

# Towards the angular analysis of $\Lambda_b \rightarrow \Lambda(1520)\mu^+\mu^-$ at LHCb

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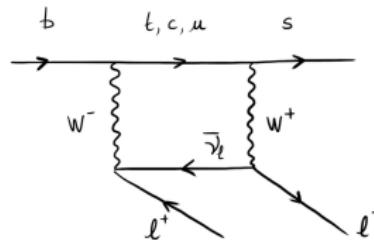
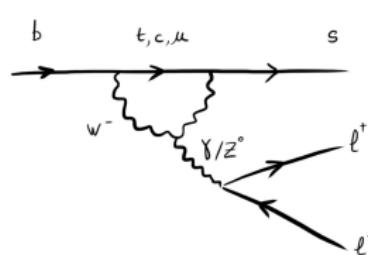


GDR-InF annual workshop

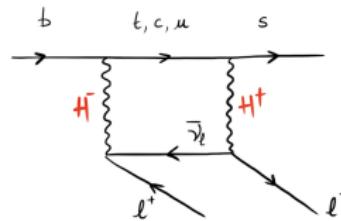
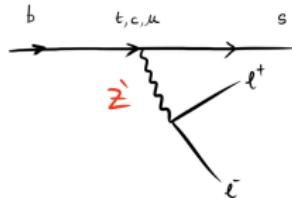
November 16th, 2021

# Why are rare decays interesting ?

$b \rightarrow s l^+ l^-$  transitions suppressed in Standard Model



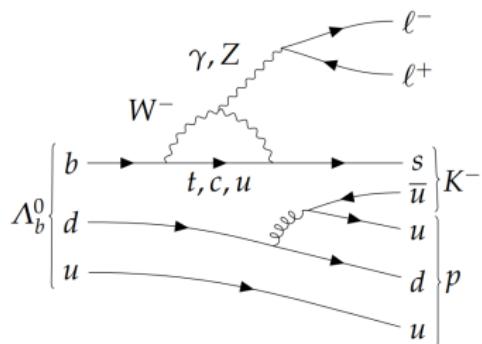
New Physics processes could contribute



drawn by Yasmine

Only few measurements of rare  $b$ -baryon decays !

# Our favorite decay : $\Lambda_b \rightarrow p K^- \mu^+ \mu^-$



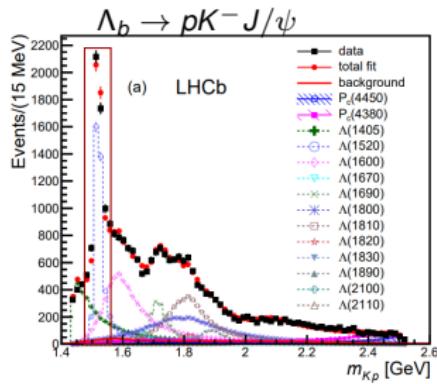
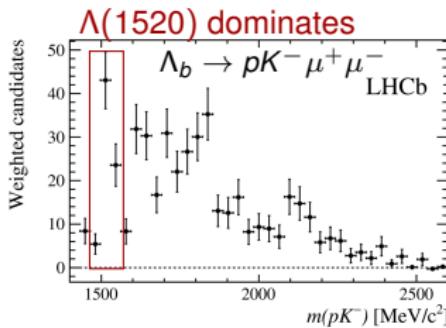
CDS:2699822 (top) PDG Live (right)

**Strong decay of  $\Lambda^* \rightarrow p K^-$**

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

Rich  $\Lambda^*$  spectrum

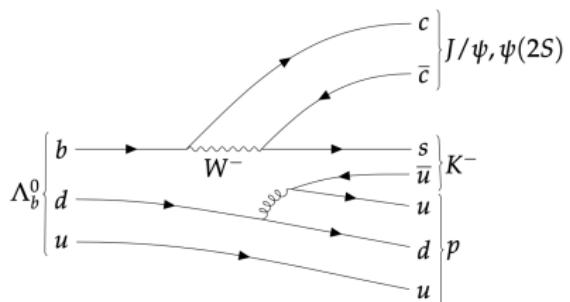
# How does the $pK^-$ mass spectrum look like ?



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  $\Lambda_b \rightarrow pK^- J/\psi (\rightarrow \mu^+\mu^-)$  on lower left.

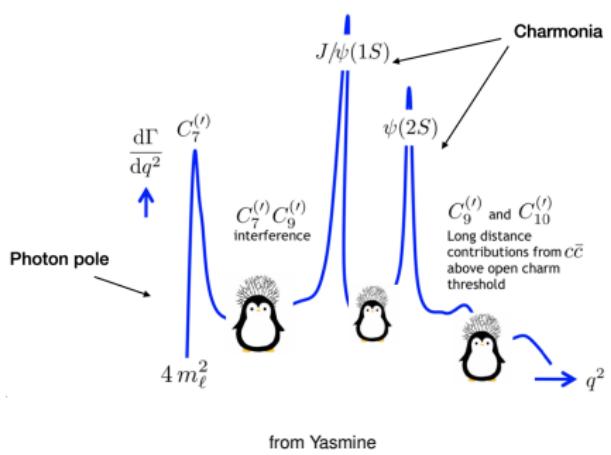


CDS:2699822

Idea is focusing on dominating  $\Lambda(1520)$  resonance.

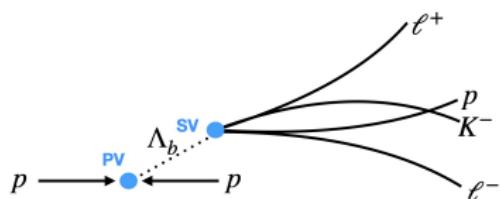
# Selection of the $\Lambda_b \rightarrow \Lambda(1520)\mu^+\mu^-$ decay

Distinguish rare mode from  $c\bar{c}$  resonances via  $q^2 = (2m_\ell)^2$ :



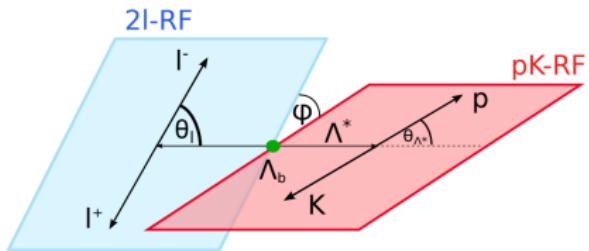
The rare mode is sensitive to New Physics !

Decay topology :

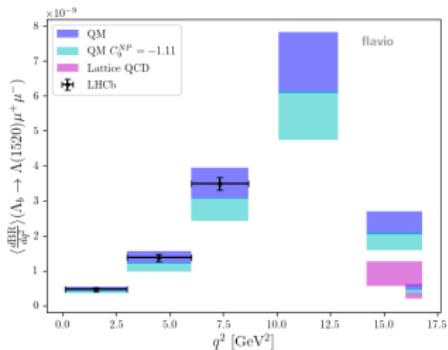


Detached  $\Lambda_b$  decay vertex (secondary vertex), where all the traces come from.

# Angular observables



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



$$\begin{aligned}d\vec{\Omega} &= d \cos \theta_\ell d \cos \theta_p d\phi \\ \frac{d^4 \Gamma}{dq^2 d\vec{\Omega}} &= \sum_i \text{physics}_i \times \text{kinematics}_i \\ &= \frac{9\pi}{32} \sum_i \text{L}_i(q^2, \mathcal{C}, ff) \times f_i(\vec{\Omega})\end{aligned}$$

$\mathcal{C}$  = Wilson Coefficients → short distance part → sensitive to NP

$ff$  = form factors → long distance part

Observables :

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

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

## Simplifications :

- ① Heavy quark limit  
 $(m_b \rightarrow \infty)$

- ② Normalization:

$$1/2S_{1cc} + S_{1ss} = 1$$
$$A_{FB,3/2}^\ell = 3/4S_{1c}$$

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

arXiv:1903.00448, arXiv:2005.09602

$$\begin{aligned} \frac{8\pi}{3} \frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_p d\phi} &\simeq \frac{1}{4} (1 + 3\cos^2\theta_p) \left( \left(1 - \frac{1}{2}S_{1cc}\right) (1 - \cos^2\theta_\ell) \right. \\ &\quad \left. + S_{1cc}\cos^2\theta_\ell + \frac{4}{3}A_{FB,3/2}^\ell \cos\theta_\ell \right) \end{aligned}$$

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

# Angular PDF of $\Lambda_{1/2}$ (i.e. $\Lambda(1405)$ , $\Lambda(1600)$ , $\Lambda(1800)$ )

## Simplifications :

- 1 Strong decay :

$$\alpha = 0$$

- 2 Normalization:

$$K_{1cc} + 2K_{1ss} = 1$$
$$A_{FB,1/2}^\ell = 3/2K_{1c}$$

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

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

$$\frac{8\pi}{3} \frac{d^4\Gamma}{dq^2 d \cos \theta_\ell d \cos \theta_\Lambda d\phi} \simeq \frac{1}{2} (1 - K_{1cc}) (1 - \cos^2 \theta_\ell) + K_{1cc} \cos^2 \theta_\ell$$
$$+ \frac{2}{3} A_{FB,1/2}^\ell \cos \theta_\ell$$

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

# Total 3-dimensional PDF

$$\text{PDF}_{\text{physics}} = f_{3/2} \text{PDF}_{\text{angular},3/2} \text{PDF}_{\text{mass},3/2} + (1 - f_{3/2}) \text{PDF}_{\text{angular},1/2} \text{PDF}_{\text{mass},1/2}$$

$$\begin{aligned}\text{PDF}_{\text{physics}} &= \frac{f_{3/2}}{4} (1 + 3 \cos^2 \theta_p) \left( \left( 1 - \frac{1}{2} S_{1cc} \right) (1 - \cos^2 \theta_\ell) \right. \\ &\quad \left. + S_{1cc} \cos^2 \theta_\ell + \frac{4}{3} A_{FB,3/2}^\ell \cos \theta_\ell \right) \times \text{BW}_{\text{nrel}}(M_{pK}, M_{\Lambda^*}, W_{\Lambda^*}) \\ &\quad + (1 - f_{3/2}) \left( \frac{1}{2} (1 - K_{1cc}) (1 - \cos^2 \theta_\ell) + K_{1cc} \cos^2 \theta_\ell + \frac{2}{3} A_{FB,1/2}^\ell \cos \theta_\ell \right) \\ &\quad \times \text{Polynomial}_{o2}(M_{pK}, a_0, a_1, a_2)\end{aligned}$$

# Total 3-dimensional PDF

$$\text{PDF}_{\text{physics}} = f_{3/2} \text{PDF}_{\text{angular},3/2} \text{PDF}_{\text{mass},3/2} + (1 - f_{3/2}) \text{PDF}_{\text{angular},1/2} \text{PDF}_{\text{mass},1/2}$$

$$\begin{aligned}\text{PDF}_{\text{physics}} &= \frac{f_{3/2}}{4} (1 + 3 \cos^2 \theta_p) \left( \left( 1 - \frac{1}{2} S_{1cc} \right) (1 - \cos^2 \theta_\ell) \right. \\ &\quad \left. + S_{1cc} \cos^2 \theta_\ell + \frac{4}{3} A_{FB,3/2}^\ell \cos \theta_\ell \right) \times \text{BW}_{\text{nrel}}(M_{pK}, M_{\Lambda^*}, W_{\Lambda^*}) \\ &\quad + (1 - f_{3/2}) \left( \frac{1}{2} (1 - K_{1cc}) (1 - \cos^2 \theta_\ell) + K_{1cc} \cos^2 \theta_\ell + \frac{2}{3} A_{FB,1/2}^\ell \cos \theta_\ell \right) \\ &\quad \times \text{Polynomial}_{o2}(M_{pK}, a_0, a_1, a_2)\end{aligned}$$

Interferences are neglected up to now.

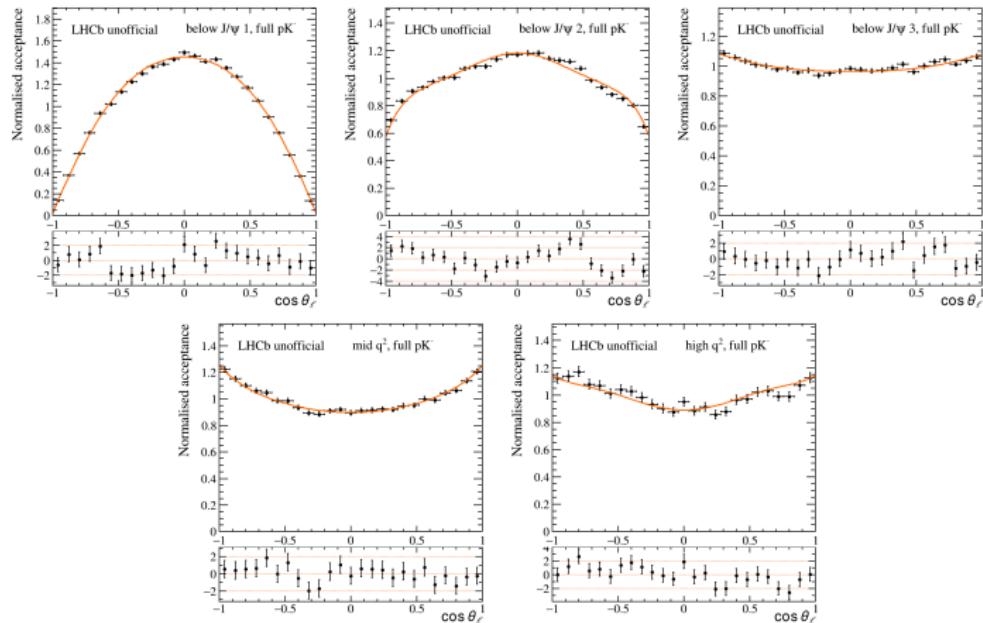
Take into account the impact of the selection, described by  $\text{PDF}_{\text{acceptance}}$  :

$$\text{PDF}_{\text{total}} = \text{PDF}_{\text{physics}} \times \text{PDF}_{\text{acceptance}}$$

# Acceptance of $\cos \theta_\ell$

Full selection and PID weights applied on phase-space  $pK\mu\mu$ -MC.

Legendre polynomials of **even orders up to 6** to describe acceptance of  $\cos \theta_\ell$ .



Good description, but not finalized yet.

# Pseudo-experiments

**AIM :** Is fit converging ? Are the observables biased ? How big are the uncertainties of the observables?

**Nbr of toys:** 1000 with number of events per toy from extrapolated yields

**Initial values:**  $f_{3/2} = 0.8$ ,  $A_{FB,3/2}^\ell$  and  $S_{1cc}^\ell$  from SM prediction,  $A_{FB,1/2}^\ell$  and  $K_{1cc}^\ell$  estimated

**Fit procedure:**

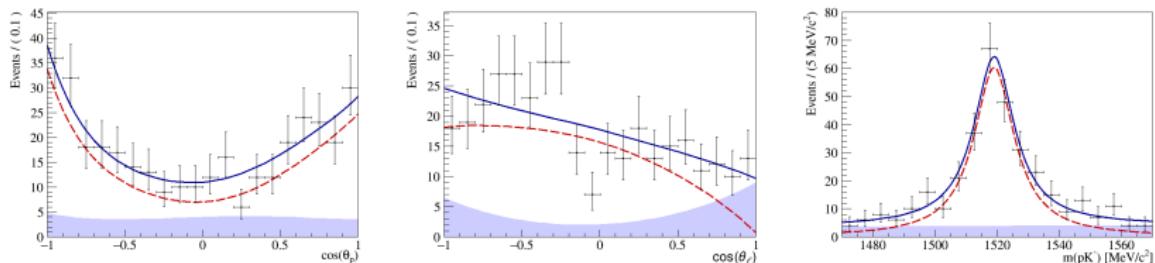
- ➊ Fit with  $f_{3/2}$ ,  $A_{FB,3/2}^\ell$ ,  $S_{1cc}^\ell$  free-floating,  $A_{FB,1/2}^\ell$ ,  $K_{1cc}^\ell$  fixed
- ➋ Refit with  $f_{3/2}$ ,  $A_{FB,3/2}^\ell$ ,  $S_{1cc}^\ell$ ,  $A_{FB,1/2}^\ell$ ,  $K_{1cc}^\ell$  free-floating
- ➌ If fit 2 failed or the resulting fit value is close to observable boundary ( $< 0.0005$ ) : reset values, fit again and keep result

**Acceptances:** angular ones included

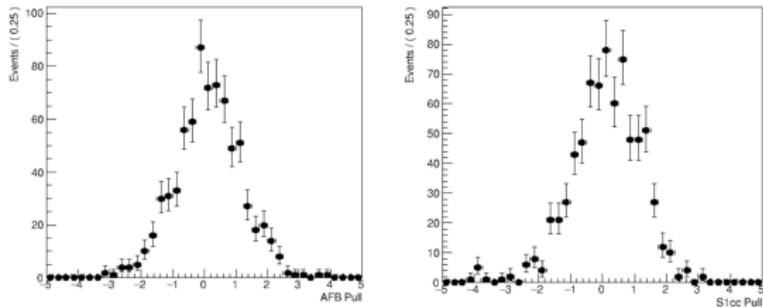
**Interferences:** neglected up to now

# Toy with angular acceptance in below- $J/\psi$ 3 bin

Color code :  $\text{PDF}_{1/2}$ ,  $\text{PDF}_{3/2}$ ,  $\text{PDF}_{\text{tot}}$



3D fit :  $M_{pK}$  important to separate  $\Lambda_{3/2}$  and  $\Lambda_{1/2}$  contributions



Pull distributions : Observables seem unbiased. Studies ongoing.

# Conclusion

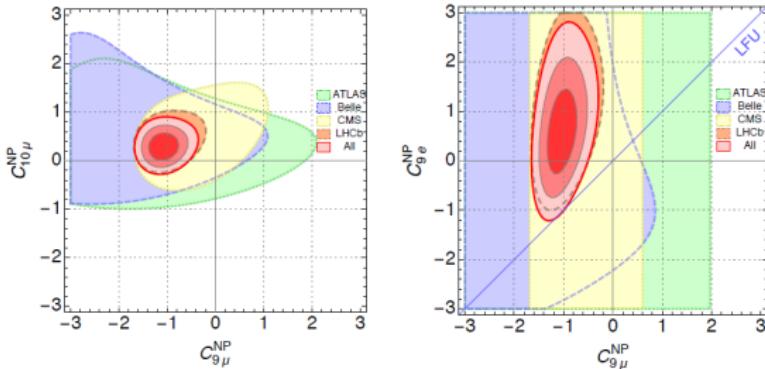
- $b$ -anomalies studied mostly in rare meson decays  
→ Continue further exploration in  $b$ -baryon decays
- Challenge of  $\Lambda_b \rightarrow p K^- \mu^+ \mu^-$  is the rich  $\Lambda^*$  spectrum and low statistics
- Selection of signal process is in place
- 3 dimensional PDF including  $\Lambda_{1/2}$  and  $\Lambda_{3/2}$  components
- First pseudo-experiment studies

Looking forward to exciting  $b$ -baryon results



Thank you for your  
attention !

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

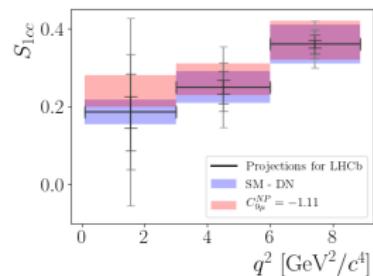
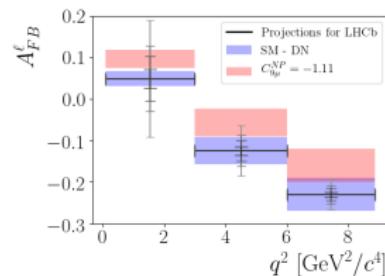
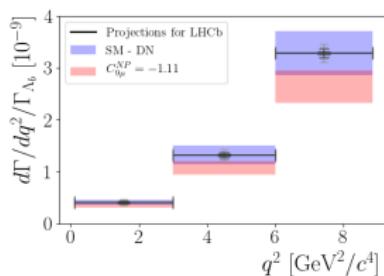
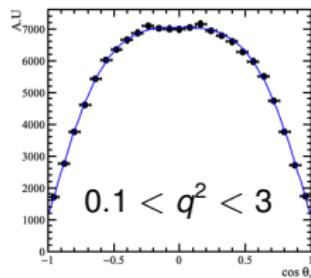


- Muonic final states hint to New Physics contributions
- Electronic mode shows smaller effects
- Up to now, only poor constraints in  $b \rightarrow s\tau^+\tau^-$

*b*-baryons provide complementary tests

# 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  $A_{FB}^\ell$  &  $S_{1cc}$
- 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 uncertainties improve.

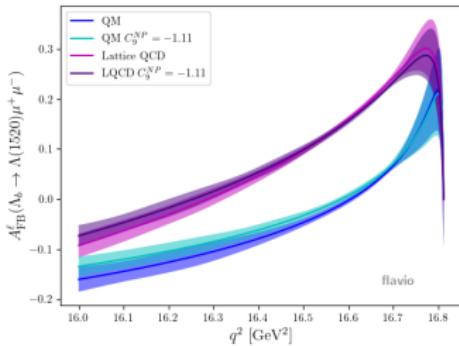
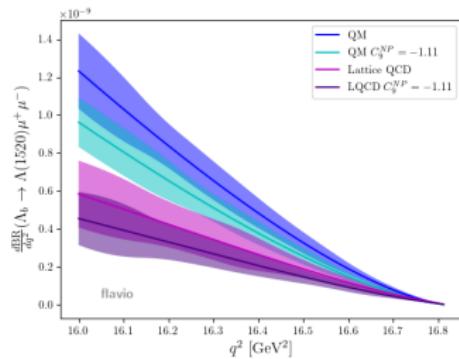
# Implementation of angular observables in flavio

- Implemented angular observables:

- 1  $d\Gamma/dq^2$
- 2  $A_{FB}, F_L$
- 3 CP-averaged, CP-asymmetries

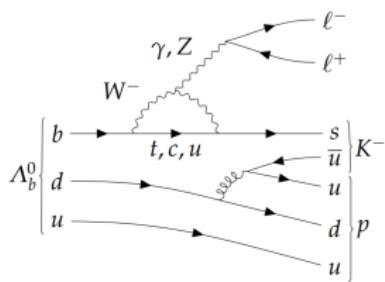
- Form factors from full Quark Model wave function [arXiv:1108.6129](https://arxiv.org/abs/1108.6129)
- Using 10% uncertainty on  $f_{0,\perp,t}$  form factors and 30% on  $f_g$  as in [arXiv:1903.00448](https://arxiv.org/abs/1903.00448)
- In addition, LQCD form factors [arXiv:2009.09313v3](https://arxiv.org/abs/2009.09313v3)

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



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

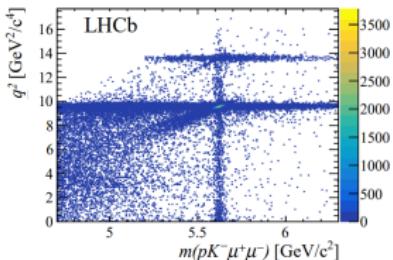
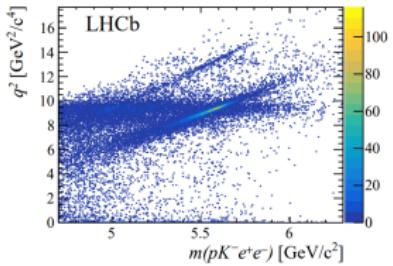
## Feynman diagram



## Experimental status

- ▶  $\Lambda_b^0 \rightarrow pK^- \mu^+ \mu^-$   
observation &  
CPV  
measurement  
[arXiv:1703.00256](https://arxiv.org/abs/1703.00256)
- ▶  $\Lambda_b^0 \rightarrow pK^- e^+ e^-$   
observation  
[JHEP 05 2020 \(040\)](https://doi.org/10.1007/JHEP05(2020)040)
- ▶ LFU test  $R_{pK^-}$   
[JHEP 05 2020 \(040\)](https://doi.org/10.1007/JHEP05(2020)040)

## $R_{pK^-}$ analysis



CDS 2699822

# Full angular PDF of $\Lambda_{3/2}$

Full angular PDF :

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

Simplified PDF via Heavy Quark limit :

$$\begin{aligned}
 &\frac{8\pi}{3} \frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_p d\phi} \\
 &\simeq \frac{1}{4} (1 + 3 \cos^2 \theta_p) (L_{1c} \cos \theta_\ell + L_{1cc} \cos^2 \theta_\ell + L_{1ss} \sin^2 \theta_\ell)
 \end{aligned}$$

# Stripping selection

Event	$n_{\text{PV}} \geq 1$
$\mu$	hasMuon && isMoun $p_{\text{T}} > 200 \text{ MeV}/c$ $\chi^2_{\text{IP}} > 1$ $\text{Prob}_{\text{track ghost}} < 0.5$
$J/\psi$	$\chi^2_{\text{vtx}} < 16$ DOCA $\chi^2 < 30$ $m < 5 \text{ GeV}/c^2$
$p$	$\text{ProbNNp} > 0.05$ $p_{\text{T}} > 300 \text{ MeV}/c$ $\chi^2_{\text{IP}} > 4$ $\text{Prob}_{\text{track ghost}} < 0.4$
$K$	$\text{ProbNNk} > 0.1$ $p_{\text{T}} > 300 \text{ MeV}/c$ $\chi^2_{\text{IP}} > 4$ $\text{Prob}_{\text{track ghost}} < 0.4$
$\Lambda(1520)^*$	$m < 5.6 \text{ GeV}/c^2$ $\chi^2_{\text{vtx}} < 25$
$A_b^0$	$m \in (4.0, 6.8) \text{ GeV}/c^2$ $\chi^2_{\text{vtx}}/\text{ndf} < 25$ $\text{DIRA} > 0.999$ $\chi^2_{\text{IP}} < 400$ Decay Length Significance (BPVDLS) $> 0$
MVA selection	$\text{BDT} > -0.11$

# Variables in BDTG training - now without $p_T(\mu)$

Rank	Variable	Variable Importance [ $\times 10^{-2}$ ]
1	$\log(\chi^2_{\text{DTF}}/\text{ndf})$	7.613
2	$\log(\text{H2\_PT})$	7.075
3	$\log(\text{H1\_PT})$	6.786
4	$\log(\text{X\_LOKI\_IPCHI2})$	6.151
5	$\log(\text{H1\_LOKI\_IPCHI2})$	5.901
6	$\log(\text{B\_ENDVERTEX\_CHI2})$	5.730
7	$\log(\text{Jpsi\_FDCHI2\_OWNPV})$	5.423
8	$\log(\text{H2\_LOKI\_IPCHI2})$	5.377
9	$\log(\text{B\_PT})$	5.375
10	$\log(\text{B\_LOKI\_IPCHI2})$	5.169
11	$\log(\text{L1\_LOKI\_IPCHI2})$	5.166
12	$\log(\text{L2\_LOKI\_IPCHI2})$	4.982
13	$\log(\text{L1\_PT})$	4.814
14	$\log(\text{Jpsi\_LOKI\_IPCHI2})$	4.616
15	$\log(\text{L2\_PT})$	4.482
16	$\log(\text{acos}(\text{B\_DIRA\_OWNPV}))$	4.295
17	$\log(\text{B\_FDCHI2\_OWNPV})$	4.289
18	$\log(\text{X\_ENDVERTEX\_CHI2})$	3.549
19	$\log(\text{Jpsi\_ENDVERTEX\_CHI2})$	3.207

# Selection

$\Lambda_b \rightarrow \Lambda(1520)\mu^+\mu^-$  Phase space MC samples of full Run1+2

Stripping : B2LLXBDT\_ Lb2mumuPKLine

Category : (Quasi-)Signal Lb\_BKGCAT  $\leq 10$  (93%), Photon radiation 50 (7%)

L0 : Muon or DiMuon (always TOS)

Hlt1 : RUN1: TrackAllL0 or TrackMuon

RUN2: TrackMVA or TwoTrackMVA

Hlt2 : RUN1: Topo(2,3,4)Body or TopoMu(2,3,4)Body

RUN2: Topo(2,3,4)BBDT or TopoMu(2,3,4)BBDT

Preselection : RUN1:  $\chi^2_{ndof}(\Lambda_b) < 100$ ,  $p_T$ ,  $K$ ,  $\mu$ 's in RICH,  $\mu$  'has muon',

$P_T(p) > 250$ ,  $P_T(p) > 9300$ ,  $P_K > 2000$ ,  $P_T(\mu) > 800$ ,

$P(\mu) > 3000$ ,  $P_T(\Lambda_b) \in [1000, 25000]$  MeV/c

RUN2: same, besides  $P_T(p) > 1000$ ,  $P_T(\mu) > 200$

Bkg vetoes :  $\phi(1020)$  veto ( $B_s^0 \rightarrow J/\psi K^+K^-$ ), Overreco bkg ( $B^+ \rightarrow K^+\ell^+\ell^-$  and  $K^+ \leftrightarrow p$ ),  $D^0$  veto ( $\Lambda_b \rightarrow p D^0\pi$ ),  $J/\psi$  veto (MisID of  $K^-\mu^+$ )

BDTG : reduce combinatorial bkg (wo  $P_T(\mu)$ )

$\Lambda_b$  mass : [5500, 5950] MeV/c<sup>2</sup>

PID weights : ✓