$\Lambda_b \to \Lambda(1520)\mu^+\mu^-$ angular analysis

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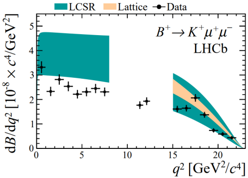
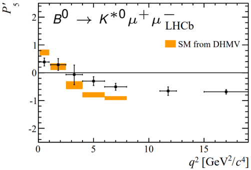
Flavor at the Crossroads

April 26th, 2022

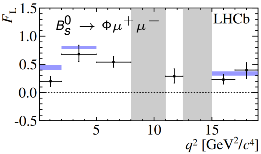
Rare decays show deviations from the SM predictions



arXiv:1403.8044v3

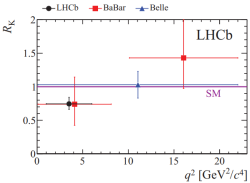


arXiv:1512.04442

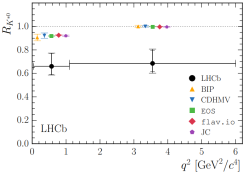


arXiv:1506.08777

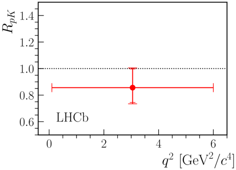
Differential branching ratios and angular observables



doi: 10.1393/ncc/i2017-17171-9



arXiv:1705.05802

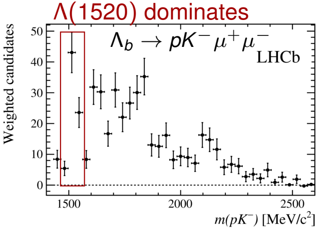


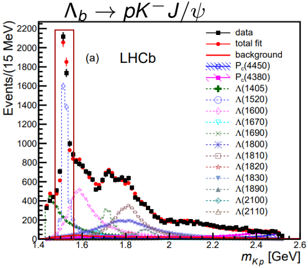
LHCb Paper 2018 040

Lepton Flavour Universality (LFU) tests

Only few measurements with *b*-baryon decays

$\Lambda_b \to pK^-\mu^+\mu^-$





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

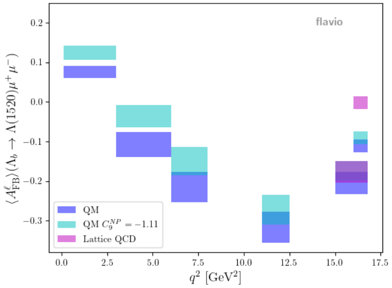
Particle	J^P	Overall status	Status as seen in — $N\overline{K}$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	$1/2^+$	****			$N\pi$ (weak decay)
$\Lambda(1380)$	$1/2^-$	**	**	**	
$\Lambda(1405)$	$1/2^-$	****	****	****	
$\Lambda(1520)$	$3/2^-$	****	****	****	$\Lambda\pi\pi$, $\Lambda\gamma$
$\Lambda(1600)$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

PDG Live

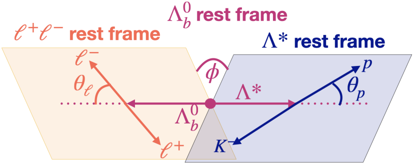
$\Lambda(1405)$ and $\Lambda(1600)$ under $\Lambda(1520)$ mass peak

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 $\Lambda_b \to pK^-\ell^+\ell^-$ phenomenology with lattice QCD or QM form-factors [arXiv:1903.00448, arXiv.1108.6129, arXiv:2009.09313]



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 → short distance part → sensitive to NP
ff = form factors → long distance part

Observables :

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

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

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

Simplifications :

1. Heavy quark limit ($m_b \to \infty$)
2. Normalization ($\frac{d\Gamma}{dq^2} = 1$):
   $^1/_2 L_{1cc} + L_{1ss} = 1$
   $A^{\ell}_{FB,3/2} = {}^3/_4 L_{1c}$
3. CP-average ($L_i \to S_i$)

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

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: $K_{1cc} + 2K_{1ss} = 1$; $A^{\ell}_{FB,1/2} = 3/2 K_{1c}$
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

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

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

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

Modeling the $\Lambda(1520)$ mass peak

Difficulty to estimate fraction of $\Lambda(1520)$ events $f_{3/2}$ from an angular fit only
$\rightarrow$ get $f_{3/2}$ by fitting the $m(pK^-)$ spectrum

$\Lambda_b \rightarrow \Lambda(1520)\mu^+\mu^-$ MC underlines need of relativistic Breit-Wigner :

$$|\mathrm{BW_{rel}}(M_{pK}, M_{\Lambda^*}, \Gamma_{\Lambda^*})|^2 = \left[\left(\frac{q(M_{pK})}{q(M_{\Lambda^*})} \right)^{L_{\Lambda_b \to \Lambda^* \mu\mu}} \left(\frac{p(M_{pK})}{p(M_{\Lambda^*})} \right)^{L_{\Lambda^* \to pK}} \right.$$

$$\left. \times\, F_{\Lambda_b \to \Lambda^* \mu\mu}(q(M_{pK}), q(M_{\Lambda^*}, r_{\Lambda_b})) \frac{F_{\Lambda^* \to pK}(p(M_{pK}), p(M_{\Lambda^*}), r_{\Lambda^*})}{M_{\Lambda^*}^2 - M_{pK}^2 - iM_{\Lambda^*}\Gamma(M_{pK}, M_{\Lambda^*})} \right]^2$$

$$\Gamma(M_{pK}, M_{\Lambda^*}) = \Gamma_{\Lambda}^* \left(\frac{p(M_{pK})}{p(M_{\Lambda^*})} \right)^{2L_{\Lambda^* \to pK}+1} \frac{M_{\Lambda^*}}{M_{pK}} F_{\Lambda^* \to pK}^2(p(M_{pK}), p(M_{\Lambda}^*))$$

p, q	Λ^*, K^- momentum in Λ_b, Λ^* restframe
F	Blatt-Weißkopf form factors
r_{Λ_b}, r_{Λ^*}	Interaction radius of the Λ_b, Λ^*
$L_{\Lambda^* \to pK}$	orbital angular momentum between p and K^- in the $\Lambda^* \rightarrow pK^-$ decay
$L_{\Lambda_b \to \Lambda^* \mu\mu}$	orbital angular momentum between Λ^* and the dimuon system in the $\Lambda_b \rightarrow \Lambda^* \mu\mu$ decay
M_{Λ^*}, Γ_{Λ^*}	pole mass and width of Λ^*

Fit strategy / physics PDF

1. Fit pK^- spectrum with

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

   by fixing $M_{\Lambda(1520)}$ and $\Gamma_{\Lambda(1520)}$ to their PDG value, $L_{\Lambda_b \to \Lambda^* \mu\mu} = 1$, $L_{\Lambda^* \to pK} = 2$, $r_{\Lambda_b} = 5\,\mathrm{GeV}^{-1}$, $r_{\Lambda^*} = 3\,\mathrm{GeV}^{-1}$
2. Extract $f_{3/2}$
3. Fit angles ($\cos\theta_\ell$, $\cos\theta_p$) with

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

Angular acceptance is not included here, but studies are on-going

Realistic samples

- Generator developed by A.Beck, T.Blake and M.Kreps
- Full angular distribution without angular acceptance is worked out
- Generation of single resonances and combinations of several resonances
- Resonances might have global complex phases between them
- Only phase differences important
- Generate random phase combinations for phase differences $\Delta\psi_{1405/1600}$:

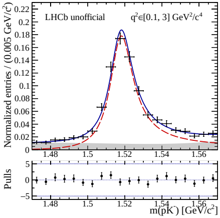
phase combination	$\Delta\psi_{1405}$	$\Delta\psi_{1600}$
0	0.00π	0.00π
1	1.38π	1.93π
2	1.10π	1.61π
3	0.43π	0.62π
4	0.06π	1.38π
5	1.41π	0.70π

Fit realistic samples

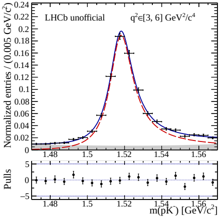
1. Fit mixture of three individual resonances, namely the $\Lambda(1405)$, $\Lambda(1520)$ and $\Lambda(1600)$
   - ✓ $f_{3/2}$ is known
   - ✓ No interference
   - ✓ Validation of fit model without interferences
2. Fit samples with random phase combinations
   - × $f_{3/2}$ is à priori not known
   - ✓ Interferences of $\Lambda(1405)$, $\Lambda(1520)$ and $\Lambda(1600)$ are included
   - ✓ Adapt fit model

Color code : distribution of the $\Lambda(1520)$, $\Lambda(1405) + \Lambda(1600)$, total PDF

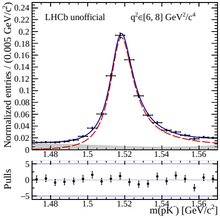
The $m(pK^-)$ fit



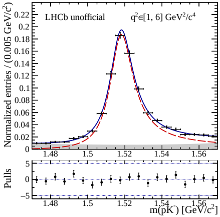
(a) $f^{fit}_{3/2}$ ✓



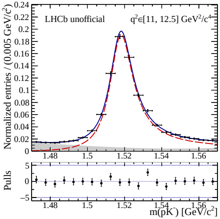
(b) 3σ away from $f^{true}_{3/2}$



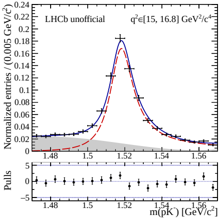
(c) 4σ away from $f^{true}_{3/2}$



(d) 3σ away from $f^{true}_{3/2}$



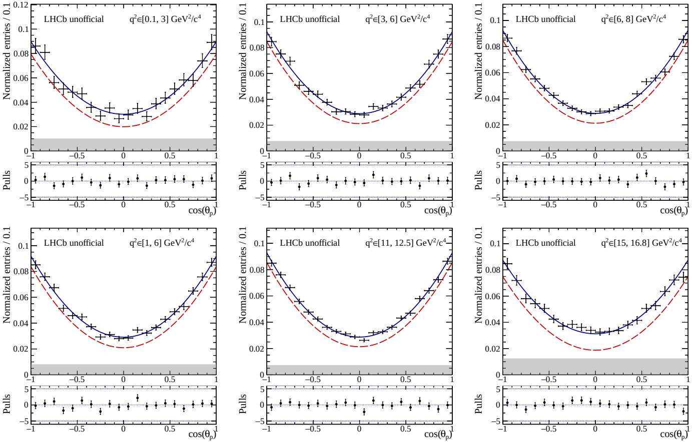
(e) 6σ away from $f^{true}_{3/2}$



(f) 5σ away from $f^{true}_{3/2}$

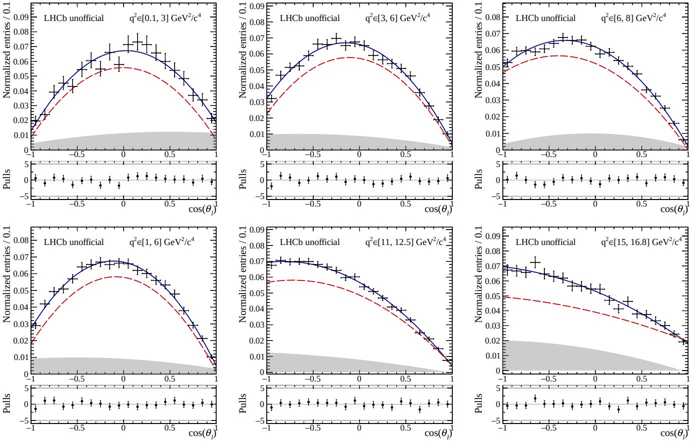
Bias via slightly higher $f^{fit}_{3/2}$ values $\rightarrow$ bias has to be corrected for

Angular fit of $\Lambda_{1/2} + \Lambda_{3/2}$ mixture without interferences



All the fits converge nicely and the $\cos\theta_p$ projections look good

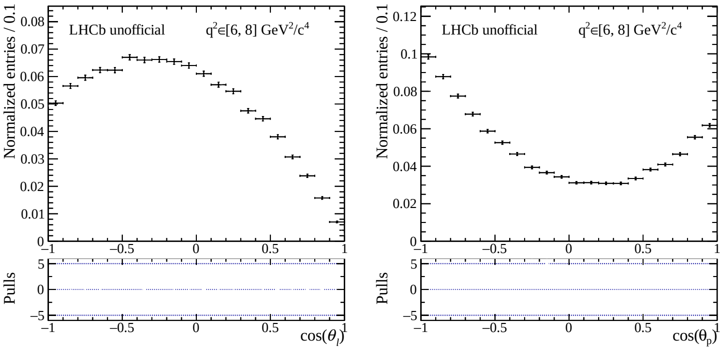
Angular fit of $\Lambda_{1/2} + \Lambda_{3/2}$ mixture without interferences



$\cos\theta_\ell$ projections looks good as well

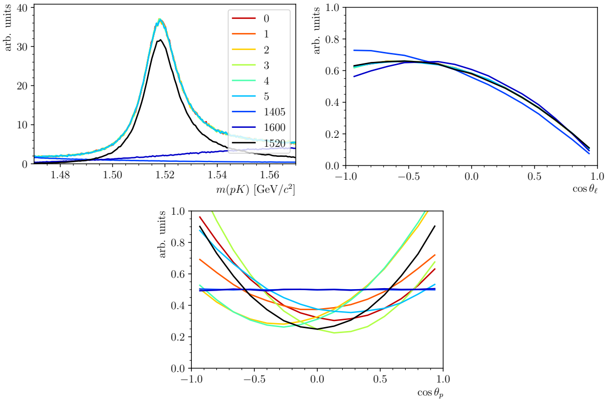
Shape of realistic samples with interference

Phase combination 0 :



With interferences asymmetry in $\cos\theta_p$, but our PDF symmetric.
Need of asymmetric terms in $\cos\theta_p$.

Recall from Anja



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 !

Update angular fit model

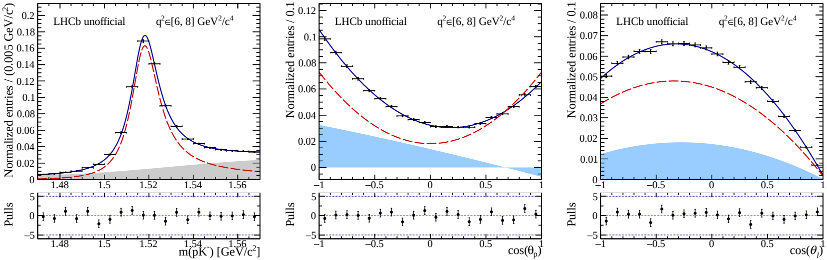
Adding interference terms proportional to $\cos\theta_p$ and $\cos^2\theta_p$ to the angular PDF of the $\Lambda_{1/2}$ resonances.

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

Color code : distribution of the $\Lambda(1520)$, ~~$\Lambda(1405)+\Lambda(1600)$~~, $\Lambda(1405)+\Lambda(1600)+$ interferences of 3 resonances, total PDF

Fit realistic samples with updated angular fit model

Phase combination 0:

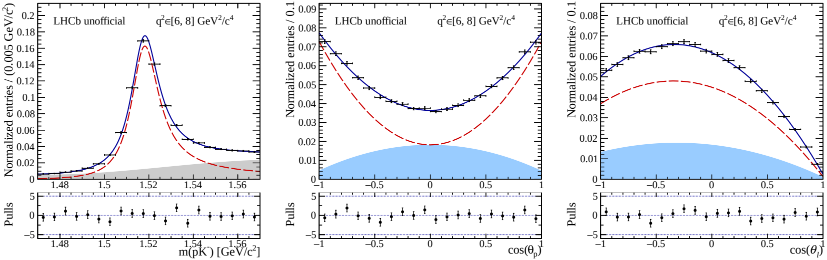


New interference term can catch the asymmetric shape.

Since interference term added to the $\Lambda_{1/2}$ PDF, it can get negative.

Fit realistic samples

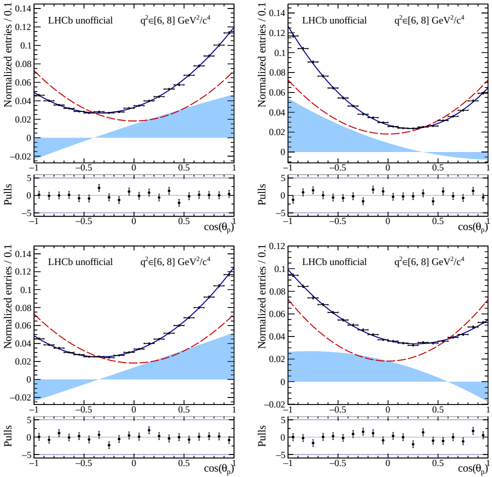
Phase combination 1:



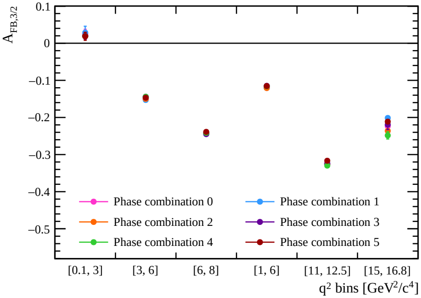
Only the distribution of $\cos\theta_p$ changes, $m(pK^-)$ and $\cos\theta_\ell$ stay the same.

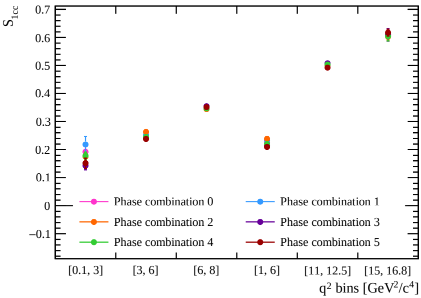
Fit realistic samples

Phase combination 2, 3, 4 and 5:



Verification of observables stability

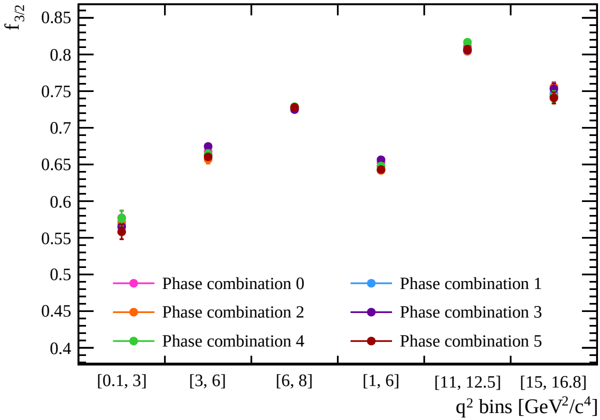




Observable values from the fit are similar for different phase combinations

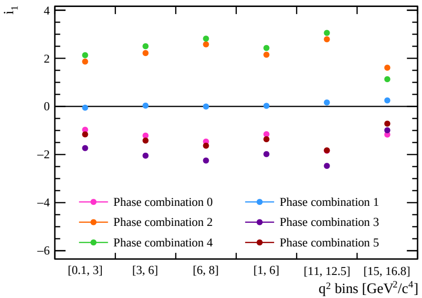
Uncertainties are linked to sample size → not scaled

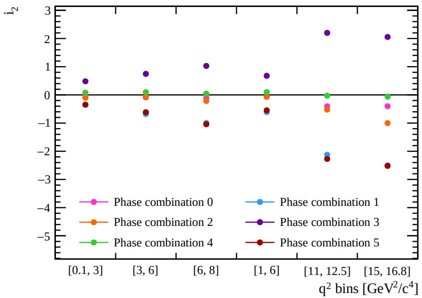
Checking differences in $f_{3/2}$



Small deviations of $f_{3/2}$ found

Strength of interference terms





Interferences are treated as nuisance parameters

Conclusion

- ✓ Validation of physics PDF without interference terms
- ✓ Set up of physics PDF including interference terms
- ✓ Resulting fit values of the observables are the same for all the samples with different phase combinations
- ☐ Estimation of bias on fit fraction from $m(pK^-)$ fit
- ☐ Scaling the samples to Run 1+2 yields and redo the fit
- ☐ Add angular acceptance
- ☐ Fit to control mode
- ☐ Systematic uncertainties
- ☐ ...

Thank you for your attention !

Blatt-Weißkopf form factors

$$B'_0(p, p_0, d) = 1\,,$$

$$B'_1(p, p_0, d) = \sqrt{\frac{1 + (p_0\,d)^2}{1 + (p\;\;d)^2}}\,,$$

$$B'_2(p, p_0, d) = \sqrt{\frac{9 + 3(p_0\,d)^2 + (p_0\,d)^4}{9 + 3(p\;\;d)^2 + (p\;\;d)^4}}\,,$$

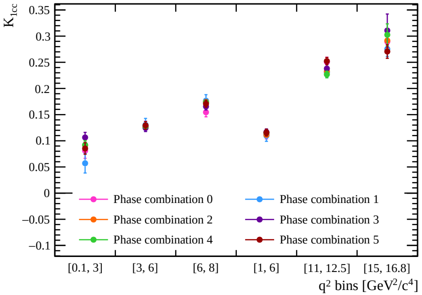
$$B'_3(p, p_0, d) = \sqrt{\frac{225 + 45(p_0\,d)^2 + 6(p_0\,d)^4 + (p_0\,d)^6}{225 + 45(p\;\;d)^2 + 6(p\;\;d)^4 + (p\;\;d)^6}}\,,$$

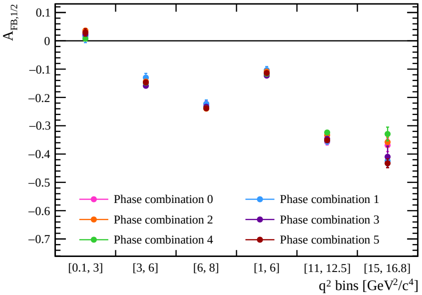
$$B'_4(p, p_0, d) = \sqrt{\frac{11025 + 1575(p_0\,d)^2 + 135(p_0\,d)^4 + 10(p_0\,d)^6 + (p_0\,d)^8}{11025 + 1575(p\;\;d)^2 + 135(p\;\;d)^4 + 10(p\;\;d)^6 + (p\;\;d)^8}}\,,$$

$$B'_5(p, p_0, d) = \sqrt{\frac{893025 + 99225(p_0\,d)^2 + 6300(p_0\,d)^4 + 315(p_0\,d)^6 + 15(p_0\,d)^8 + (p_0\,d)^{10}}{893025 + 99225(p\;\;d)^2 + 6300(p\;\;d)^4 + 315(p\;\;d)^6 + 15(p\;\;d)^8 + (p\;\;d)^{10}}}\,,$$

from LHCb-ANA-2013-053

K_{1cc} and $A^{\ell}_{FB,1/2}$





Uncertainties are linked to sample size $\rightarrow$ not scaled !

Minuit output

```
RooMinimizerFcn: Minimized function has error status.
Returning maximum FCN so far (129656) to force MIGRAD to back out of this region. Error log
follows.
Parameter values:        AFB=-0.250593    AFBOneHalf=-0.232013     K1cc=0.175359
S1cc=0.323543    i1=-0.981721     i2=-0.960783
PID28680/
RooRealMPFE::nll_AngularPdf_full_data_a136c70_MPFE5[ arg=nll_AngularPdf_full_data_GOF5
vars=(AFB,AFBOneHalf,K1cc,S1cc,ThreeHalfFrac,i1,i2,ml,qSquared) ]
    p.d.f value of (AngularPdf) is less than zero (-0.001624) for entry 2447 @ !
refCoefNorm=(), !pdfs=(dGThreeHalfPdf = 0.209557/1.33333,dGOneHalfPdf =
0.41232/0.906319), !coefficients=(ThreeHalfFrac = 0.727957 +/- 0.0049118)
    p.d.f value of (AngularPdf) is less than zero (-0.003250) for entry 3656 @ !
refCoefNorm=(), !pdfs=(dGThreeHalfPdf = 0.209557/1.33333,dGOneHalfPdf =
0.41232/0.906319), !coefficients=(ThreeHalfFrac = 0.727957 +/- 0.0049118)
    p.d.f value of (AngularPdf) is less than zero (-0.001624) for entry 2447 @ !
refCoefNorm=(), !pdfs=(dGThreeHalfPdf = 0.209557/1.33333,dGOneHalfPdf =
0.41232/0.906319), !coefficients=(ThreeHalfFrac = 0.727957 +/- 0.0049118)
    p.d.f value of (AngularPdf) is less than zero (-0.003250) for entry 3656 @ !
refCoefNorm=(), !pdfs=(dGThreeHalfPdf = 0.209557/1.33333,dGOneHalfPdf =
0.41232/0.906319), !coefficients=(ThreeHalfFrac = 0.727957 +/- 0.0049118)
    p.d.f value of (AngularPdf) is less than zero (-0.010652) for entry 840 @ !
refCoefNorm=(), !pdfs=(dGThreeHalfPdf = 0.209557/1.33333,dGOneHalfPdf =
0.41232/0.906319), !coefficients=(ThreeHalfFrac = 0.727957 +/- 0.0049118)
    p.d.f value of (AngularPdf) is less than zero (-0.009655) for entry 1407 @ !
refCoefNorm=(), !pdfs=(dGThreeHalfPdf = 0.209557/1.33333,dGOneHalfPdf =
0.41232/0.906319), !coefficients=(ThreeHalfFrac = 0.727957 +/- 0.0049118)
    p.d.f value of (AngularPdf) is less than zero (-0.010652) for entry 840 @ !
refCoefNorm=(), !pdfs=(dGThreeHalfPdf = 0.209557/1.33333,dGOneHalfPdf =
0.41232/0.906319), !coefficients=(ThreeHalfFrac = 0.727957 +/- 0.0049118)
    p.d.f value of (AngularPdf) is less than zero (-0.009655) for entry 1407 @ !
refCoefNorm=(), !pdfs=(dGThreeHalfPdf = 0.209557/1.33333,dGOneHalfPdf =
0.41232/0.906319), !coefficients=(ThreeHalfFrac = 0.727957 +/- 0.0049118)
    p.d.f value of (AngularPdf) is less than zero (-0.004703) for entry 532 @ !
refCoefNorm=(), !pdfs=(dGThreeHalfPdf = 0.209557/1.33333,dGOneHalfPdf =
0.41232/0.906319), !coefficients=(ThreeHalfFrac = 0.727957 +/- 0.0049118)
    p.d.f value of (AngularPdf) is less than zero (-0.004703) for entry 532 @ !
refCoefNorm=(), !pdfs=(dGThreeHalfPdf = 0.209557/1.33333,dGOneHalfPdf =
0.41232/0.906319), !coefficients=(ThreeHalfFrac = 0.727957 +/- 0.0049118)
RooNLLVar::nll_AngularPdf_full_data[ paramSet=(AFB,AFBOneHalf,K1cc,S1cc,ThreeHalfFrac,i1,i2
,ml,qSquared) ]
    function value is NAN @ paramSet=(AFB = -0.250593,AFBOneHalf = -0.232013,K1cc =
0.175359,S1cc = 0.323543,ThreeHalfFrac = 0.727957 +/- 0.0049118,i1 = -0.981721,i2 =
-0.960783,ml = 0,qSquared = 7)

MIGRAD MINIMIZATION HAS CONVERGED.
MIGRAD WILL VERIFY CONVERGENCE AND ERROR MATRIX.
COVARIANCE MATRIX CALCULATED SUCCESSFULLY
FCN=88213.5 FROM MIGRAD    STATUS=CONVERGED     522 CALLS         523 TOTAL
                     EDM=7.81173e-06    STRATEGY= 2      ERROR MATRIX ACCURATE
```

```
**********
COVARIANCE MATRIX CALCULATED SUCCESSFULLY
FCN=88213.5 FROM HESSE     STATUS=OK             40 CALLS         563 TOTAL
                     EDM=7.81718e-06    STRATEGY= 2      ERROR MATRIX ACCURATE
 EXT PARAMETER                                INTERNAL      INTERNAL
 NO.   NAME      VALUE            ERROR       STEP SIZE       VALUE
  1  AFB        -2.38781e-01   4.01788e-03   2.33974e-05  -2.41111e-01
  2  AFBOneHalf -2.38269e-01   8.37365e-03   4.77853e-05  -2.40584e-01
  3  K1cc        1.70811e-01   6.72561e-03   9.94670e-05  -7.18662e-01
  4  S1cc        3.51643e-01   6.51424e-03   7.75063e-05  -3.01250e-01
  5  i1         -1.21203e+00   2.48641e-02   9.59349e-05  -6.51038e-01
  6  i2         -7.72697e-01   2.58713e-02   8.60677e-05  -2.74492e+00
                               ERR DEF= 0.5
EXTERNAL ERROR MATRIX.    NDIM=  25    NPAR=  6    ERR DEF=0.5
 1.614e-05 -1.635e-05  8.415e-06 -1.628e-05 -2.670e-07  1.615e-08
-1.635e-05  7.012e-05 -3.610e-05  1.683e-05  7.111e-07 -2.382e-08
 8.415e-06 -3.610e-05  4.524e-05 -2.098e-05  1.158e-06  2.142e-06
-1.628e-05  1.683e-05 -2.098e-05  4.244e-05 -8.081e-07 -1.823e-06
-2.670e-07  7.111e-07  1.158e-06 -8.081e-07  6.183e-04  4.267e-04
 1.615e-08 -2.382e-08  2.142e-06 -1.823e-06  4.267e-04  6.694e-04
PARAMETER  CORRELATION COEFFICIENTS
      NO.  GLOBAL      1      2      3      4      5      6
       1  0.72477   1.000 -0.486  0.311 -0.622 -0.003  0.000
       2  0.73741  -0.486  1.000 -0.641  0.308  0.003 -0.000
       3  0.73471   0.311 -0.641  1.000 -0.479  0.007  0.012
       4  0.72180  -0.622  0.308 -0.479  1.000 -0.005 -0.011
       5  0.66336  -0.003  0.003  0.007 -0.005  1.000  0.663
       6  0.66341   0.000 -0.000  0.012 -0.011  0.663  1.000
[#1] INFO:Minization -- RooMinimizer::optimizeConst: deactivating const optimization

>>> ANGULAR FIT RESULT :
Refit =  False , Failed =  False , Minuit Status =  0 , AtLimit =  False


 RooFitResult: minimized FCN value: 88213.5, estimated distance to minimum: 7.81718e-06
               covariance matrix quality: Full, accurate covariance matrix
               Status : MINIMIZE=0 HESSE=0

   Floating Parameter    FinalValue +/-  Error
 --------------------  --------------------------
                  AFB   -2.3878e-01 +/-  4.02e-03
           AFBOneHalf   -2.3827e-01 +/-  8.37e-03
                 K1cc    1.7081e-01 +/-  6.73e-03
                 S1cc    3.5164e-01 +/-  6.51e-03
                   i1   -1.2120e+00 +/-  2.49e-02
                   i2   -7.7270e-01 +/-  2.59e-02
```