Angular analysis of $\Lambda_b \to \Lambda(1520)\mu^+\mu^-$ at LHCb

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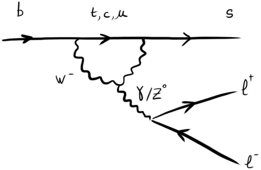
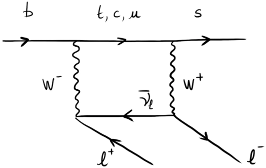
Journées de Rencontre des Jeunes Chercheurs 2022

24 October 2022

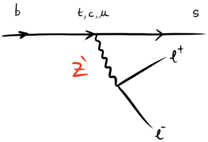
Why are rare decays interesting ?

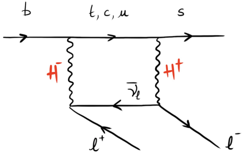
$b \to s\ell^+\ell^-$ transitions suppressed in Standard Model





New Physics processes could contribute

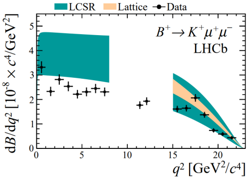


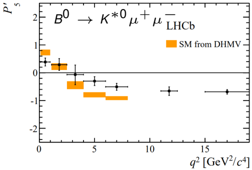


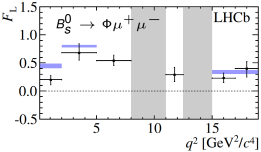
drawn by Yasmine

Deviations from SM are measured

Rare decays show deviations from the SM predictions





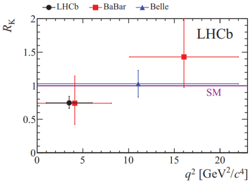


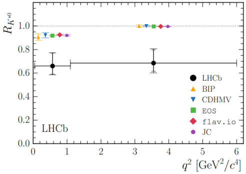
arXiv:1403.8044v3

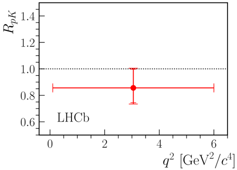
arXiv:1512.04442

arXiv:1506.08777

Differential branching ratios and angular observables







doi: 10.1393/ncc/i2017-17171-9

arXiv:1705.05802

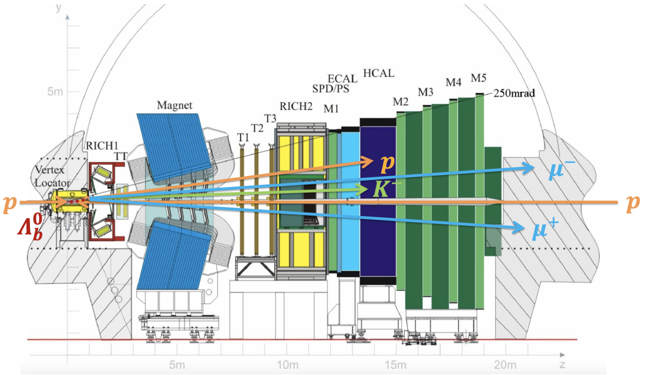
LHCb Paper 2018 040

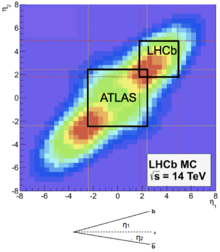
Lepton Flavour Universality (LFU) tests

Only few measurements with *b*-baryon decays

LHCb detector

- $b\bar{b}$ production mostly in forward region
- Run1+2 : 9 fb^{-1} of pp-collisions
- Forward spectrometer with excellent vertexing, tracking and particle identification

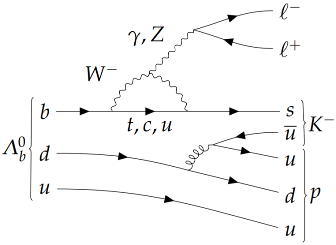




CHEAT SHEET

- Good vertex and impact parameter resolution σ (IP) = 15+29/p_T mm.
- Excellent momentum resolution ~ 25 MeV/c² two-body decays.
- Excellent particle ID (μ-ID 97% for (π → μ) misID of 1-3%).
- Versatile & efficient trigger.

Our favorite decay : $\Lambda_b \to pK^-\mu^+\mu^-$



CDS:2699822 (top) PDG Live (right)

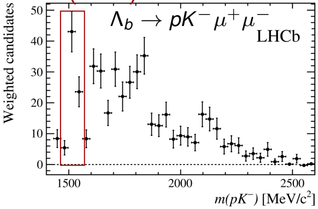
Strong decay of $\Lambda^* \to pK^-$

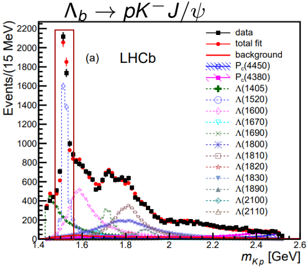
		Overall	Status as seen in —		
Particle	J^P	status	$N\overline{K}$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	$1/2^+$	****			$N\pi$ (weak decay)
$\Lambda(1380)$	$1/2^-$	**	**	**	
$\Lambda(1405)$	$1/2^-$	****	****	****	
$\Lambda(1520)$	$3/2^-$	****	****	****	$\Lambda\pi\pi, \Lambda\gamma$
$\Lambda(1600)$	$1/2^+$	****	***	****	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1670)$	$1/2^-$	****	****	****	$\Lambda\eta$
$\Lambda(1690)$	$3/2^-$	****	****	***	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1710)$	$1/2^+$	*	*	*	
$\Lambda(1800)$	$1/2^-$	***	***	**	$\Lambda\pi\pi, \Sigma(1385)\pi, N\overline{K}^*$
$\Lambda(1810)$	$1/2^+$	***	**	**	$N\overline{K}_2^*$
$\Lambda(1820)$	$5/2^+$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1830)$	$5/2^-$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1890)$	$3/2^+$	****	****	**	$\Sigma(1385)\pi, N\overline{K}^*$
$\Lambda(2000)$	$1/2^-$	*	*	*	
$\Lambda(2050)$	$3/2^-$	*	*	*	
$\Lambda(2070)$	$3/2^+$	*	*	*	
$\Lambda(2080)$	$5/2^-$	*	*	*	
$\Lambda(2085)$	$7/2^+$	**	**	*	
$\Lambda(2100)$	$7/2^-$	****	****	**	$N\overline{K}^*$
$\Lambda(2110)$	$5/2^+$	***	**	**	$N\overline{K}^*$
$\Lambda(2325)$	$3/2^-$	*	*		
$\Lambda(2350)$	$9/2^+$	***	***	*	
$\Lambda(2585)$		*	*		

Rich Λ^* spectrum

How does the pK^- mass spectrum look like ?

Λ(1520) dominates

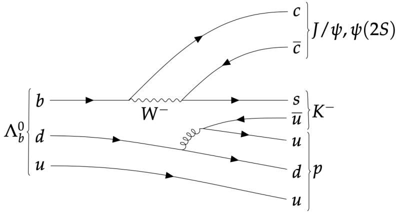




arXiv:1912.08139v2 (top), arXiv:1507.03414 (bottom)

pK^- spectrum using Run 1 + 2016 data on the upper left. Statistically limited.

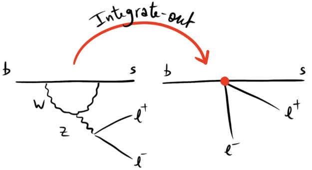
Higher statistics via tree-level diagram of $\Lambda_b \to pK^- J/\psi(\to \mu^+\mu^-)$ on lower left.



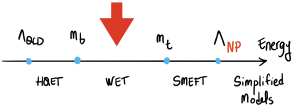
CDS:2699822

Idea is focusing on dominating Λ(1520) resonance.

Effective Field Theory

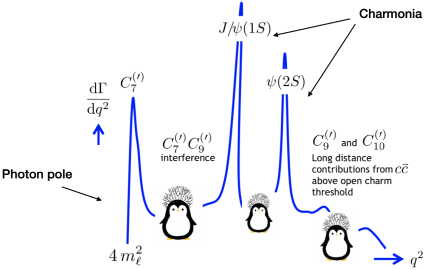


$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda^{\text{CKM}} \sum_i C_i \mathcal{O}_i + h.c,$$



Parametrisation of NP via Wilson Coefficients

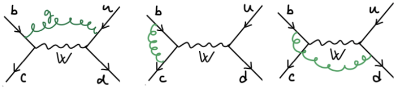
Dilepton invariant mass spectrum
$q^2 = (2m_\ell)^2$:



from Yasmine

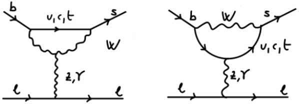
The rare mode is sensitive to New Physics !

Operators (drawn by Claudia Cornella)



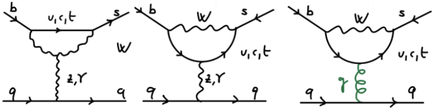
CURRENT-CURRENT operators

$$\mathcal{O}_1^{(c)} = (\bar{s}\gamma_\mu P_L c)\,(\bar{c}\gamma_\mu P_L b)$$
$$\mathcal{O}_2^{(c)} = (\bar{s}^j\gamma_\mu P_L c^i)\,(\bar{c}^i\gamma_\mu P_L b^j)$$



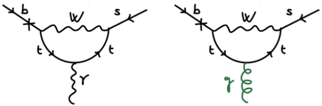
SEMILEPTONIC operators

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}\,(\bar{s}\gamma_\mu P_L b)\,(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}\,(\bar{s}\gamma_\mu P_L b)\,(\bar{\ell}\gamma^\mu\gamma^5\ell)$$



QCD penguins

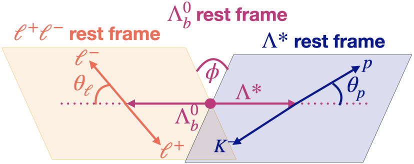
$$\mathcal{O}_3 = (\bar{s}\gamma_\mu P_L b)\sum_{q=u,d,s,c,b}(\bar{q}\gamma^\mu P_L q)$$
$$\mathcal{O}_4 = (\bar{s}^i\gamma_\mu P_L b^j)\sum_{q=u,d,s,c,b}(\bar{q}^j\gamma^\mu P_L q^i)$$



DIPOLE operators

$$\mathcal{O}_7 = m_b\frac{e}{(4\pi)^2}\,(\bar{s}\sigma^{\mu\nu}P_R b)\,F_{\mu\nu}$$
$$\mathcal{O}_8 = m_b\frac{g_s}{(4\pi)^2}\,(\bar{s}\sigma^{\mu\nu}P_R T^a b)\,G^a_{\mu\nu}$$

Angular observables



$(\theta_\ell, \theta_p, \phi)$ in helicity basis

$$d\vec{\Omega} = d\cos\theta_\ell d\cos\theta_p d\phi$$

$$\frac{d^4\Gamma}{dq^2 d\vec{\Omega}} = \sum_i \text{physics}_i \times \text{kinematics}_i$$

$$= \frac{9\pi}{32} \sum_i L_i(q^2, \mathcal{C}, ff) \times f_i(\vec{\Omega})$$

$\mathcal{C}$ = Wilson Coefficients $\rightarrow$ short distance part $\rightarrow$ sensitive to NP
ff = form factors $\rightarrow$ long distance part

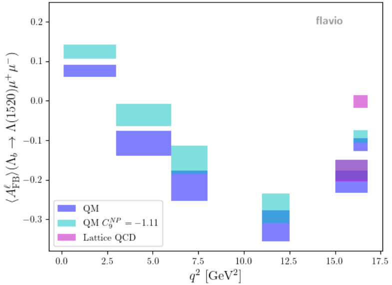
Observables :

$$S_i = \frac{L_i + \bar{L}_i}{d(\Gamma + \bar{\Gamma})/dq^2}, A_i = \frac{L_i - \bar{L}_i}{d(\Gamma + \bar{\Gamma})/dq^2},$$

$$A_{FB}^\ell = \frac{3(L_{1c} + 2L_{2c})}{2(L_{1cc} + 2(L_{1ss} + L_{2cc} + 2L_{2ss} + L_{3ss}))}$$

Analysis overview

- Mass window : $m(pK^-) \in [1470; 1570]$ MeV/c^2
- q^2 bins : $[0.1, 3], [3, 6], [6, 8], [11, 12.5], [15, 16.8], [1, 6]$
- Observable predictions through flavio
    - based on $\Lambda_b \to \Lambda(1520)\ell^+\ell^-$ phenomenology with lattice QCD or QM form-factors [arXiv:1903.00448, arXiv.1108.6129, arXiv:2009.09313]



Separation of New Physics and Standard Model predictions in A_{FB}^{ℓ}

Ingredients for an angular analysis

1. Development of angular fit model using theory input
2. Selection to get our decay ✓
3. Corrections of Monte Carlo samples to look like data ✓
4. Parametrize disturbtion of angular shape introduced by selection
5. Deal with backgrounds
6. Angular fit of control mode in data
7. ... Systematics, Unblinding, etc.

Start with angular fit model (1) and continue with data (4-6)

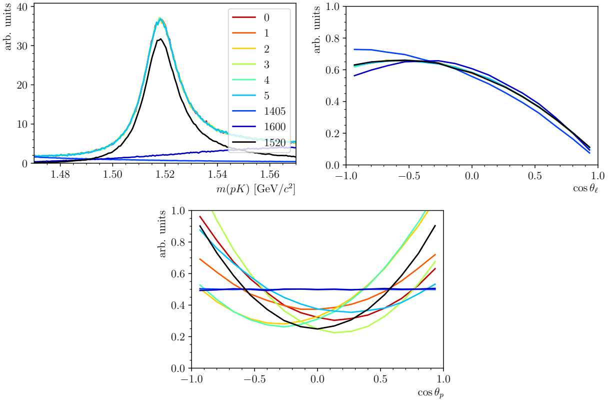
“Realistic“ Monte-Carlo samples

- Pseudo-experiment generator
- Full angular distribution
- Generation of mixture of $\Lambda(1520)$, $\Lambda(1405)$ and $\Lambda(1600)$ resonance
- Resonances might have global complex phases between them
$$\exp(\pm i(\varphi_{1520} - \varphi_{1405}))$$
- Generate random phase combinations for phase differences $\Delta\varphi_{1405/1600}$:

phase combination	$\Delta\varphi_{1405}$	$\Delta\varphi_{1600}$
0	0.00π	0.00π
1	1.38π	1.93π
2	1.10π	1.61π
3	0.43π	0.62π
4	0.06π	1.38π
5	1.41π	0.70π

developed by A.Beck, T.Blake and M.Kreps

How do the distributions change ?



No impact of interferences on $m(pK^-)$ and $\cos\theta_\ell$, but changes shape of $\cos\theta_p$ even with few $\Lambda_{1/2}$ events !

Our angular fit model

Angular PDF of Λ(1520) in HQlimit, of the spin-1/2 Λ resonances, interferences of the three Λ resonances

$$
\begin{aligned}
\mathrm{PDF}_{\mathrm{ang}} = f_{3/2}\Bigg(& \left(1-\frac{1}{2}S_{1cc}\right)\left(1-\cos^2\theta_\ell\right) + S_{1cc}\cos^2\theta_\ell + \frac{4}{3}A^{\ell}_{FB,3/2}\cos\theta_\ell\Bigg) \\
& \times\left(\frac{1}{4}+\frac{3}{4}\cos^2\theta_p\right) \\
& + (1-f_{3/2})\left(\frac{1}{2}(1-K_{1cc})\left(1-\cos^2\theta_\ell\right) + K_{1cc}\cos^2\theta_\ell + \frac{2}{3}A^{\ell}_{FB,1/2}\cos\theta_\ell\right) \\
& \times\left(\frac{3-i_2}{3} + i_1\cos\theta_p + i_2\cos^2\theta_p\right)
\end{aligned}
$$

Our fit strategy

1. Fit pK^- mass spectrum with

$$\text{PDF}_{\text{mass}} = f_{3/2}|\text{BW}_{\text{rel}}(M_{pK}, M_{\Lambda(1520)}, \Gamma_{\Lambda(1520)})|^2 + (1 - f_{3/2})\text{Polynomial}_{o3}(M_{pK}, a_1, a_2, a_3)$$

2. Extract $f_{3/2}$
3. Fit angles ($\cos\theta_\ell$, $\cos\theta_p$) with

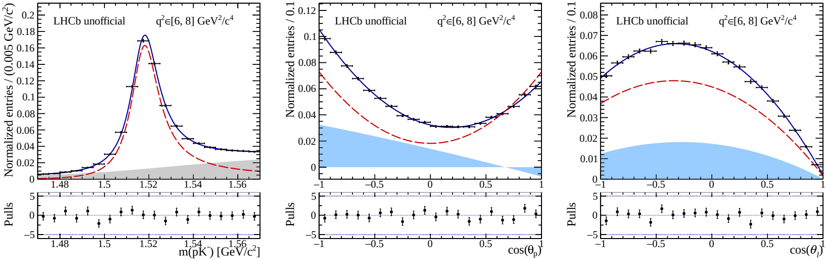
$$\text{PDF}_{\text{ang}} = f_{3/2}\text{PDF}_{\text{ang,3/2}}(A^{\ell}_{FB,3/2}, S_{1cc}) + (1 - f_{3/2})\text{PDF}_{\text{ang,1/2 + int}}(A^{\ell}_{FB,1/2}, K_{1cc}, i_1, i_2)$$

Polynomial covers anything but pure $\Lambda(1520)$

Fit of a realistic sample from MC generator

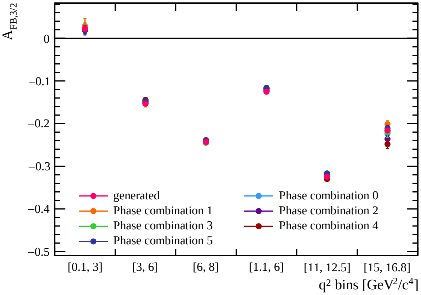
Example fit of realistic MC sample with phase combination 0:

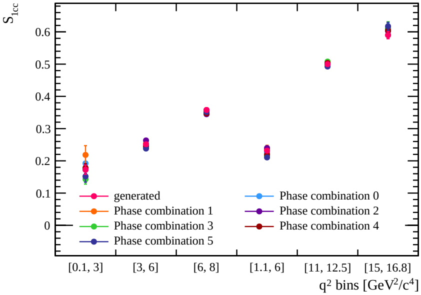
Projection of the $\Lambda(1520)$, $\Lambda_{1/2}$'s, $\Lambda_{1/2}$'s + interferences, total PDF



Fit can get negative due to interferences

Stability of the angular observable fit values





Uncertainties are linked to sample size $\rightarrow$ not scaled to data expectations.
Fit values of angular observables are similar for different phase combinations.

Angular acceptance

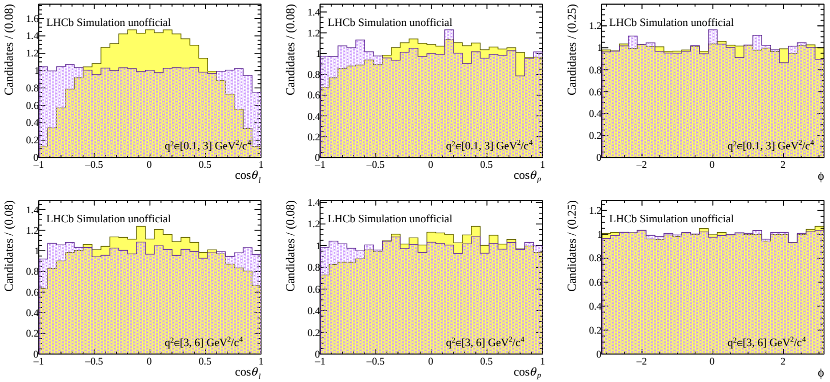
- Parametrize disturbtion of angular distribution
- Use $\Lambda_b \to \Lambda(1520)\mu^+\mu^-$ "LHCb" MC flat in angles
- Full selection and correction are applied
- Model unfactorized angular acceptance via Legendre Polynomials P_ℓ

$$\varepsilon(\cos\theta_\ell, \cos\theta_p, \phi) = P_{\ell,o=6even}(\cos\theta_\ell)P_{\ell,o=4}(\cos\theta_p)P_{\ell,o=10even}(\phi)$$

- Extraction of angular acceptance event weights

Cross-check of angular acceptance event weights

(1 solid) Extract angular acceptance from MC.
(2 line) Applying the inverse of the angular acceptance weights to same MC sample should lead flat distributions.



Flatness test passed ✓

How can we get rid of background ?

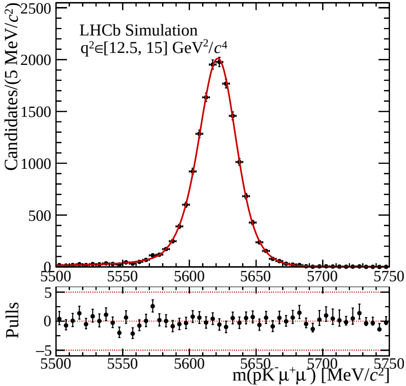
Two possibilities :

1. Model background distribution in angular fit
   - New free parameter
     $\rightarrow$ complicated with few statistics
2. Using sWeight method
   - Fit $m(pK^-\mu^+\mu^-)$ to get event weights
   - Apply weights to get background substracted distribution
   - Necessary to have no correlations between angles/$m(pK^-)$ and $m(pK^-\mu^+\mu^-)$

Gaëlle wants to use method 1, while I'm using method 2

Fitting $m(pK^-\mu^+\mu^-)$ in $\psi(2S)$ region

(1) Shape of Hypatia 2 is fixed to MC (left)
(2) Signal and exponential for combinatorial background fit to data (right)



... My m_{Λ_b} fit on data ..

Hypatia 2 is found to describe well the Λ_b peak

First look at angular fit – starting with $\psi(2S)$ control mode

Prodcedure : sWeighted and acceptance weights applied on angular distributions
Color code : Projection of $\Lambda(1520)$, $\Lambda_{1/2}$'s, $\Lambda_{1/2}$'s + interferences, total PDF

... My angular fit (m_{pK^-}, $\cos\theta_\ell$, $\cos\theta_p$) of the $\psi(2S)$ control mode on data ...

Fit converged ✓
A_{FB}^{ℓ} compatible with 0 in one standard deviation ✓

Conclusion

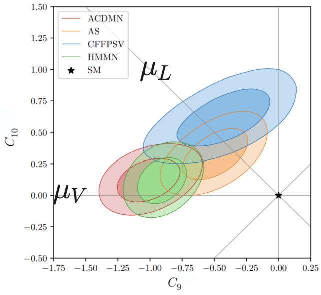
- *b*-anomalies studied mostly in rare meson decays
  $\rightarrow$ Continue further exploration in *b*-baryon decays
- Challenge of $\Lambda_b \rightarrow pK^-\mu^+\mu^-$ is the rich Λ^* spectrum and low statistics
- Selection of signal process is in place
- Angular acceptance is calculated
- sWeights are extracted via $m(pK^-\mu^+\mu^-)$ fit
- Angular fit model is worked out
- Fit to $\psi(2S)$ control mode works

Stay tuned !

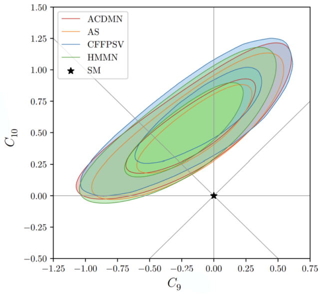
Thank you for your attention !

Global fits to $b \to s\ell^+\ell^-$ transitions

$$\mathcal{L} = N[C_9(\bar{b}_L\gamma^\mu s_L)(\bar{\mu}\gamma_\mu\mu) + C_{10}(\bar{b}_L\gamma^\mu s_L)(\bar{\mu}\gamma^5\gamma_\mu\mu)] + H.c.$$



global fit



fit to LFU observables + $B_s \to \mu\mu$

Consistent deviation with respect to SM prediction

2104.08921; 2103.13370; 2011.01212; 2104.10058

Angular PDF of $\Lambda_{3/2}$ (i.e. $\Lambda(1520)$) in HQlimit

Simplifications :

1. Heavy quark limit ($m_b \to \infty$)
2. Normalization ($\frac{d\Gamma}{dq^2} = 1$):
   $12L_{1cc} + L_{1ss} = 1$
   $A^{\ell}_{FB,3/2} = 34L_{1c}$
3. CP-average ($L_i \to S_i$)

$$\frac{8\pi}{3}\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_{\Lambda^*} d\phi}$$
$$= \cos^2\theta_{\Lambda^*}\left(L_{1c}\cos\theta_\ell + L_{1cc}\cos^2\theta_\ell + L_{1ss}\sin^2\theta_\ell\right)$$
$$+ \sin^2\theta_{\Lambda^*}\left(L_{2c}\cos\theta_\ell + L_{2cc}\cos^2\theta_\ell + L_{2ss}\sin^2\theta_\ell\right)$$
$$+ \sin^2\theta_{\Lambda^*}\left(L_{3ss}\sin^2\theta_\ell\cos^2\phi + L_{4ss}\sin^2\theta_\ell\sin\phi\cos\phi\right)$$
$$+ \sin\theta_{\Lambda^*}\cos\theta_{\Lambda^*}\cos\phi(L_{5s}\sin\theta_\ell + L_{5sc}\sin\theta_\ell\cos\theta_\ell)$$
$$+ \sin\theta_{\Lambda^*}\cos\theta_{\Lambda^*}\sin\phi(L_{6s}\sin\theta_\ell + L_{6sc}\sin\theta_\ell\cos\theta_\ell),$$

arXiv:1903.00448, arXiv:2005.09602

$$\frac{8\pi}{3}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_\ell\mathrm{d}\cos\theta_p\mathrm{d}\phi} \simeq \frac{1}{4}\left(1 + 3\cos^2\theta_p\right)\left(\left(1 - \frac{1}{2}S_{1cc}\right)\left(1 - \cos^2\theta_\ell\right) + S_{1cc}\cos^2\theta_\ell + \frac{4}{3}A^{\ell}_{FB,3/2}\cos\theta_\ell\right)$$

Angular PDF is only dependent on $\cos\theta_\ell$ and $\cos\theta_p$.
ϕ integration, instead of using the HQlimit, is under investigation.

Angular PDF of $\Lambda_{1/2}$ (i.e. $\Lambda(1405)$, $\Lambda(1600)$)

Simplifications :

1. Strong decay : $\alpha = 0$
2. Normalization: $K_{1cc} + 2K_{1ss} = 1$ $A^{\ell}_{FB,1/2} = 3/2K_{1c}$
3. CP-average

$$K(q^2, \cos\theta_\ell, \cos\theta_\Lambda, \phi) \equiv \frac{8\pi}{3} \frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_\Lambda\,\mathrm{d}\phi},$$

which can be decomposed in terms of a set of trigonometric functions,

$$K(q^2, \cos\theta_\ell, \cos\theta_\Lambda, \phi) = (K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell)$$

~~$+ (K_{2ss}\sin^2\theta_\ell + K_{2cc}\cos^2\theta_\ell + K_{2c}\cos\theta_\ell)\cos\theta_\Lambda$~~

~~$+ (K_{3sc}\sin\theta_\ell\cos\theta_\ell + K_{3s}\sin\theta_\ell)\sin\theta_\Lambda\sin\phi$~~

~~$+ (K_{4sc}\sin\theta_\ell\cos\theta_\ell + K_{4s}\sin\theta_\ell)\sin\theta_\Lambda\cos\phi\,.$~~

arXiv:1410.2115

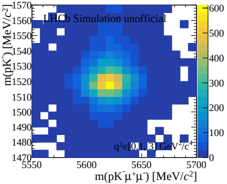
$$\frac{8\pi}{3}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_\ell\mathrm{d}\cos\theta_p\mathrm{d}\phi} \simeq \frac{1}{2}\left(1 - K_{1cc}\right)\left(1 - \cos^2\theta_\ell\right) + K_{1cc}\cos^2\theta_\ell + \frac{2}{3}A^{\ell}_{FB,1/2}\cos\theta_\ell$$

Angular PDF is only dependent on $\cos\theta_\ell$.

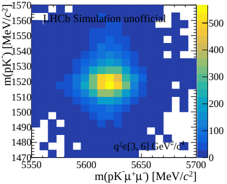
K parameter encode information about $\Lambda_{1/2}$ resonances in m_{pK} window.

Linear correlation

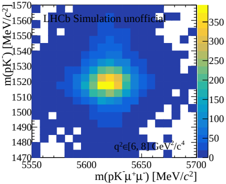
Pearson correlation coefficient of angles and $m(pK^-\mu^+\mu^-)$ < 2%.
Biggest correlation between $m(pK^-\mu^+\mu^-)$ and $m(pK^-)$:



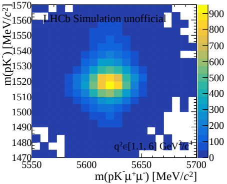
(a) 0.0411



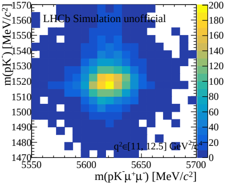
(b) 0.0134



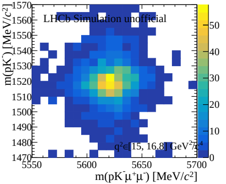
(c) 0.0201



(d) 0.0307



(e) 0.0121

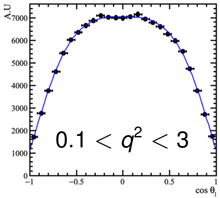


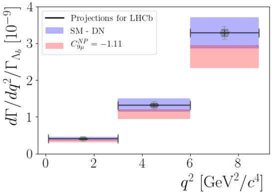
(f) 0.0180

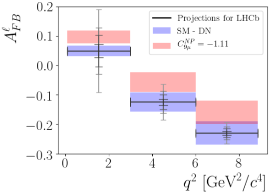
Correlations of up to 4 %, therefore sWeight procedure doable

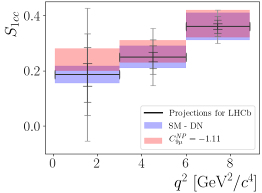
Sensitivity study arXiv:2005.09602

- Yield extrapolated from R_{pK}
- Background neglected
- PDF $=$ physics $\times$ acceptance
- Generate pseudo-experiments
- Fit with same PDF and free A_{FB}^{ℓ} & S_{1cc}
- 10'000 times repeated per run period and q^2 bin







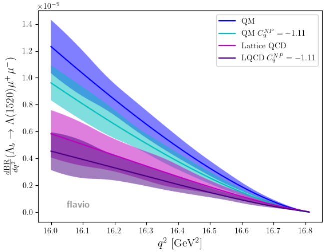


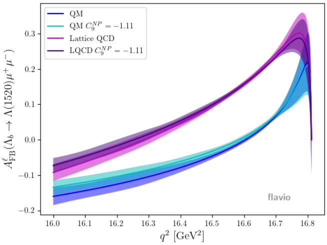
LHCb could start to be sensitive to New Physics with full Run 1+2, especially when theoretical uncertenties improve.

Implementation of angular observables in flavio

- Implemented angular observables:
  1. $d\Gamma/dq^2$
  2. A_{FB}, F_{L}
  3. CP-averaged, CP-asymmetries
- Form factors from full Quark Model wave function arXiv:1108.6129
- Using 10% uncertainty on $f_{0,\perp,t}$ form factors and 30% on f_g as in arXiv:1903.00448
- In addition, LQCD form factors arXiv:2009.09313v3

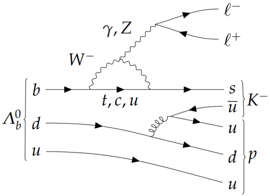
Discrepancy between LQCD form factors and Quark model ones at high q^2!





Exploring $\Lambda_b^0 \to \Lambda^{*0}(\to pK^-)\ell^+\ell^-$

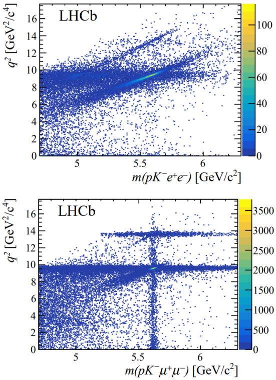
Feynman diagram



Experimental status

- $\Lambda_b^0 \to pK^-\mu^+\mu^-$ observation & CPV measurement arXiv:1703.00256
- $\Lambda_b^0 \to pK^-e^+e^-$ observation JHEP 05 2020 (040)
- LFU test R_{pK^-} JHEP 05 2020 (040)

R_{pK^-} analysis



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