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

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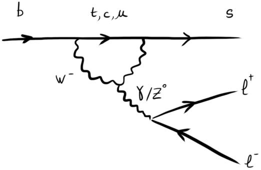
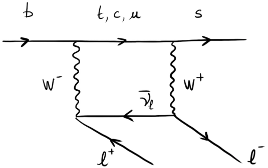
First flavor day

October 27th, 2021

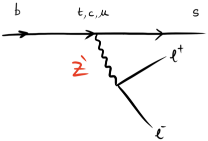
Why are rare decays interesting ?

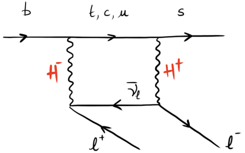
$b \to s\ell^+\ell^-$ transitions suppressed in Standard Model





Enhencement through New Physics contributions ?

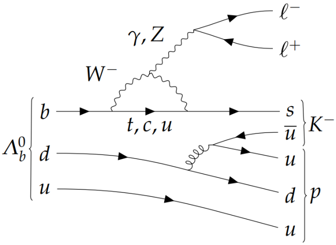




Feynman diagrams are stolen from Yasmine

Only few measurements of rare b-baryon decays !

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



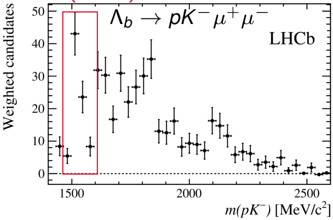
Strong decay of $\Lambda^* \to pK^-$

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

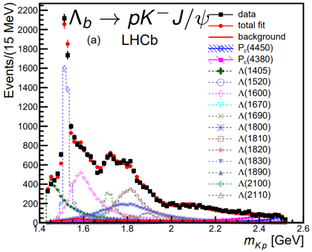
Rich Λ^* spectrum

How does the pK^- spectrum look like ?

$\Lambda(1520)$ dominates

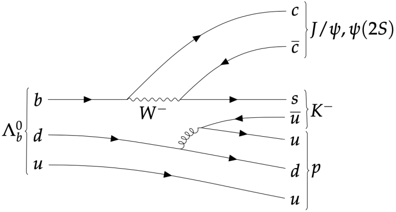


arXiv:1912.08139v2 (top), arXiv:1507.03414 (bottom)



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

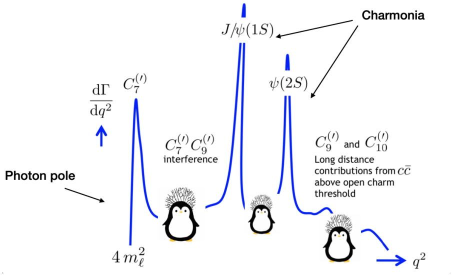
Higher statistics via tree-level diagram of $\Lambda_b \to pK^-J/\psi$ on lower left.



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

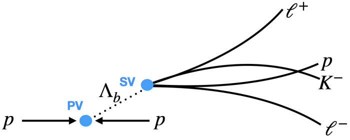
Selection of the $\Lambda_b \to \Lambda(1520)\mu^+\mu^-$ decay

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



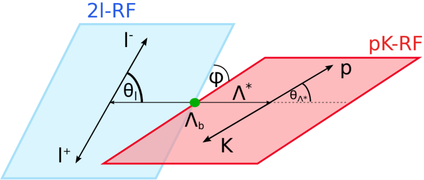
The rare mode is sensitive to New Physics !

Decay topology :

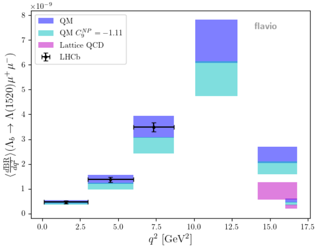


Detached Λ_b decay vertex (secondary vertex), where all the traces come from.

Decay description



$(\theta_\ell, \theta_p, \phi)$ 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 :

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

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

Simplifications :

1. Heavy quark limit ($m_b \to \infty$)
2. Normalization: $1/2 S_{1cc} + S_{1ss} = 1$
   $A^{\ell}_{FB,3/2} = 3/4 S_{1c}$

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

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 $\cos\theta_p$.

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

Simplifications :

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

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

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

$$\begin{aligned} K(q^2, \cos\theta_\ell, \cos\theta_\Lambda, \phi) = & \left(K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right) \\ & \cancel{+\left(K_{2ss}\sin^2\theta_\ell + K_{2cc}\cos^2\theta_\ell + K_{2c}\cos\theta_\ell\right)\cos\theta_\Lambda} \\ & \cancel{+\left(K_{3sc}\sin\theta_\ell\cos\theta_\ell + K_{3s}\sin\theta_\ell\right)\sin\theta_\Lambda\sin\phi} \\ & \cancel{+\left(K_{4sc}\sin\theta_\ell\cos\theta_\ell + K_{4s}\sin\theta_\ell\right)\sin\theta_\Lambda\cos\phi}. \end{aligned}$$

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 $\cos\theta_\ell$.

Total 3-dimensional PDF

$$\mathrm{PDF_{physics}} = f_{3/2}\mathrm{PDF_{angular,3/2}}\mathrm{PDF_{mass,3/2}} + (1 - f_{3/2})\mathrm{PDF_{angular,1/2}}\mathrm{PDF_{mass,1/2}}$$

$$\begin{aligned}\mathrm{PDF_{physics}} = \frac{f_{3/2}}{4}\left(1 + 3\cos^2\theta_p\right)\Bigg(\left(1 - \frac{1}{2}S_{1cc}\right)\left(1 - \cos^2\theta_\ell\right) \\ + S_{1cc}\cos^2\theta_\ell + \frac{4}{3}A^{\ell}_{FB,3/2}\cos\theta_\ell\Bigg) \times \mathrm{BW_{nrel}}(M_{pK}, M_{\Lambda^*}, W_{\Lambda^*}) \\ + (1 - f_{3/2})\Big(\frac{1}{2}\left(1 - K_{1cc}\right)\left(1 - \cos^2\theta_\ell\right) + K_{1cc}\cos^2\theta_\ell + \frac{2}{3}A^{\ell}_{FB,1/2}\cos\theta_\ell\Big) \\ \times \mathrm{Polynomial_{o2}}(M_{pK}, a_0, a_1, a_2)\end{aligned}$$

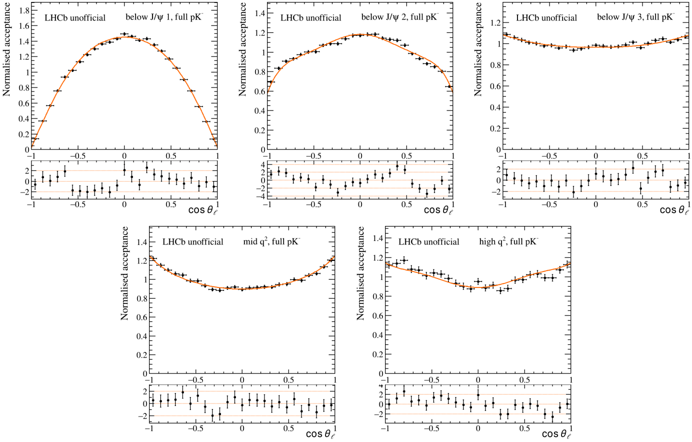
Interferences are neglected up to now.

Take into account the impact of the selection, described by $\mathrm{PDF_{acceptance}}$:

$$\mathrm{PDF_{total}} = \mathrm{PDF_{physics}} \times \mathrm{PDF_{acceptance}}$$

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: $f_{3/2} = 0.8$, $A^{\ell}_{FB,3/2}$ and S^{ℓ}_{1cc} from SM prediction, $A^{\ell}_{FB,1/2}$ and K^{ℓ}_{1cc} estimated

Fit procedure:

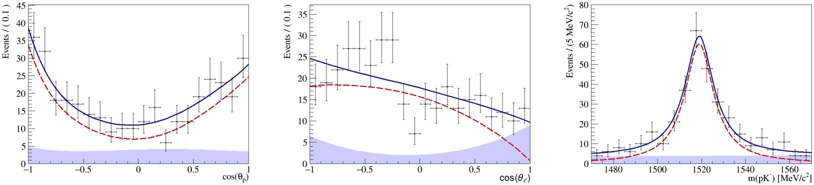
1. Fit with $f_{3/2}$, $A^{\ell}_{FB,3/2}$, S^{ℓ}_{1cc} free-floating, $A^{\ell}_{FB,1/2}$, K^{ℓ}_{1cc} fixed
2. Refit with $f_{3/2}$, $A^{\ell}_{FB,3/2}$, S^{ℓ}_{1cc}, $A^{\ell}_{FB,1/2}$, K^{ℓ}_{1cc} free-floating
3. If fit 2 failed or the resulting fit value is close to observable boundary (< 0.0005) : reset values, fit again and keep result

Acceptances: angular ones included

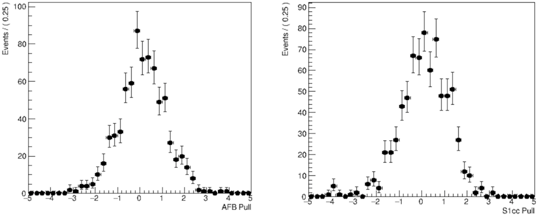
Interferences: neglected up to now

Toy with angular acceptance in below J/ψ 3 bin

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



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



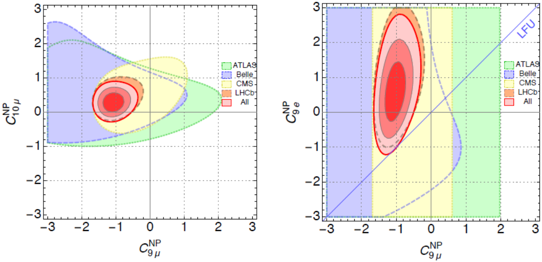
<u>Pull distributions</u> : Fit of observable seems unbiased. Studies ongoing.

Conclusion and outlook

- *b*-anomalies studied mostly in rare meson decays $\rightarrow$ confirmation in *b*-baryon decays ?
- Difficulty of $\Lambda_b \rightarrow pK^-\mu^+\mu^-$ is the rich Λ^* spectrum and low statistics.
- Selection of process in place.
- Legendre polynomials describe acceptance of $\cos\theta_\ell$ and $\cos\theta_p$.
- 3 dimensional PDF including $\Lambda_{1/2}$ and $\Lambda_{3/2}$ components is constructed.
- First pseudo-experiment studies are presented.

Thank you for your attention !

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



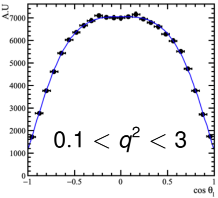
JHEP 01(2018)093

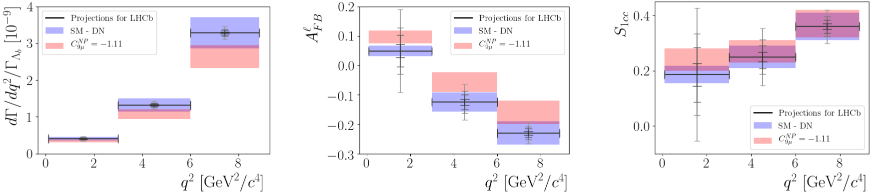
- Muonic final states hint to New Physics contributions
- Electronic mode shows smaller effects
- Up to now, only poor constraints in $b \to s\tau^+\tau^-$

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}^{ℓ} & S_{1cc}
- 10'000 times repeated per run period and q^2 bin



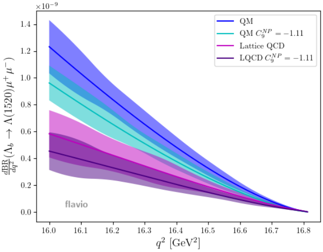


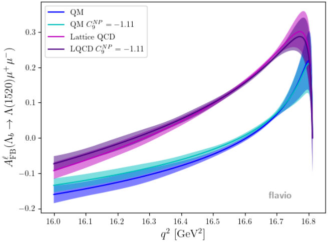
LHCb could start to be sensitive to New Physics with full Run 1+2, especially when theoretical uncertenties improve.

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

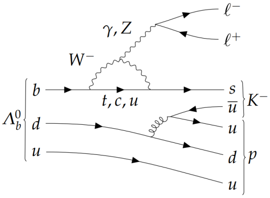
Discrepancy between LQCD form factors and Quark model ones at high q^2!





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

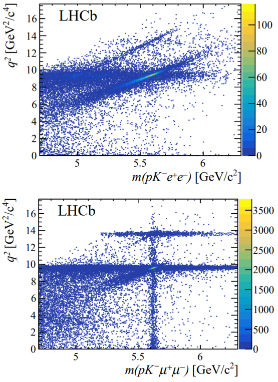
Feynman diagram



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

Full angular PDF :

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

Simplified PDF via Heavy Quark limit :

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

Stripping selection

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

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

Rank	Variable	Variable Importance [$\times 10^{-2}$]
1	$\log(\chi^2_{DTF}/ndf)$	7.613
2	log(H2_PT)	7.075
3	log(H1_PT)	6.786
4	log(X_LOKI_IPCHI2)	6.151
5	log(H1_LOKI_IPCHI2)	5.901
6	log(B_ENDVERTEX_CHI2)	5.730
7	log(Jpsi_FDCHI2_OWNPV)	5.423
8	log(H2_LOKI_IPCHI2)	5.377
9	log(B_PT)	5.375
10	log(B_LOKI_IPCHI2)	5.169
11	log(L1_LOKI_IPCHI2)	5.166
12	log(L2_LOKI_IPCHI2)	4.982
13	log(L1_PT)	4.814
14	log(Jpsi_LOKI_IPCHI2)	4.616
15	log(L2_PT)	4.482
16	log(acos(B_DIRA_OWNPV))	4.295
17	log(B_FDCHI2_OWNPV)	4.289
18	log(X_ENDVERTEX_CHI2)	3.549
19	log(Jpsi_ENDVERTEX_CHI2)	3.207

Selection

$\Lambda_b \to \Lambda(1520)\mu^+\mu^-$ 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, K, μ's in RICH, μ 'has muon',
$P_T(p) > 250$, $P(p) > 9300$, $P_K > 2000$, $P_T(\mu) > 800$,
$P(\mu) > 3000$, $P_T(\Lambda_b) \in [1000, 25000]$ MeV/c
RUN2: same, besides $P_T(p) > 1000$, $P_T(\mu) > 200$

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

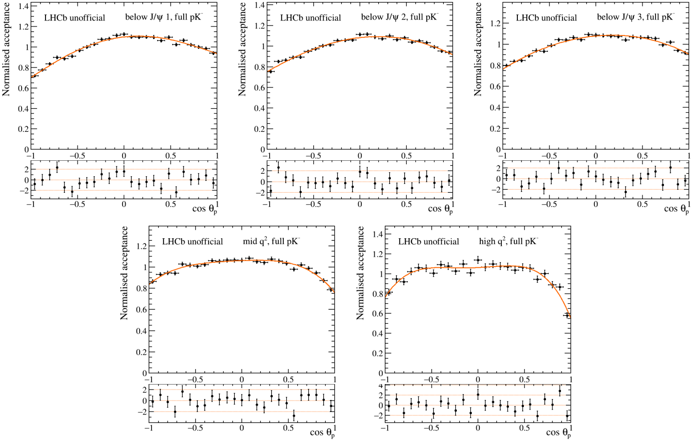
BDTG : reduce combinatorial bkg (wo $P_T(\mu)$)

Λ_b mass : $[5500, 5950]$ MeV/c^2

PID weights : ✓

Acceptance of $\cos\theta_p$

Full selection and PID weights applied on phase-space $pK\mu\mu$-MC.
Legendre polynomials of **up to order 4** to describe acceptance of $\cos\theta_p$.



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