Search for $\Lambda_b^0 \to p K^- \eta'$ at LHCb

Tim Williams

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1 Motivation & Strategy

2 Selection

3 Efficiencies

4 Mass Fit

Physics Motivation

- η' still not fully understood - size of gluon component in meson wavefunction? Why is the M(η')-M(η) so large? Interference between η' and η still not fully predicatable.
- The decay of a b baryon to an $\eta^{(\prime)}$ final state has never been observed, completely unexplored area of charmless B physics.
- An enhanced branching fraction could be explained by large gluon component to η' wave function.
- 3σ evidence seen for $\Lambda_b^0 \to \Lambda\eta$ at LHCb, $\mathcal{B} = 9.3^{+7.3}_{-5.3} \times 10^{-6}$
- Limit set on $\Lambda_b^0 \to \Lambda\eta'$, $\mathcal{B} < 3.1 \times 10^{-6}$ (90%) JHEP 1509 (2015) 006.
- No theory predictions for branching fraction of $\Lambda_b^0 \to pK\eta'$ - but experimentally easier to detect than $\Lambda_b^0 \to \Lambda\eta'$.
    - Long lived Λ causes low trigger efficiencies.

Analysis Strategy

- Perform blind search for $\Lambda_b^0 \to pK\eta'$ using 3 fb^{-1} Run I data.
- Reconstruct η' in two channels:
  - $\eta' \to \pi^+\pi^-\gamma$, BF=0.291
  - $\eta' \to \pi^+\pi^-\eta$ ($\eta \to \gamma\gamma$) , BF=0.169
- $B^+ \to K^+\eta'$ ($\eta' \to \pi^+\pi^-\gamma$) used as a control channel for both rare channels.

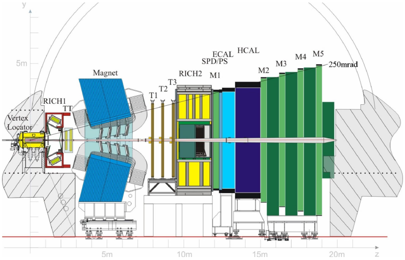
Ratio of branching fractions extracted as:

$$R = \frac{\mathcal{B}(\Lambda_b^0 \to pK\eta')}{\mathcal{B}(B^+ \to K^+\eta')} = \left(\frac{\epsilon_c N_\gamma}{\epsilon_\gamma N_c} \left(\frac{f_u}{f_{\Lambda_b^0}} \right)_\gamma + \frac{\epsilon_c N_\eta}{\epsilon_\eta N_c} \left(\frac{f_u}{f_{\Lambda_b^0}} \right)_\eta \right) \frac{\mathcal{B}_\gamma}{\mathcal{B}_\gamma + \mathcal{B}_\eta}$$

- $N_C(\varepsilon_C)$,$N_\gamma(\varepsilon_\gamma)$ and $N_\eta(\varepsilon_\eta)$ are yields (efficiencies) in control, $\eta' \to \pi^+\pi^-\gamma$ and $\eta' \to \pi^+\pi^-\eta$ channels respectively.
- $\frac{f_u}{f_{\Lambda_b^0}}$ is the ratio of B^+/ Λ_b^0 fragmentation fractions - measured by LHCb.

LHCb Detector

- Acceptance: $2 < \eta < 5$, 25% of $b\bar{b}$ pairs within acceptance
- Luminosity levelling: mean interactions per bunch crossing = 2.5 (2012).
- 2 RICH sub detectors provide excellent PID ability, ε(K) ∼ 95% with misID($\pi^- \rightarrow K^-$) ∼ 5%
- Scintillator/lead sampling calorimeter provides $\sim \frac{9\%}{\sqrt{E}}$ energy resolution.



Detector Performance [Int. J. Mod. Phys. A 30 (2015) 1530022]

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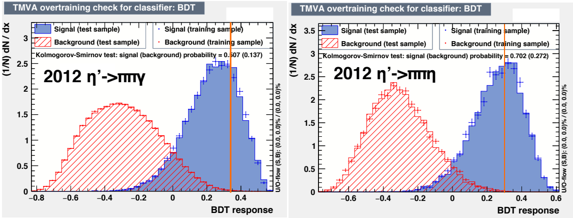
Offline Selection

- Majority of background events rejected with BDTs.
- Use topological, kinematic and vertex quality variables, along with χ^2/ndf of kinematic fit to entire decay chain and photon confidence level.

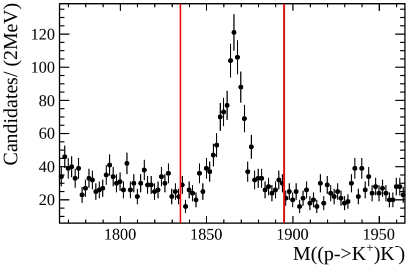


- Optimised cuts shown on the plot.
- Apply tight cuts on neural network based PID variables for Proton and Kaon, looser cuts for Pions.

Further Selection Requirements

$\eta' \to \pi^+\pi^-\gamma$ Channel

- Vetoes for charm backgrounds e.g Λ_c^+/D^0 decays
- Remove background from $\Lambda_b^0 \to pK^-\pi^+\pi^-$ by requiring $|M(pK^-\pi^+\pi^-) - M(\Lambda_b^0)| > 60.0\,\mathrm{MeV}$.
- Require M(π^+ π^-)>510.0 MeV to remove low mass background.



$\eta' \to \pi^+\pi^-\eta$ Channel

- Require 480.0 MeV <M(η) <620.0 MeV where M(η) is determined from kinematic fit of entire decay chain.

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Efficiency Calculation Procedure

- Rich Λ^* resonant structure expected but not a priori known - need to account for efficiency variation over phase space.
- Bin efficiency in $\cos(\theta_{\eta' K^-})$, where $\theta_{\eta' K^-}$ is the helicity angle of the η' K^- system, and m'':

$$m'' = \frac{m_{\eta' p} - m_{\eta' p}^{min}}{m_{\eta' p}^{max} - m_{\eta' p}^{min}} \quad (1)$$

if Significance $>3\sigma$

- Extract sWeights from mass fit - background subtraction.
- Efficiency taken as:

$$\epsilon = \frac{\sum_i^N W_i}{\sum_i^N \frac{W_i}{\epsilon_i}} \quad (2)$$

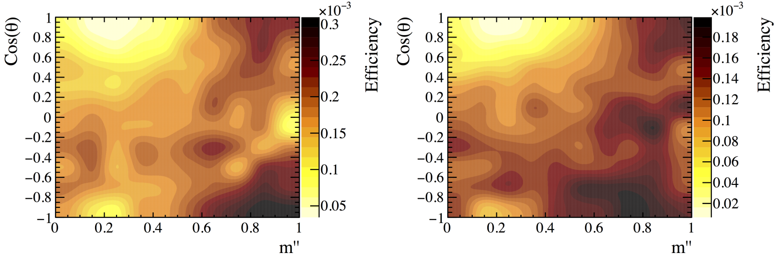
where ϵ_i is efficiency in the bin of phase space occupied by event i.

if Significance $<3\sigma$

- Use phase space integrated efficiencies.
- Assign systematic for variation of efficiency over phase space.

Efficiency Variation over Phase Space

- Efficiency maps are interpolated with 2D cubic splines to reduce systematic uncertainties.



- Highest Efficiencies in bottom right region where $\Lambda^* \to pK^-$ resonances are expected.

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Mass Fit Strategy

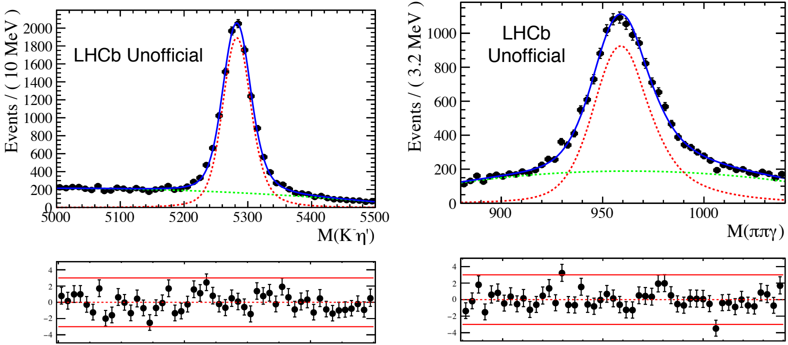
- Merge 2012 and 2011 data, perform simultaneous fit to control channel and both rare channels
  - Share Data/MC correction factor for signal shape width between all channels - control channel constrains rare channels
  - Fix $M(\Lambda_b^0) - M(B^+)$ to LHCb measurement
- First fit to extract yields, determine signal significance with Wilks' theorem and calculate efficiencies.
- Add efficiency information etc. into fit; extract ratio of branching fractions directly from fit.
  - Systematic uncertainty calculated by performing fit 1000 times whilst varying fixed paramaters.

Ratio of Branching Fractions:

$$\frac{\mathcal{B}(\Lambda_b^0 \to pK\eta')}{\mathcal{B}(B^+ \to K^+\eta')} = \left(\frac{\epsilon_c N_\gamma}{\epsilon_\gamma N_c} \left(\frac{f_u}{f_{\Lambda_b^0}} \right)_\gamma + \frac{\epsilon_c N_\eta}{\epsilon_\eta N_c} \left(\frac{f_u}{f_{\Lambda_b^0}} \right)_\eta \right) \frac{\mathcal{B}_\gamma}{\mathcal{B}_\gamma + \mathcal{B}_\eta}$$

Control Channel Fit

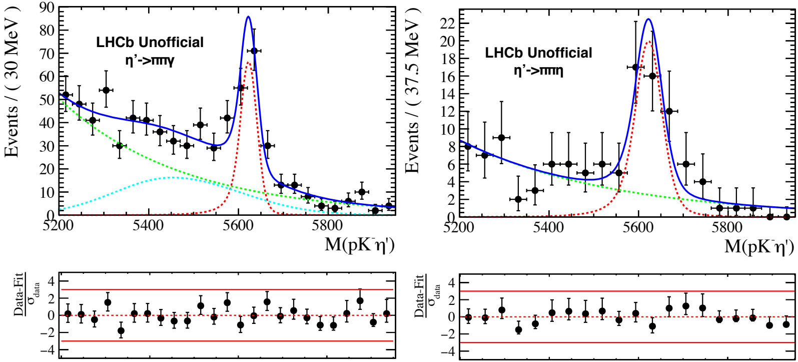
- 2D fit in M(B^+) and M(η'), signal shapes modelled with double tailed Crystal Ball functions.
- Second order polynomials for combinatorial background.



- Healthy signal yield of 11683 ± 131 events.

Unblinded Mass Fit Results

- Signal (red) - Crystal Ball functions
- Combinatorial background (green) - exponential
- Partially reconstructed background (blue) - bifurcated Gaussian



- **N($\eta' \to \pi^+\pi^-\gamma$) = 116 $\pm$ 15** **N($\eta' \to \pi^+\pi^-\eta$) = 45 $\pm$ 8**
- Combined Significance (stat. only) of 12.7σ

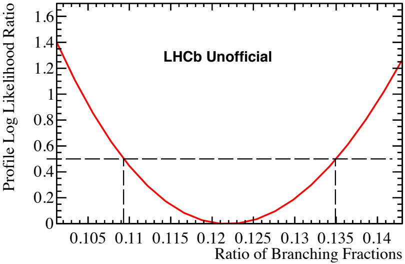
Branching Fraction Results

- Corrected efficiencies used to extract combined ratio of branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \to pK\eta')}{\mathcal{B}(B^+ \to K^+\eta')} = 0.122 \pm 0.013(stat.only)$$

- Using $\mathcal{B}(B^+ \to K^+\eta') = (7.06 \pm 0.25) \times 10^{-5}$:

$$\mathcal{B}(\Lambda_b^0 \to pK\eta') = (8.61 \pm 0.90(stat.)) \times 10^{-6})$$



Conclusions

- A b-baryon decay to η' final state has been observed for the first time with a combined significance of 12.7σ.
- 116 ± 15 signal events observed in $\eta' \to \pi^+\pi^-\gamma$ decay channel
- 45 ± 8 signal events observed in $\eta' \to \pi^+\pi^-\eta$ decay channel.
- Efficiencies have been corrected for variation across phase space of decay.
- Branching fraction measured to be: $\mathcal{B}(\Lambda_b^0 \to pK\eta') = (8.61 \pm 0.90) \times 10^{-6}$ (stat. only)

Backup

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In the quark flavour basis:

$$\begin{pmatrix} |\eta\rangle \\ |\eta'\rangle \end{pmatrix} = \begin{pmatrix} cos\phi_p & -sin\phi_p \\ sin\phi_p & cos\phi_p \end{pmatrix} \begin{pmatrix} |\eta_q\rangle \\ |\eta_s\rangle \end{pmatrix} \tag{3}$$

, where $\phi_p = (43.5^{+1.4}_{-1.3})^\circ$, $|\eta_q\rangle = \frac{1}{\sqrt{2}}|u\bar{u} + d\bar{d}\rangle$, $|\eta_s\rangle = |s\bar{s}\rangle$. However, in principle one has to consider contributions from all $\mathrm{SU}(3)$ flavour singlet states, but masses of $|c\bar{c}\rangle$ and $|b\bar{b}\rangle$ mean only $|gg\rangle$ is likely to contribute. Extending mixing leads to:

$$|\eta'\rangle \approx \cos\phi_g \sin\phi_p|\eta_q\rangle + \cos\phi_g \cos\phi_p|\eta_s\rangle + sin\phi_g|gg\rangle \tag{4}$$

Latest measurement by LHCb: $\phi_g = (0 \pm 24.6)^\circ$ (arXiv:1411.0943)

Square Dalitz Plot Variables

$$m' = \frac{1}{\pi} arccos \left(2 \frac{m(p\eta') - m_{p\eta'}^{min}}{m_{p\eta'}^{max} - m_{p\eta'}^{min}} - 1 \right)$$

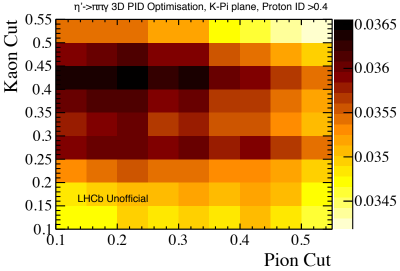
where $m_{p\eta'}^{max} = m(\Lambda_b^0) - m(K^-), m_{p\eta'}^{min} = m(p) + m(\eta')$

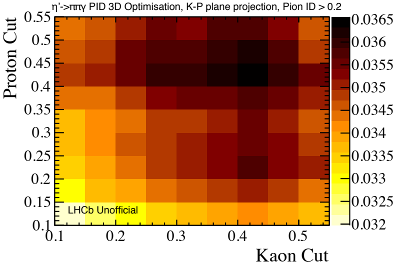
$$\theta' = \frac{1}{\pi} \theta(p\eta')$$

where $\theta(p\eta')$ is the helicity angle of the $p\ \eta'$ system (the angle between the K^- and the p in the $p\ \eta'$ rest frame)

PID Selection

- Use global neural network based particle identification variables - make use of all sub detectors not just the RICH detectors.
- 3D Optimisation of Proton-ID, Pion-ID and Kaon-ID cuts for Punzi figure of merit.





- Tight cuts chosen for Kaon and Proton ID variables but loose cuts on Pion ID variables because kinematic fit of entire decay chain requires pions to come from fixed mass η'.