Radiative baryon decays

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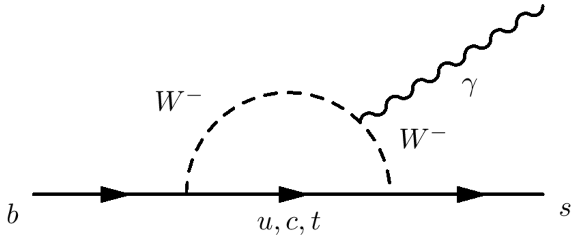
Outline

- Introduction:
  - Radiative b-decays
  - LHCb
  - Radiative b-decays at LHCb
  - Baryon b-decays

- Radiative b-baryon decays at LHCb
  - $\Lambda_b \rightarrow \Lambda^0\gamma$
  - $\Lambda_b \rightarrow \Lambda^*\gamma$

Radiative b-decays

$b \to s(d)\gamma$ are Flavour-Changing-Neutral-Currents (FCNC) → crucial tests of the Standard Model (SM)

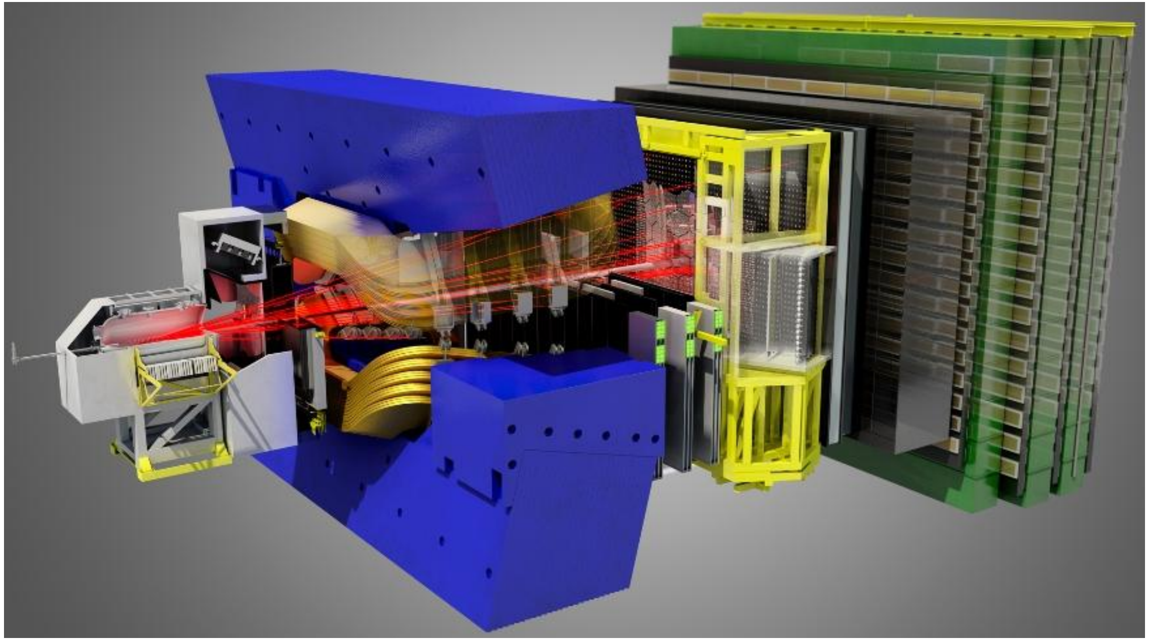


$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} (C_7 Q_7 + C_7' Q_7')$$

- generated by Q_7 at leading order (LO) in the SM, Q'_7 suppressed by m_q/m_b
- C_7 strongly constrained by BR and direct CP measurements
- room for New Physics (NP) in C'_7 [Paul and Straub] → photon polarisation

The LHCb detector

[JINST 3 (2008) S08005]

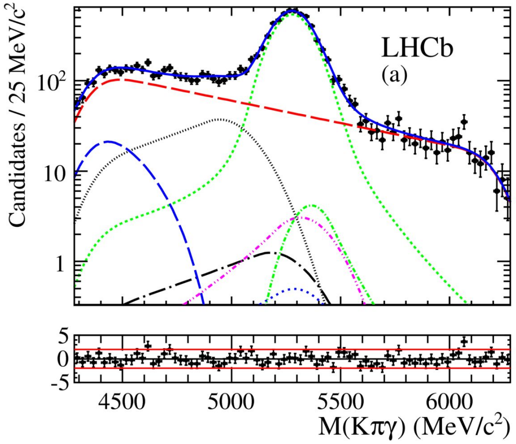


- Track momentum resolution: $\Delta p/p$ = 0.5 - 1 %
- Impact parameter resolution: $\Delta IP = (15 + 29/p_T)$ μm
- ECAL resolution: $1\% + 10\%/\sqrt{E[\text{GeV}]}$

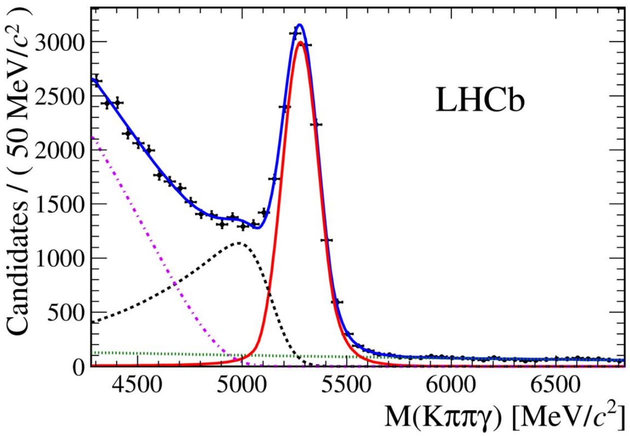
Radiative b-decays at LHCb

Main challenges:

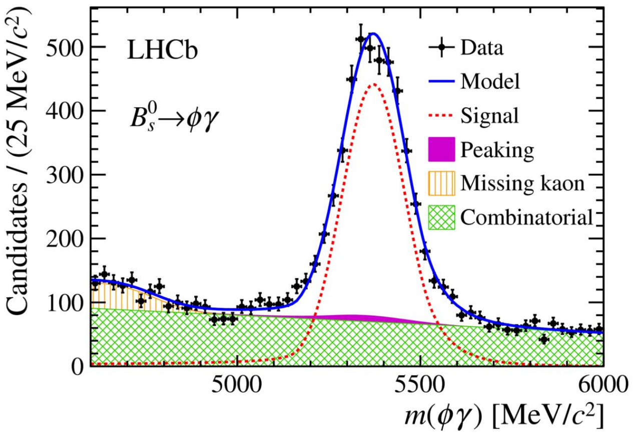
- mass resolution: ~100 MeV (~22 MeV for B → hh)
- partial and mis-id backgrounds (bkg): π^0/γ separation



[Nucl. Phys. B867 (2013)]



[Phys. Rev. Lett. 112, 161801 (2014)]



[Phys. Rev. Lett. 118, 021801 (2017)]

Radiative b-decays at LHCb

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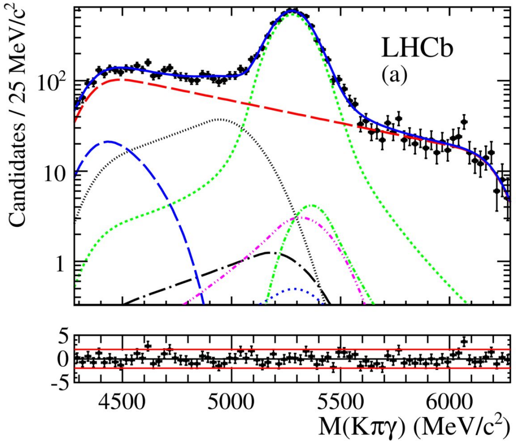
- partial and mis-id backgrounds (bkg): π^0/γ separation

Calorimeter reconstruction is crucial, working on this for the LHCb upgrade



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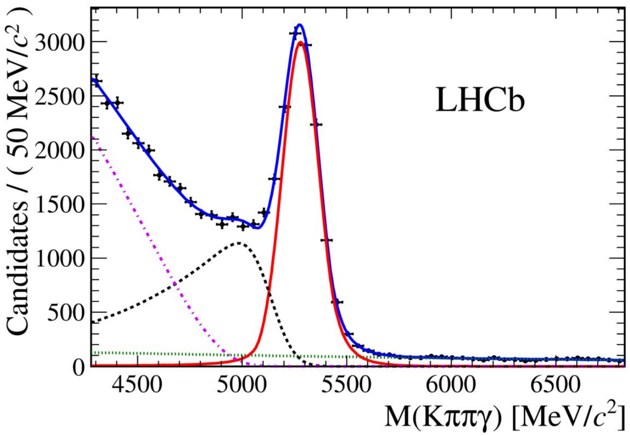

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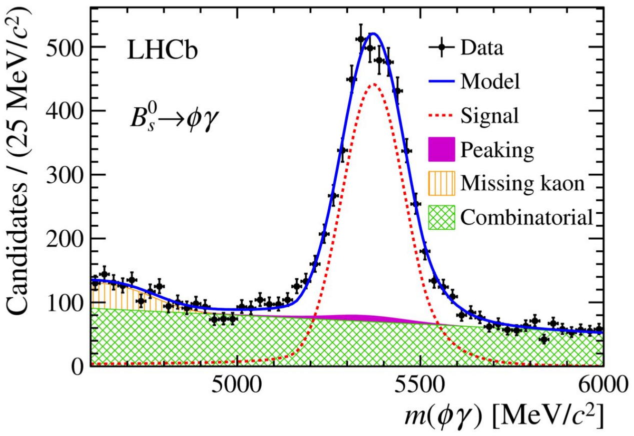


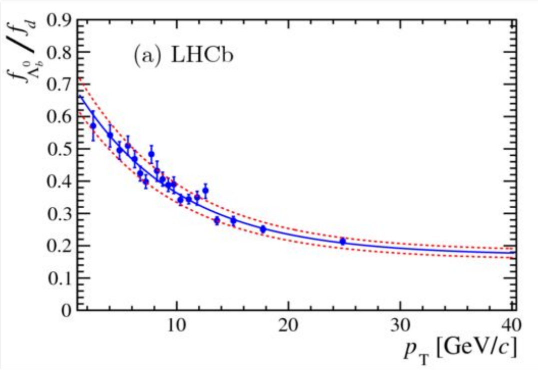
[Phys. Rev. Lett. 118, 021801 (2017)]

b-baryon decays

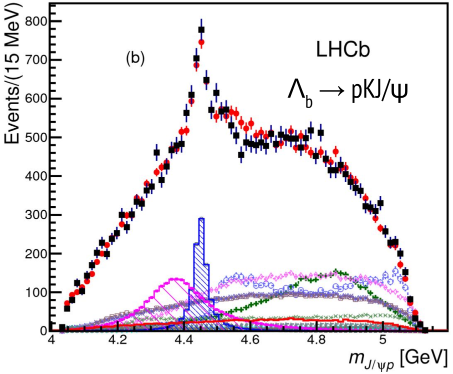
Offer complementary observables to probe the SM:

- two spectator quarks → different Form Factors
- half-integer spin → richer angular distributions

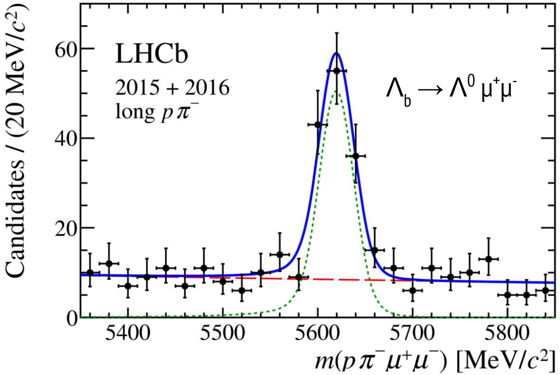
Largely unexplored so far, LHCb can exploit large production at LHC:



[JHEP 08 (2014) 143]



[Phys. Rev. Lett. 115, 072001]



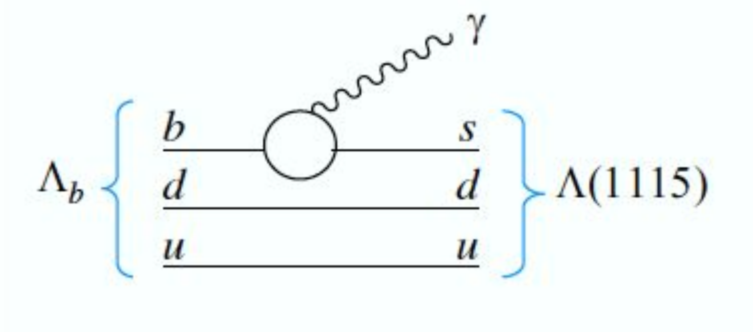
[JHEP 09 (2018) 146]

Radiative b-baryon decays at LHCb

$\Lambda_b \rightarrow \Lambda^0\gamma$

$\Lambda_b \to \Lambda^0 \gamma$

$\Lambda_b \to \Lambda^0\gamma$ is a $b \to s\gamma$ FCNC:



$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} (C_7 Q_7 + C_7' Q_7')$$

SM predicts: BR~$(0.06\text{-}1)\cdot 10^{-5}$ [Wang et al., Mannel et al., Gan et al., Faustov et al.]

- Not observed so far
- Best limit from CDF: BR < $1.9\cdot 10^{-3}$ [PhysRevD.66.112002]

Photon polarisation in $\Lambda_b \to \Lambda^0\gamma$

[Legger and Schietinger]

Most interesting observable is the photon polarisation:

$$\alpha_\gamma = \frac{P(\gamma_L) - P(\gamma_R)}{P(\gamma_L) + P(\gamma_R)}$$

at LO in the SM:

$$\alpha_\gamma^{LO} = \frac{1 - |r|^2}{1 + |r|^2} \qquad r = \frac{C'_7}{C_7} \sim \frac{m_s}{m_b}$$

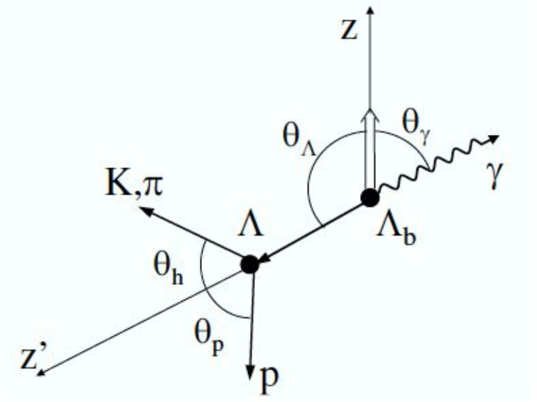
Accessible in $\Lambda_b \to \Lambda^0\gamma$ through angular analysis:

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

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

$P_{\Lambda b}$ = (0.06 ± 0.07) [Phys. Lett. B 724 (2013) 27]

$\alpha_{p,½}$ = (0.642 ± 0.013) [PDG]

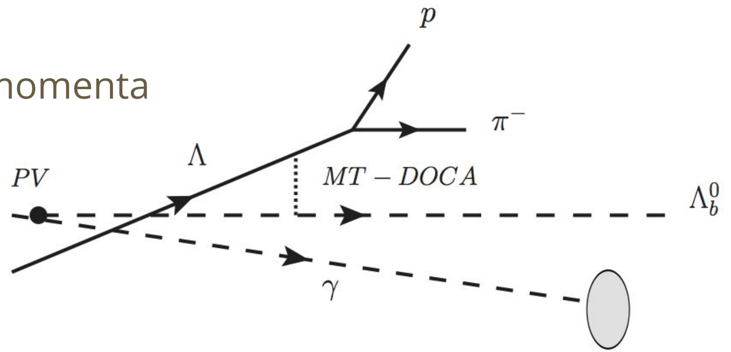


$\Lambda_b \to \Lambda^0\gamma$ at LHCb

[LHCb-ANA-2018-033]

Blinded search using 2016 data (no trigger in Run 1)

- Very challenging reconstruction due to decay topology ($\Lambda^0 \to p\pi$ weakly):
  - ~80% decay outside the LHCb vertex detector
  - cannot reconstruct Λ_b decay vertex → sum of momenta
  - large combinatorial bkg expected
  - exploit MT-DOCA [LHCb-CONF-2015-001]
  - dedicated trigger and offline selections



- Key analysis step: BDT selection
  - ~750 signal with ~150 x 10^3 bkg events expected after pre-selection
  - exploit xgboost algorithm with optimised variables

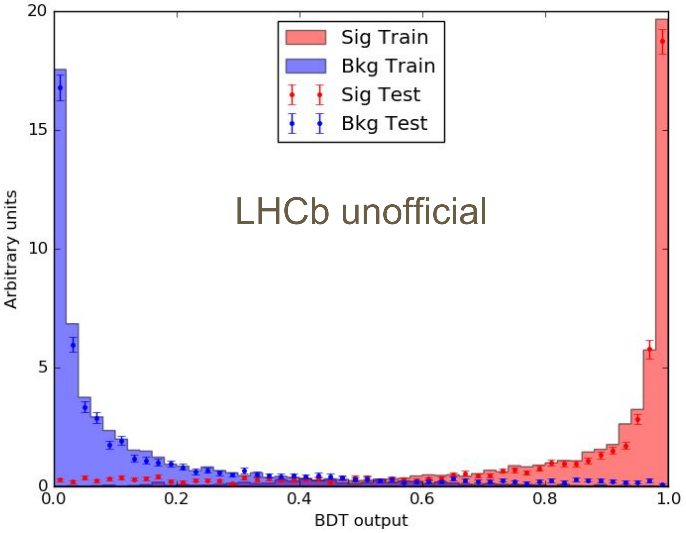
BDT selection

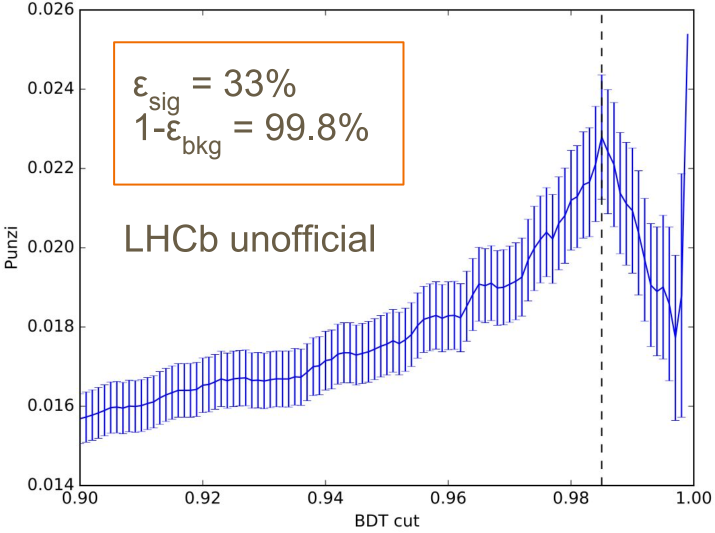
[LHCb-ANA-2018-033]

High signal to bkg separation is crucial

- 2-fold technique to avoid overtraining
- Punzi figure of merit (σ=5) for cut optimisation

$$FoM = \frac{\epsilon_S}{\sqrt{\sigma + N_B}}$$





[LHCb-ANA-2018-033]

Extraction of the BR

Exploit well known $B^0 \to K^*\gamma$ as normalisation:

$$\frac{N(\Lambda_b^0 \to \Lambda\gamma)}{N(B^0 \to K^{*0}\gamma)} = \frac{f_{\Lambda_b^0}}{f_{B^0}} \cdot \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma)}{\mathcal{B}(B^0 \to K^{*0}\gamma)} \cdot \frac{\mathcal{B}(\Lambda \to p\pi^-)}{\mathcal{B}(K^{*0} \to K^+\pi^-)} \cdot \frac{\epsilon_{sel}(\Lambda_b^0 \to \Lambda\gamma)}{\epsilon_{sel}(B^0 \to K^{*0}\gamma)}$$

- extract BR directly from the fit using:

$$N(\Lambda_b^0 \to \Lambda\gamma) = \boxed{\frac{f_{\Lambda_b^0}}{f_{B^0}} \times \alpha} \times \mathcal{B}(\Lambda_b^0 \to \Lambda\gamma) \times N(B^0 \to K^{*0}\gamma)$$

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[LHCb-ANA-2018-033]

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$$\alpha = \boxed{\frac{1}{\mathcal{B}(B^0 \rightarrow K^{*0}\gamma)}} \times \boxed{\frac{\mathcal{B}(\Lambda \rightarrow p\pi^-)}{\mathcal{B}(K^{*0} \rightarrow K^+\pi^-)}} \times \boxed{\frac{\epsilon_{sel}(\Lambda_b^0 \rightarrow \Lambda\gamma)}{\epsilon_{sel}(B^0 \rightarrow K^{*0}\gamma)}}$$

Invariant mass fit to $B_d \rightarrow K^*\gamma$

[LHCb-ANA-2018-033]

- Main bkgs well known from previous analyses:

Signal	$B^0 \rightarrow K^*\eta$
Combinatorial	$B_s \rightarrow \Phi\gamma$
Missing pion	$\Lambda_b \rightarrow pK\gamma$
$K\pi\pi^0$ X	$B^0 \rightarrow K\pi\pi^0$

- Partial bkg yields are free in the fit, peaking bkg ones are fixed

Blinded mass fit to $\Lambda_b \to \Lambda^0\gamma$

[LHCb-ANA-2018-033]

- Bkg model fits side-bands well:

Combinatorial
$\Lambda_b \to \Lambda^0\eta$

- Full fit model for stability checks:
  - signal from MC and BR hypothesis
  - extrapolate combinatorial yield
  - partial yield constrained from MC

Fit stability and performance

[LHCb-ANA-2018-033]

Assess probability of an observation or evidence from toys (H_0 is BR = 0):

$$\sigma_i^2 = -2 \cdot \log \frac{\mathcal{L}_i(H_1)}{\mathcal{L}_i(H_0)}$$

Fit stability checked for BR > 3 x 10^{-6}: no bias on BR extraction

Systematics

[LHCb-ANA-2018-033]

LHCb unofficial

Source	Value (%)
$f_{\Lambda_b^0}/f_{B^0}$	12.8
MC/Data	X
$\mathcal{B}$	3.0
Fit model	X
Irreducible $B^0 \to K^{*0}\gamma$ backgrounds	0.47
Efficiency ratio	1.7
Total	X

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affects signal significance

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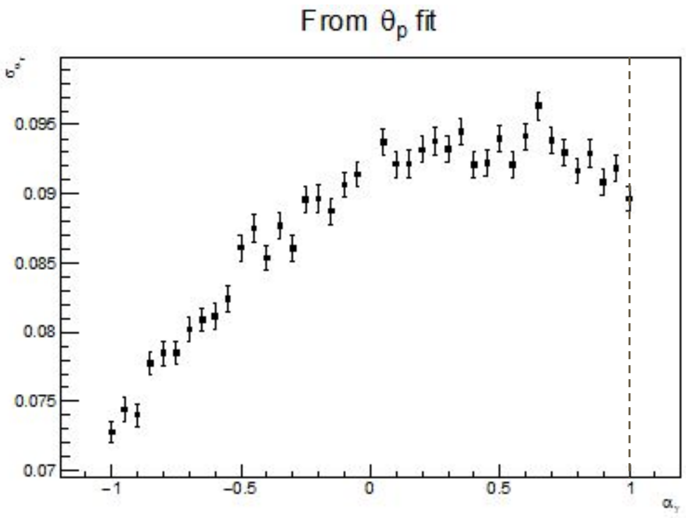
affects signal significance

Analysis under collaboration review, results expected soon, stay tuned!

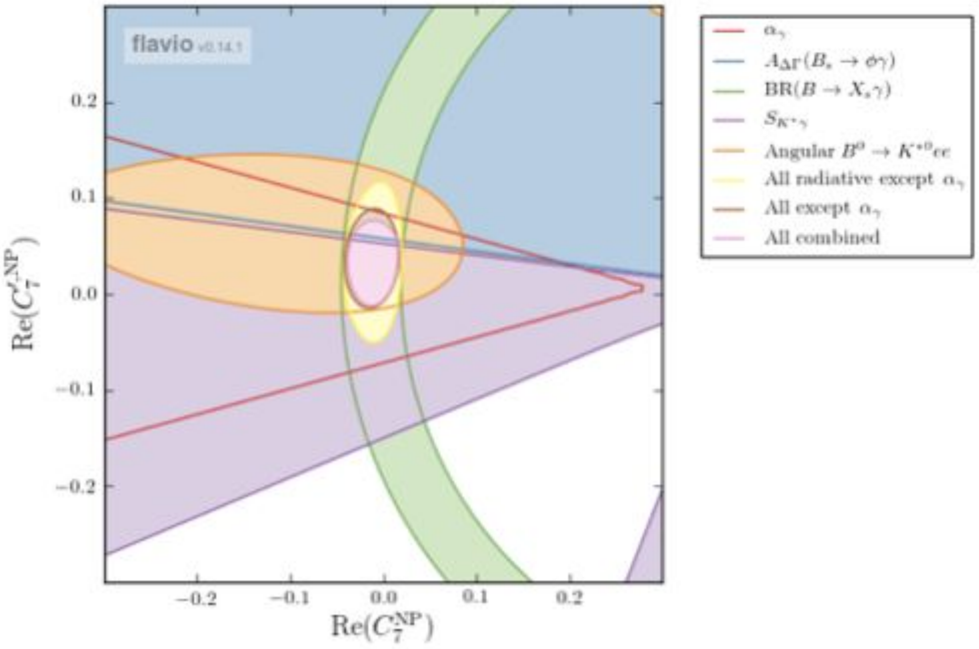
Next step: angular analysis of $\Lambda_b \to \Lambda^0\gamma$

Toys with 1k signal (no bkg), including resolution and acceptance effects:



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

Constraint on C'_7 using Flavio [D. Straub]:

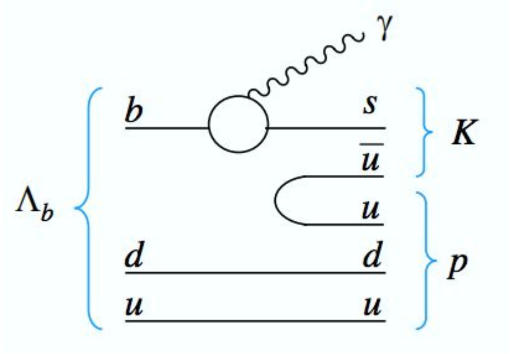


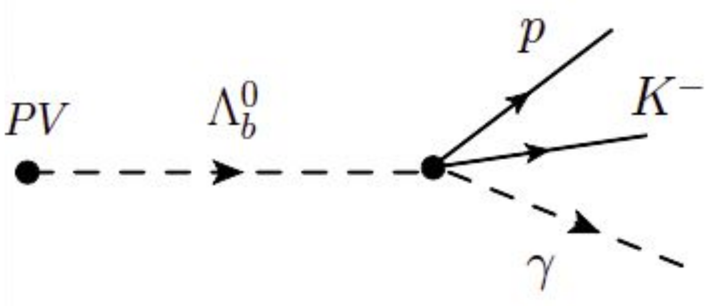
Radiative b-baryon decays at LHCb

$\Lambda_b \to pK\gamma$

$\Lambda_b \rightarrow pK\gamma$

Same $b \rightarrow s\gamma$ transition with contributions from heavier Λ^* resonances





- experimentally more accessible: $\Lambda^* \rightarrow pK$ strongly
  - prompt decay inside vertex detector
  - Λ_b vtx can be reconstructed

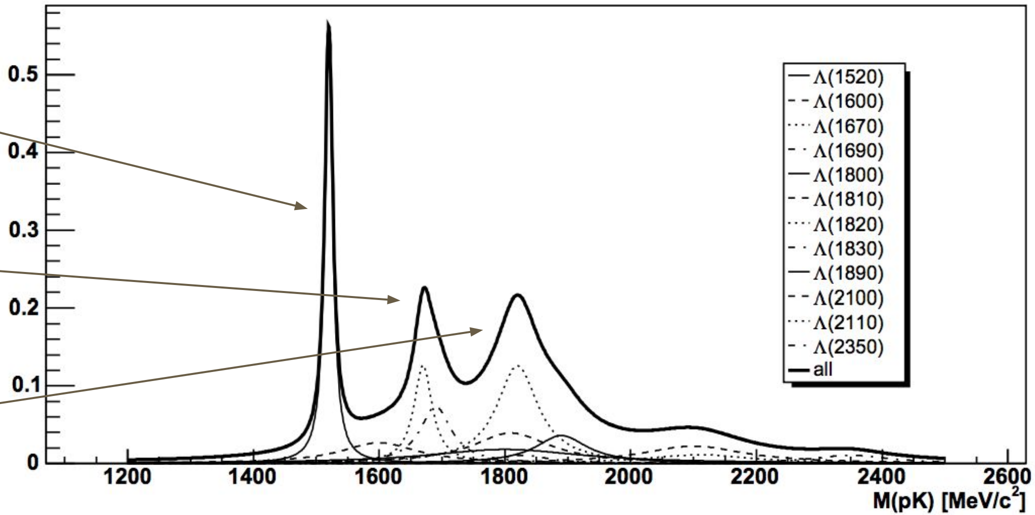
Λ* resonance contributions

- simplified model by Legger and Schietinger:

Λ(1520) J=3/2

Λ(1670) J=1/2 Λ (1690) J=3/2

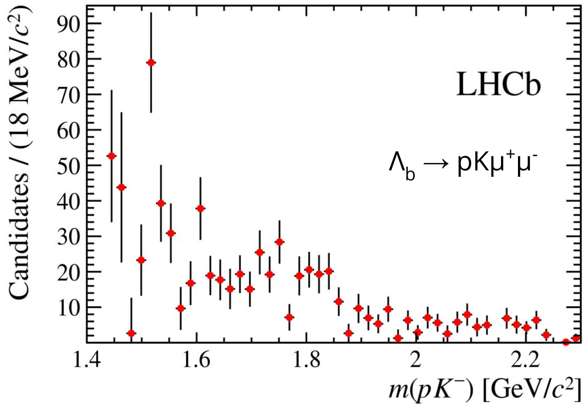
Λ(1820) J=5/2



Input for LFU in $\Lambda_b \rightarrow$ pKll

LHCb working on R(pK) as complement to R($K^{(*)}$), see talk by Vitalii

- theory can predict R(Λ(X)) for a given Λ(X), see talk by Martin
- understanding of pK spectrum needed to interpret R(pK) result
- differences between e^+e^- and $\mu^+\mu^-$ final states? Amplitude analysis of $\Lambda_b \rightarrow pK\gamma$ as 1st step



$\Lambda_b \rightarrow pKe^+e^-$?
$\Lambda_b \rightarrow pK\gamma$?

[JHEP 06 (2017) 108]

Photon polarisation in $\Lambda_b \to pK\gamma$

[Legger and Schietinger]

- J = 1/2 → angular distributions as for Λ^0

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

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

in this case:

- $\alpha_{p,½}$ = 0 (strong decay)
- $P_{\Lambda b}$ = (0.06 ± 0.07) at LHC
  [Phys. Lett. B 724 (2013) 27]

- J = 3/2

$$\frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_{\gamma,\frac{3}{2}} P_{\Lambda_b} \cos\theta_\gamma$$

$$\frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_{p,\frac{3}{2}} \cos^2\theta_p$$

with:

$$\alpha_\gamma = \frac{1}{2}\,\alpha_{\gamma,\frac{3}{2}} \left(1 - \frac{3}{\alpha_{p,\frac{3}{2}}}\right)$$

sensitivity to α_γ suppressed by initial Λ_b polarisation

*for J > 3/2, more helicity amplitudes than observables

Summary

- Radiative b decays provide crucial tests of the SM
- Radiative b-baryon decays offer complementary observables
  - largely unexplored but accessible at LHCb!

- $\Lambda_b \to \Lambda^0\gamma$ can constrain C'_7/C_7 through photon polarisation
  - search with 2016 data under review, results expected very soon!

- $\Lambda_b \to pK\gamma$ allows to study Λ^* contributions to pK spectrum
  - expand our knowledge of QCD
  - input for LFU tests with baryons

BACK-UP

BDT selection: input variables

Variables
$\pi^{\pm}\ p_{\mathrm{T}}$
$p\ p_{\mathrm{T}} + \pi^{\pm}\ p_{\mathrm{T}} + \gamma\ p_{\mathrm{T}}$
p IP χ^2
$\pi^{\pm}$ IP
Tracks DOCA
$\gamma\ p_{\mathrm{T}}$
$\Lambda\ p_{\mathrm{T}}$
Λ IP
Λ IP χ^2
Λ FD
$\Lambda_b^0\ p_{\mathrm{T}}$
Λ_b^0 MTDOCA
Λ Cone(1.0) $\mathcal{A}_p$
Λ Cone(1.0) $\mathcal{A}_{p_{\mathrm{T}}}$
γ Cone(1.0) $\mathcal{A}_{p_{\mathrm{T}}}$

$$\mathcal{A}(p_{\mathrm{T}}) = \frac{p_{\mathrm{T}\Lambda} - p_{\mathrm{T}cone}}{p_{\mathrm{T}\Lambda} + p_{\mathrm{T}cone}}$$

Ratio of hadronisation fractions

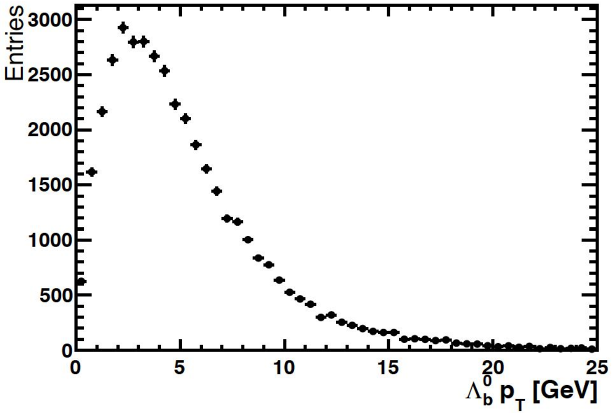
Use LHCb measurement [LHCb-PAPER-2014-004]:

$$f_{\Lambda_b^0}/f_{B^0}(p_T) = a + \exp(b + c p_T)$$

$$a = +0.151 \pm 0.016\ ^{+0.024}_{-0.025}$$
$$b = -0.573 \pm 0.040\ ^{+0.101}_{-0.097}$$
$$c = -0.095 \pm 0.007 \pm 0.014\,\mathrm{GeV}^{-1}$$

- average over generator level p_T distribution

$$f_{\Lambda_b^0}/f_{B^0}(p_T\mathrm{-av}) = 0.493 \pm 0.055$$



Assumes $f_{\Lambda b}/f_{B0}$ holds at 13 TeV:

- measure also $f_{\Lambda b}/f_{B0}$ x BR

$\Lambda_b \to pK\gamma$ model by Legger and Schietinger

$\Lambda(X)$	$L_{I\cdot 2J}$	Γ (MeV)	$\mathcal{B}_{N\overline{K}}$ (%)	$\mathcal{B}_{\Lambda(X)\gamma}$ (10^{-5})	$\mathcal{B}_{\text{tot}}$ (10^{-5})
$\Lambda(1520)$	D_{03}	15.6	45	5.84	1.31
$\Lambda(1600)$	P_{01}	150	22	5.69	0.65
$\Lambda(1670)$	S_{01}	35	25	5.56	0.69
$\Lambda(1690)$	D_{03}	60	25	5.52	0.69
$\Lambda(1800)$	S_{01}	300	32	5.30	0.84
$\Lambda(1810)$	P_{01}	150	35	5.28	0.92
$\Lambda(1820)$	F_{05}	80	60	5.26	1.57
$\Lambda(1830)$	D_{05}	95	6	5.24	0.15
$\Lambda(1890)$	P_{03}	100	22	5.12	0.56
$\Lambda(2100)$	G_{07}	200	30	4.67	0.70
$\Lambda(2110)$	F_{05}	200	15	4.65	0.34
$\Lambda(2350)$	H_{09}	150	12	4.12	0.28

Photon polarisation in $\Lambda_b \to pK\gamma$

[Legger and Schietinger]

- J = 3/2:

$$\frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_{\gamma,\frac{3}{2}} P_{\Lambda_b} \cos\theta_\gamma$$

$$\frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_{p,\frac{3}{2}} \cos^2\theta_p$$

$$\alpha_{\gamma,\frac{3}{2}} = \frac{\overbrace{|C_{\frac{3}{2},1}|^2 + |C_{-\frac{1}{2},-1}|^2}^{\lambda_\Lambda - \lambda_\gamma = 1/2} - \overbrace{|C_{-\frac{3}{2},-1}|^2 - |C_{\frac{1}{2},1}|^2}^{\lambda_\Lambda - \lambda_\gamma = -1/2}}{|C_{\frac{3}{2},1}|^2 + |C_{-\frac{1}{2},-1}|^2 + |C_{-\frac{3}{2},-1}|^2 + |C_{\frac{1}{2},1}|^2} = \frac{1-\eta}{1+\eta}\,\alpha_\gamma$$

$$\alpha_{p,\frac{3}{2}} = \frac{\overbrace{|C_{\frac{3}{2},1}|^2 + |C_{-\frac{3}{2},-1}|^2}^{|\lambda_\Lambda| = 3/2} - \overbrace{|C_{\frac{1}{2},1}|^2 - |C_{-\frac{1}{2},-1}|^2}^{|\lambda_\Lambda| = 1/2}}{|C_{\frac{3}{2},1}|^2 + |C_{-\frac{3}{2},-1}|^2 + \frac{1}{3}(|C_{-\frac{1}{2},-1}|^2 + |C_{\frac{1}{2},1}|^2)} = \frac{\eta - 1}{\eta + \frac{1}{3}}$$

$$\alpha_\gamma = \frac{1}{2}\,\alpha_{\gamma,\frac{3}{2}}\left(1 - \frac{3}{\alpha_{p,\frac{3}{2}}}\right)$$

$$\eta = \frac{|C_{\frac{3}{2},1}|^2}{|C_{\frac{1}{2},1}|^2} = \frac{|C_{-\frac{3}{2},-1}|^2}{|C_{-\frac{1}{2},-1}|^2}$$