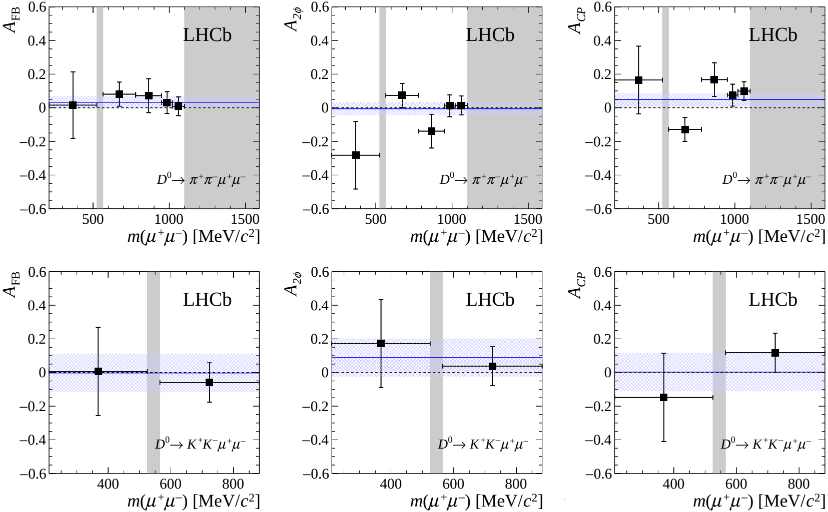

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