BnoC Status Report

Tim Williams on behalf of the BnoC PWG

84th LHCb week

13/06/2017

UNIVERSITY OF BIRMINGHAM

PWG Organisation

- WG Convenors: **Stefano Perazzini, Sean Benson**
- Sub-WG Convenors:
  - 3 Body: **Rafael Coutinho, Eli Ben-Haim**
  - 2 & 4 Body: **Roberta Cardinale, Laurence Carson**
- Regular BiWeekly Meetings: **Thursdays 2PM**

Link to BnoC Twiki Page

PWG Liaisons

Current Liaisons

- Simulation: **Maria Vieites Diaz**
- Stripping: **Tim Williams (Stepping Down) & Alvaro Gomes Dos Santos Neto**
- Trigger: **Andrea Merli**
- Tracking: **Gediminas Sarpis**
- Flavour Tagging: **Julian Garcia**
- PID: **Abhijit Mathad**
- Calo Tools: **Jason Andrews**
- Statistics and ML Tools:**Timon Schmelzer**

Thanks for all your work!

BnoC Physics Case

- Study decays of b-hadrons to charmless hadronic final states:
  - $b \to u$ tree level decays
  - $b \to s, d$ penguin decays

- Measurements of branching fractions and CPV observables provide tests of standard model and searches for new physics
- **2 & 4 Body Examples:** Searches for $B \to baryon$ decays, Angular analysis of $B \to VV$ decays, time (in)dependent CPV
- **3 Body Examples:** Dalitz analyses and CPV observables, Bc decays, searches for unobserved decays

BnoC Activities

- **Currently in review:** 6 Analyses in WG review, 7 with review committee & 1 in collaboration wide review
- **Since last LHCb week:**
  - 2 Papers Published:
    - 4.1σ evidence for the decay $B^+ \to p\overline{\Lambda}$ (LHCb-PAPER-2016-048)
    - Upper limit on $\mathcal{B}(B_s^0 \to \phi\eta') < 0.82 \times 10^{-6}$ at 90% CL. (LHCB-PAPER-2016-060)
  - 2 Papers Submitted:
    - First observation of a baryonic B_s^0 decay (LHCB-PAPER-2017-012)
    - Observation of the charmless baryonic decays $B_{(s)}^0 \to p\overline{p}h^+h^-$ (LHCb-PAPER-2017-005)
- 32 Analyses in preperation - only able to present a few today.
- Details of all past and present analyses can be found in the WG database

$B^0_{(s)} \to p\overline{p}$ Update

Link to WG Database

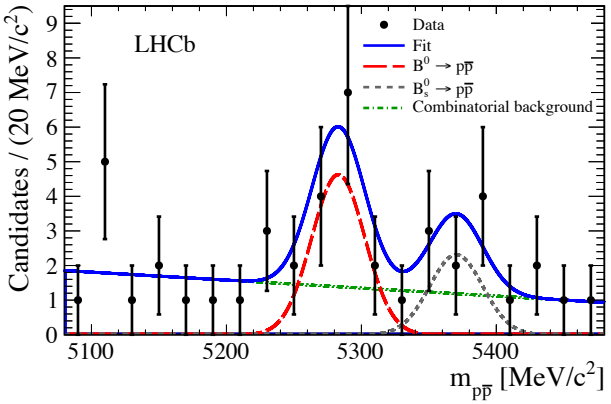
$B^0_{(s)} \to p\bar{p}$ Motivation and Status

Motivation

- No baryonic 2 body charmless B^0 decay has been observed.
- $B^0_{(s)} \to p\bar{p}$ decays predicted to be simplest to search for experimentally

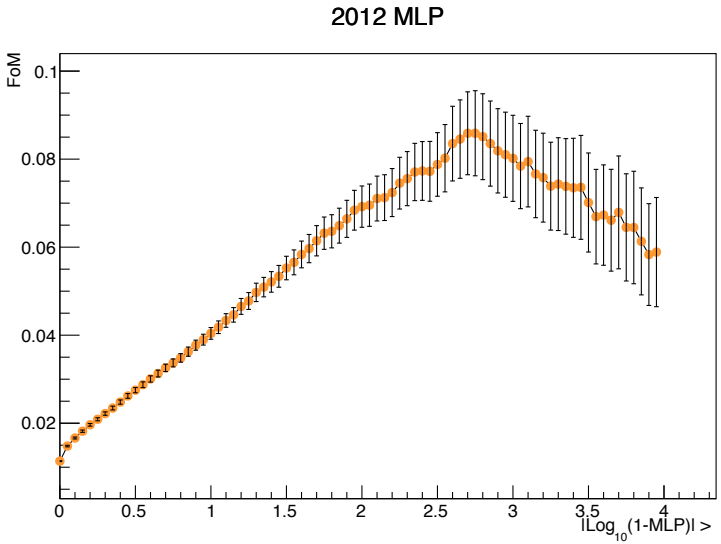
- Previous analysis using 2011 data saw 3.3σ evidence for $B^0 \to p\bar{p}$ but no evidence for the suppressed $B^0_s \to p\bar{p}$ seen [10.1007/JHEP10(2013)005].
- Hopefully addition of 2012 data can lead to an observation.

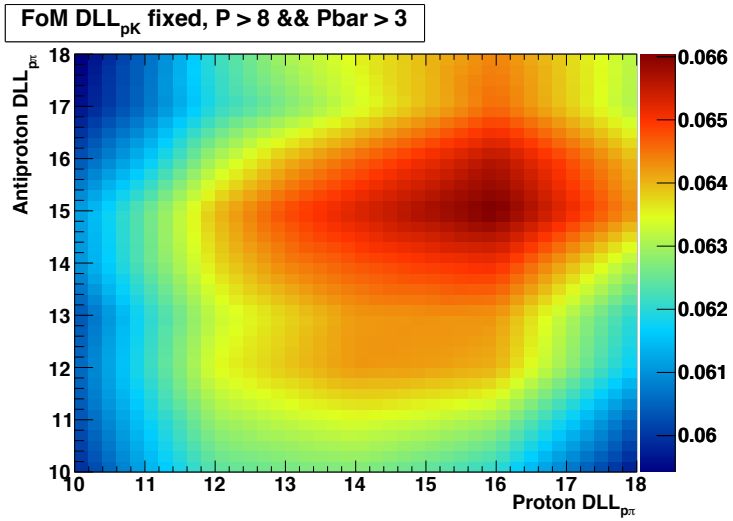
- Branching fraction results using 2011 data:
  $\mathcal{B}(B^0 \to p\bar{p}) = (1.47^{+0.62+0.35}_{-0.51-0.14}) \times 10^{-8}$
  $\mathcal{B}(B^0_s \to p\bar{p}) = (2.84^{+2.03+0.85}_{-1.68-0.18}) \times 10^{-8}$
- All previous theory calculations ruled out by at least 1 order of magnitude at the time!



Selection

- PID Selection optimises $\mathrm{DLL}_{p\pi}$ and DLL_{pK} cuts for Punzi FoM with $a = 5\sigma$
- MVA selection (applied after PID selection) makes use of MLP with 10 variables, again optimised for Punzi FoM.

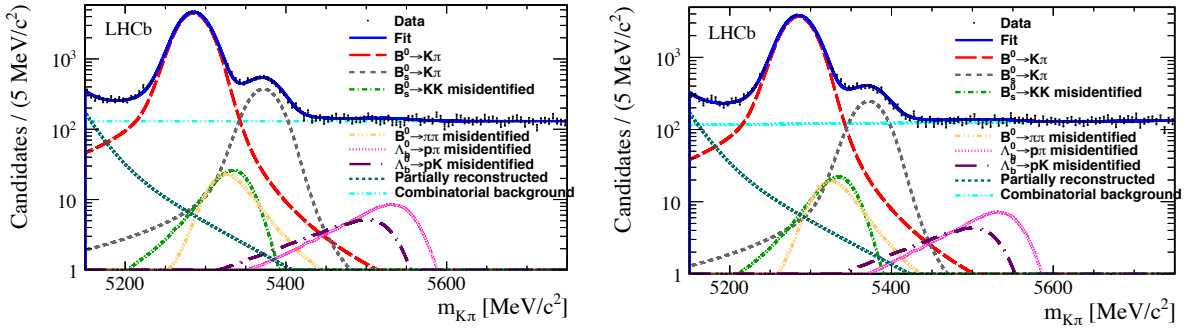




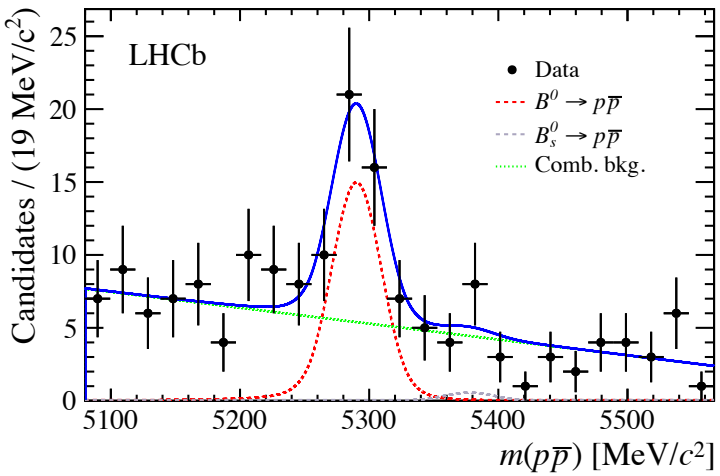
- Normalisation channel, $B^0 \to K^+\pi^-$, PID selection optimised for maximum selection efficiency whilst rejecting various mis-ID backgrounds.
- Similar MLP also used in normalisation channel, but optimised for signal significance.

Fits

- **Normalisation channel:** Mass fit separated by charge due to known production assymmetries

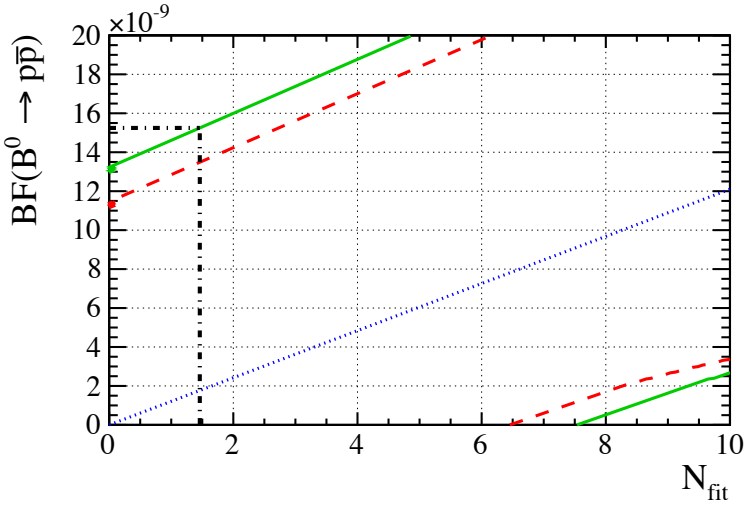


- **Signal channel:** Only signal and combinatorial background present - $38.7 \pm 8.4(statonly)$ $B^0 \to p\overline{p}$ decays observed!



Results and Outlook

- Significance of observed $B^0 \to p\overline{p}$ signal is 5.3σ
- $\mathcal{B}(B^0 \to p\overline{p}) = (1.25 \pm 0.27 \pm 0.18) \times 10^{-8}$ - Rarest hadronic decay of a B^0 meson ever observed!
- $B_s^0 \to p\overline{p}$ yield of only 1.5 ± 4.4 events, limit set using Feldman-Cousins method.



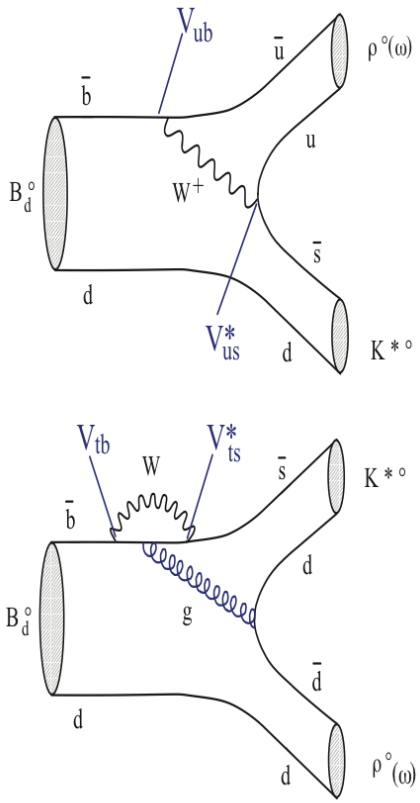
- $\mathcal{B}(B_s^0 \to p\overline{p}) < 1.5 \times 10^{-8}$ at 90% confidence level.
- Approval presentation today, circulation of paper imminent!

Amplitude analysis of $B^0 \to (\pi^+\pi^-)(K^+\pi^-)$ decays

Link to WG database

The $B^0 \to \rho^0(\pi\pi)K^{*0}(K^+\pi^-)$ decay

- Proceeds either via:
  - A doubly Cabibbo suppressed tree
  - A gluonic $b \to s$ penguin
  - Both have similar amplitudes, good for a_{cp}!
- Self tagged decay:
  $B^0 \to \rho^0(\pi\pi)K^{*0}(K^+\pi^-)$
  $\bar{B}^0 \to \rho^0(\pi\pi)K^{*0}(K^-\pi^+)$
- **Aim:** Measure longitudinal polarisation fraction f_L, $\mathcal{A}^{CP}$ and accessible triple product assymmetries.
- Amplitude analysis required to disentangle different helicity amplitudes and final states.

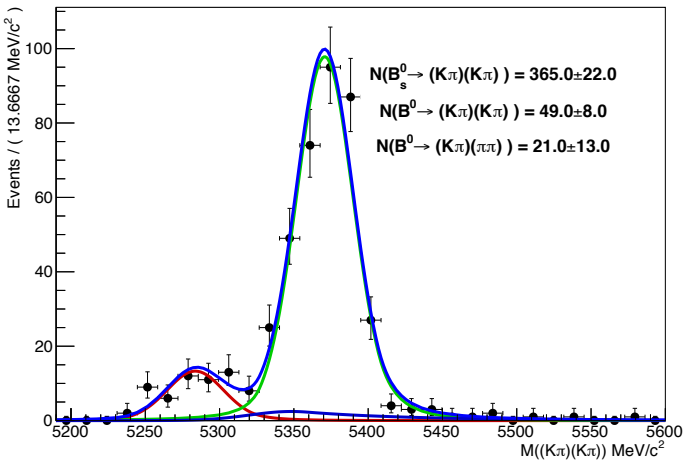


Event Selection

- A BDT is used to reject combinatorial background, cut chosen rejects 99% of background samples whilst retaining $\geq$ 90% of signal MC.
- Charm resonances removed with vetoes
- Tight PID cuts remove most mis-ID backgrounds.

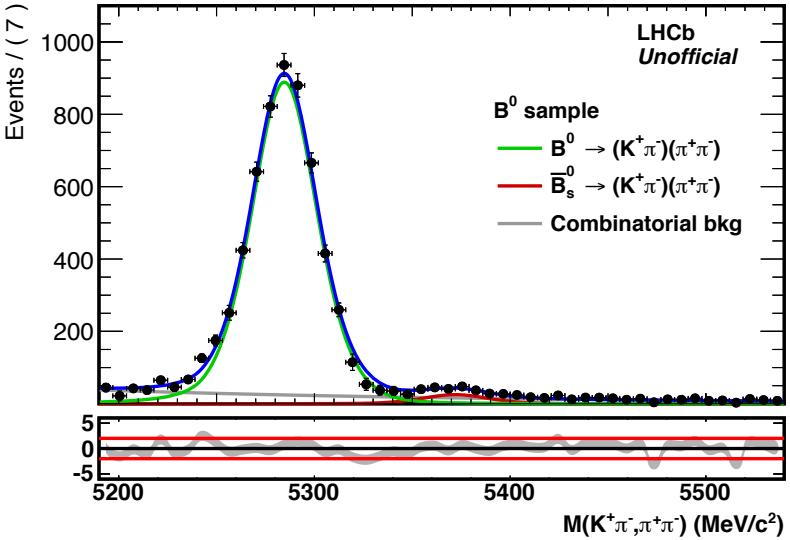
$B_s^0 \to K^{*0}\overline{K}^{*0}$ **background:**

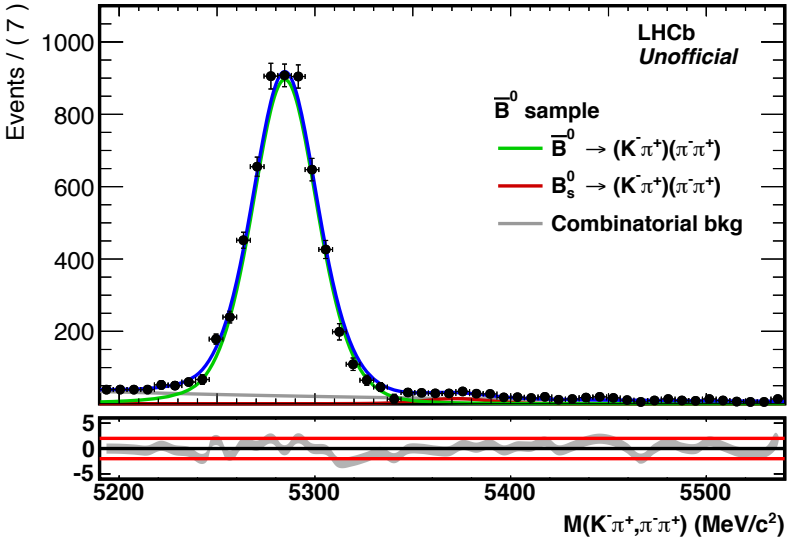
- PID cuts modified to create seperate sample with high purity of these events, M($K\ \pi\ K\ \pi$) fitted to determine level of contamination.
- Simulated $B_s^0 \to K^{*0}\overline{K}^{*0}$ events injected with negative weights to remove $B_s^0 \to K^{*0}(K^-\pi^+)\overline{K}^{*0}(K^+\pi^-)$ background.



Four Body Mass Fit

- **Aim: Perform fit to M(π π K π) distribution and extract sWeights**
- $B^0_{(s)} \to (K^+\pi^-)(\pi^+\pi^-)$ peaks modelled with Hypatia function, combinatorial background modelled with exponential.





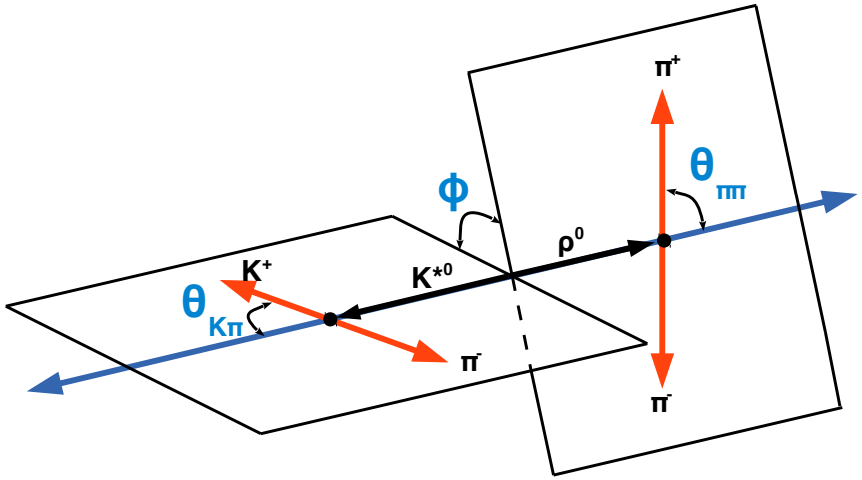
- Total of 11290 $B^0 \to (\pi^+\pi^-)(K^+\pi^-)$ signal events.

Amplitude Analysis Formalism

- Isobar model used to paramaterise the total $B^0 \to (\pi^+\pi^-)(K^+\pi^-)$ decay amplitude:

$$A_T = \sum_i A_i \times g_i(\theta_{\pi^+\pi^-}, \theta_{K^+\pi^-}, \phi) \times M_i(m_{\pi^+\pi^-}, m_{K^+\pi^-}) \qquad (1)$$

- g_i are the legendre polynomials describing the angular distributions
- $M_i(\pi^+\pi^-, K^+\pi^-)$ are functions to model the effective two body masses.



Amplitude Fit

- A PDF has been created to model 11 decay channels and 14 amplitudes.

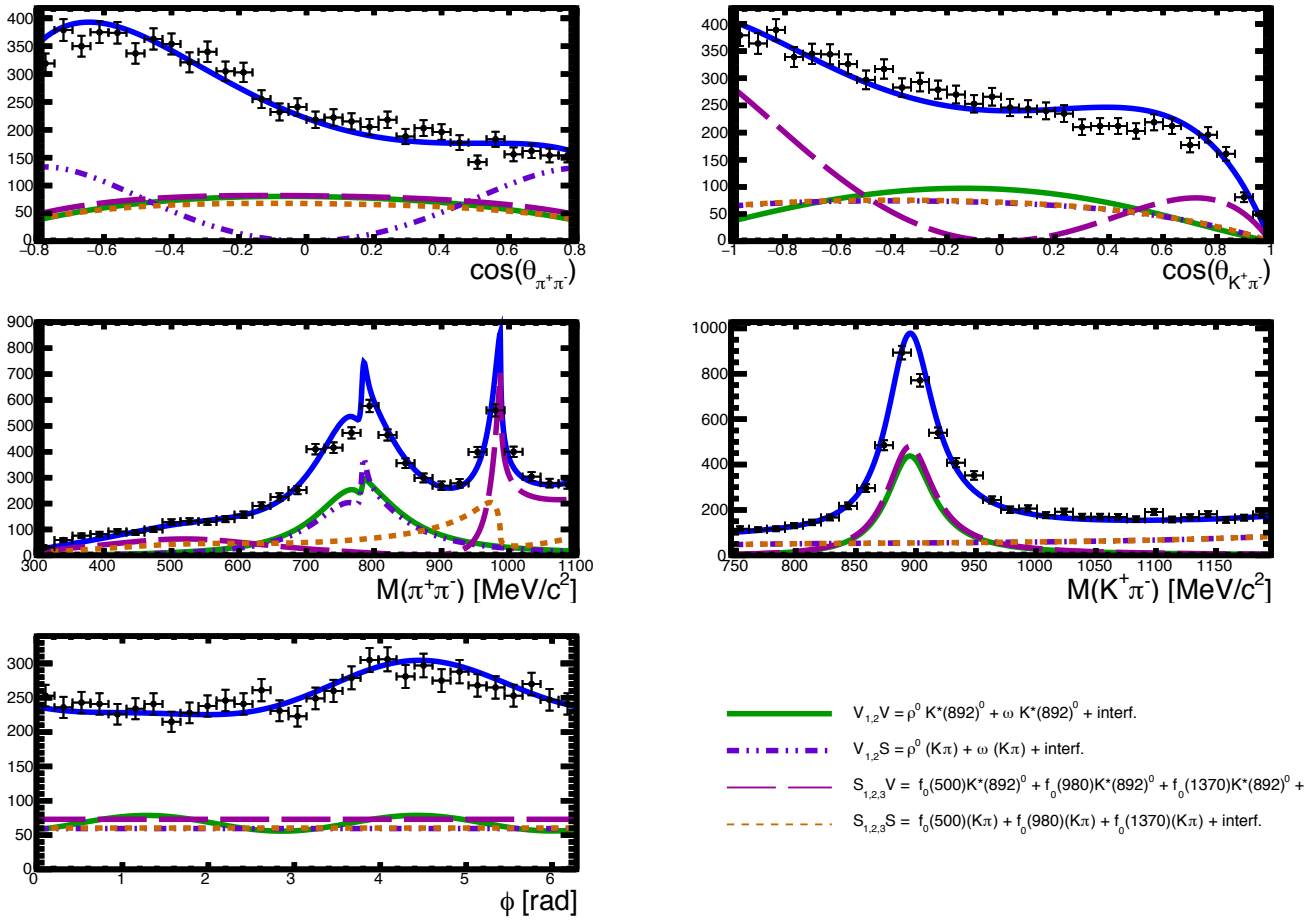
Nominal Mass Propogators:

- K^{*0}, ω, $f_0(500)$,$f_0(1370)$: Relativistic Breit-Wigner
- ρ^0: Gounaris-Sakurai
- $f_0(980)$: Flatte
- $(K\pi)_0$ LASS

i	Type	A_i	$g_i(\theta_{12}, \theta_{34}, \phi)$	$M_i(m_{12}, m_{34})$
1		$A^0_{\rho K^*}$	$\cos\theta_{12}\cos\theta_{34}$	$M_\rho(m_{12})M_{K^*}(m_{34})$
2	V_1V	$A^{\parallel}_{\rho K^*}$	$\frac{1}{\sqrt{2}}\sin\theta_{12}\sin\theta_{34}\cos\phi$	$M_\rho(m_{12})M_{K^*}(m_{34})$
3		$A^{\perp}_{\rho K^*}$	$\frac{i}{\sqrt{2}}\sin\theta_{12}\sin\theta_{34}\sin\phi$	$M_\rho(m_{12})M_{K^*}(m_{34})$
4		$A^0_{\omega K^*}$	$\cos\theta_{12}\cos\theta_{34}$	$M_\omega(m_{12})M_{K^*}(m_{34})$
5	V_2V	$A^{\parallel}_{\omega K^*}$	$\frac{1}{\sqrt{2}}\sin\theta_{12}\sin\theta_{34}\cos\phi$	$M_\omega(m_{12})M_{K^*}(m_{34})$
6		$A^{\perp}_{\omega K^*}$	$\frac{i}{\sqrt{2}}\sin\theta_{12}\sin\theta_{34}\sin\phi$	$M_\omega(m_{12})M_{K^*}(m_{34})$
7	V_1S	$A^0_{\rho(K\pi)}$	$\frac{1}{\sqrt{3}}\cos\theta_{12}$	$M_\rho(m_{12})M_{(K\pi)}(m_{34})$
8	V_2S	$A^0_{\omega(K\pi)}$	$\frac{1}{\sqrt{3}}\cos\theta_{12}$	$M_\omega(m_{12})M_{(K\pi)}(m_{34})$
9	S_1V	$A^0_{f_0(500)K^*}$	$\frac{1}{\sqrt{3}}\cos\theta_{34}$	$M_{f_0(500)}(m_{12})M_{K^*}(m_{34})$
10	S_2V	$A^0_{f_0(980)K^*}$	$\frac{1}{\sqrt{3}}\cos\theta_{34}$	$M_{f_0(980)}(m_{12})M_{K^*}(m_{34})$
11	S_3V	$A^0_{f_0(1370)K^*}$	$\frac{1}{\sqrt{3}}\cos\theta_{34}$	$M_{f_0(1370)}(m_{12})M_{K^*}(m_{34})$
12	S_1S	$A^0_{f_0(500)(K\pi)}$	$\frac{1}{3}$	$M_{f_0(500)}(m_{12})M_{(K\pi)}(m_{34})$
13	S_2S	$A^0_{f_0(980)(K\pi)}$	$\frac{1}{3}$	$M_{f_0(980)}(m_{12})M_{(K\pi)}(m_{34})$
14	S_3S	$A^0_{f_0(1370)(K\pi)}$	$\frac{1}{3}$	$M_{f_0(1370)}(m_{12})M_{(K\pi)}(m_{34})$

- Detector acceptance accounted for with normalisation weights

Results and Outlook



- All CPV observables still blind
- Analysis in WG review.

Search for the decay $\Lambda_b^0 \to pK\eta'$

Link to WG database

Motivation

- η' still not fully understood - size of gluon component in meson wavefunction?

$$|\eta'\rangle \approx \cos\phi_g \sin\phi_p \frac{1}{\sqrt{2}}|u\bar{u} + d\bar{d}\rangle + \cos\phi_g \cos\phi_p |s\bar{s}\rangle + sin\phi_g |gg\rangle \quad (2)$$

  Latest measurement by LHCb: $\phi_g = (0 \pm 24.6)^\circ$ (arXiv:1411.0943), $\phi_p = (43.5^{+1.4}_{-1.3})^\circ$.
- The decay of a b baryon to an $\eta^{(\prime)}$ final state has never been observed, completely unexplored area of charmless B physics.
- 3σ evidence seen for $\Lambda_b^0 \to \Lambda\eta$ at LHCb, $\mathcal{B} = 9.3^{+7.3}_{-5.3} \times 10^{-6}$, and limit set on $\Lambda_b^0 \to \Lambda\eta'$, $\mathcal{B} < 3.1 \times 10^{-6}$ (90%) (LHCB-PAPER-2015-019).

Analysis Strategy

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

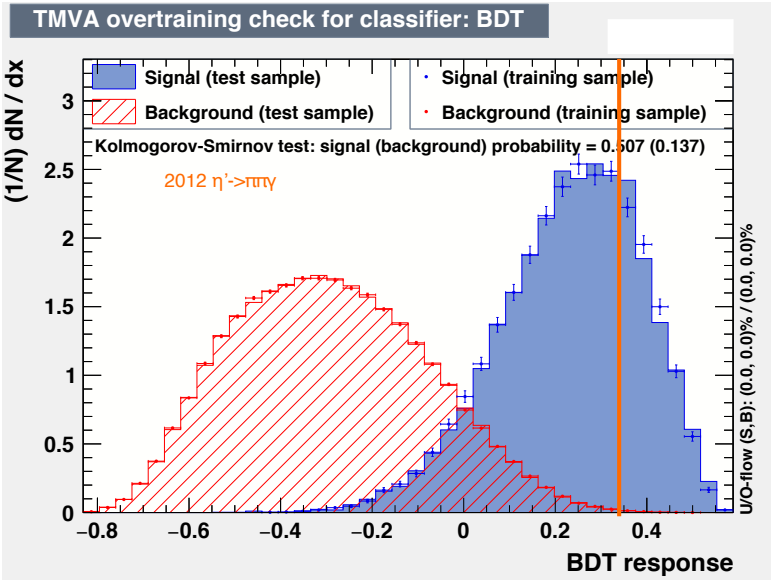
Ratio of branching fractions extracted as:

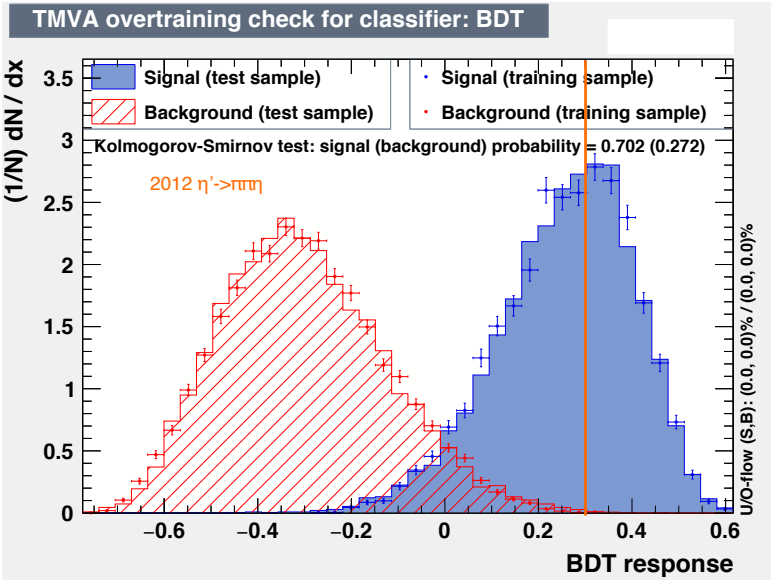
$$\frac{\mathcal{B}(\Lambda_b^0)}{\mathcal{B}(B^+)} = \left(\frac{\epsilon_C N_\gamma}{\epsilon_\gamma N_C} + \frac{\epsilon_C N_\eta}{\epsilon_\eta N_C}\right) \frac{\mathcal{B}(\eta' \to \pi^+\pi^-\gamma)}{\mathcal{B}(\eta' \to \pi^+\pi^-\eta) + \mathcal{B}(\eta' \to \pi^+\pi^-\gamma)} \frac{f_u}{f_\Lambda}$$

- $N_C(\epsilon_C)$,$N_\gamma(\epsilon_\gamma)$ and $N_\eta(\epsilon_\eta)$ are yields (efficiencies) in control, $\eta' \to \pi^+\pi^-\gamma$ and $\eta' \to \pi^+\pi^-\eta$ channels respecitvely.
- Fit all channels simultaneously and extract ratio of branching fractions directly from fit.

Selection

- Train seperate BDTs for each rare channel and optimise for Punzi FoM with $\sigma = 5$.





- Similar BDT used for normalisation channel but optimised for signal significance.
- 3D PID optimisation performed, results in tight cuts on `ProbNN` PID variables for Proton and Kaon, looser cuts for Pions.
- Specific mass vetoes for charm resonances and $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decays.

Efficiency Calculation Procedure

- Rich resonant structure expected in M($p\ K^-$) spectrum but not a priori known.

if Significance $>5\sigma$

- Bin efficiency in square Dalitz plot (SDP) variables m' and θ'.
- Extract sWeights from mass fit - background subtraction.
- Efficiency taken as:

$$\epsilon = \frac{\sum_i^N W_i}{\sum_i^N \frac{W_i}{\epsilon_i}} \qquad (3)$$

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

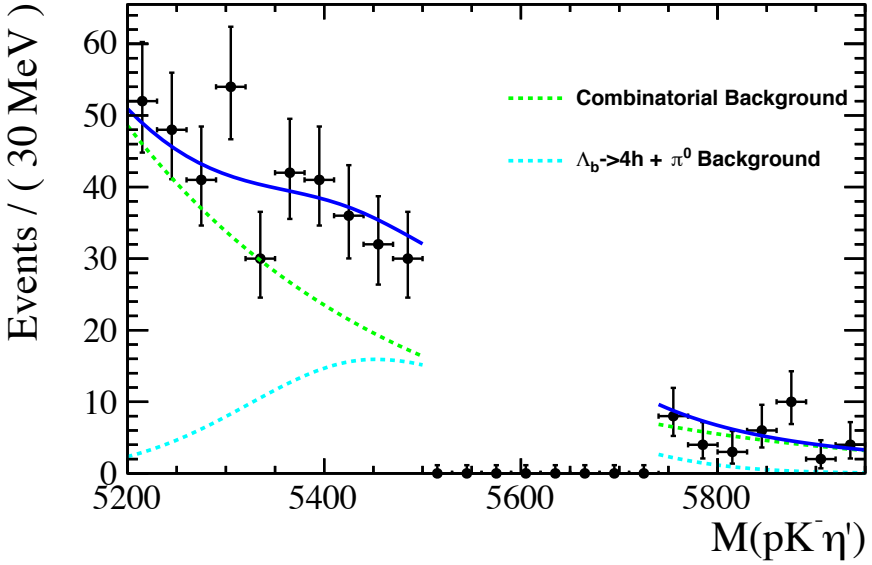
- Need to take into account efficiency variation over phase space of $\Lambda_b^0 \to pK\eta'$ decay.

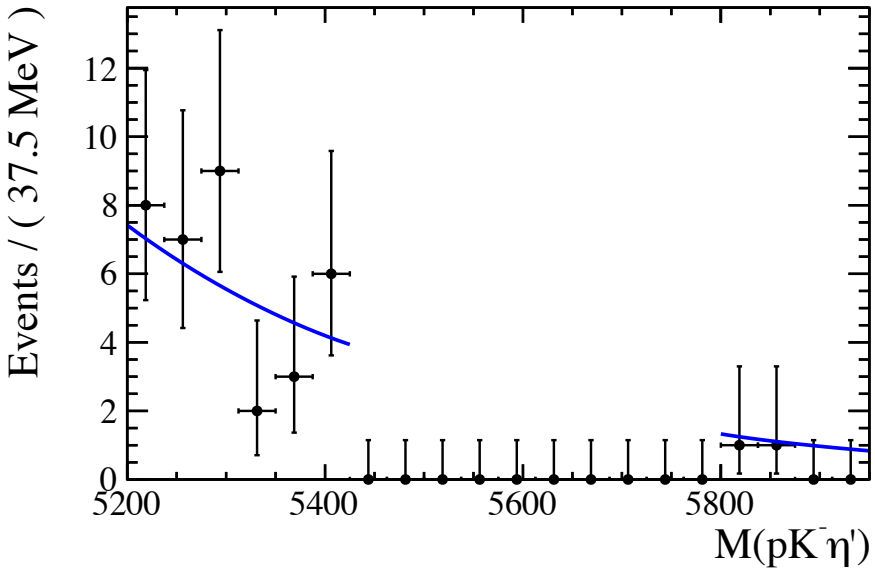
if Significance $<5\sigma$

- Fill 1D histogram of efficiency for each bin of SDP.
- Use mean value for efficiency and assign RMS as systematic uncertainty.

Signal Channel Mass Fits

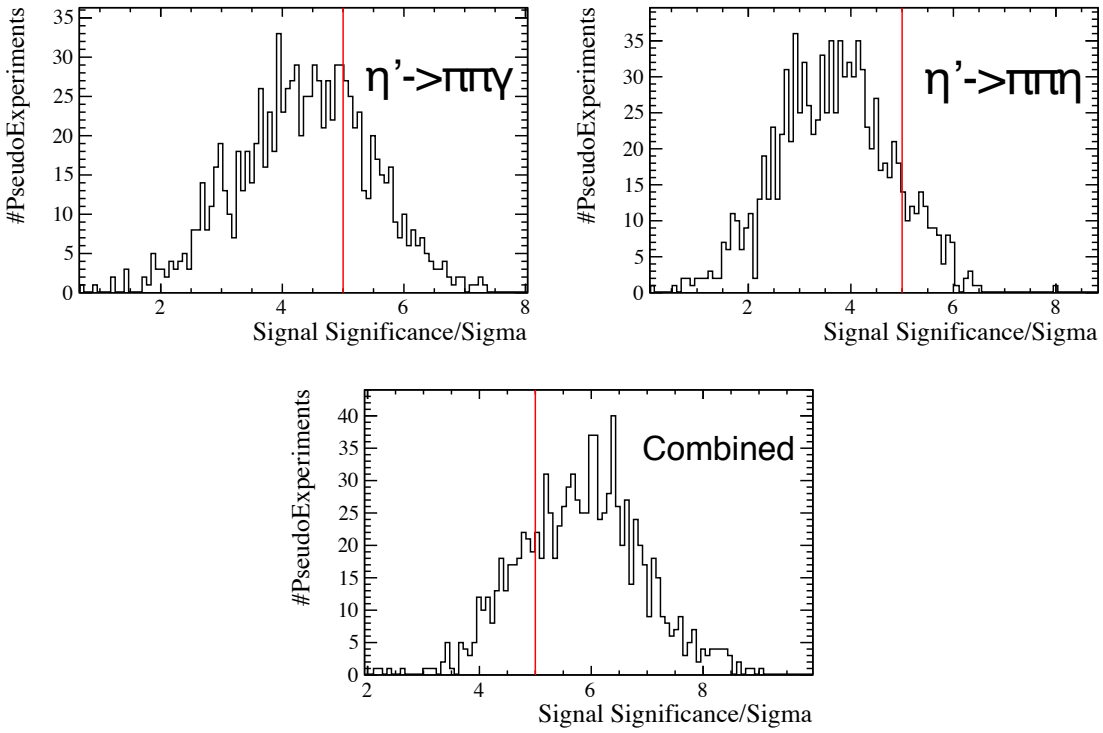
- All signal shapes modelled with DCB
- Combinatorial background modelled with exponential (2nd order polynomial) in rare (control) channel.
- $\eta' \to \pi^+\pi^-\gamma$ channel also suffers from $\Lambda_b^0 \to 4h + \pi^0$ background, modelled with bifurcated Gaussian - shape fixed to MC.





Expected Sensitivity and Outlook

- Toy studies have been performed for a range of $\mathcal{B}$ assumptions - statistical significance caluclated with Wilk's theorem.

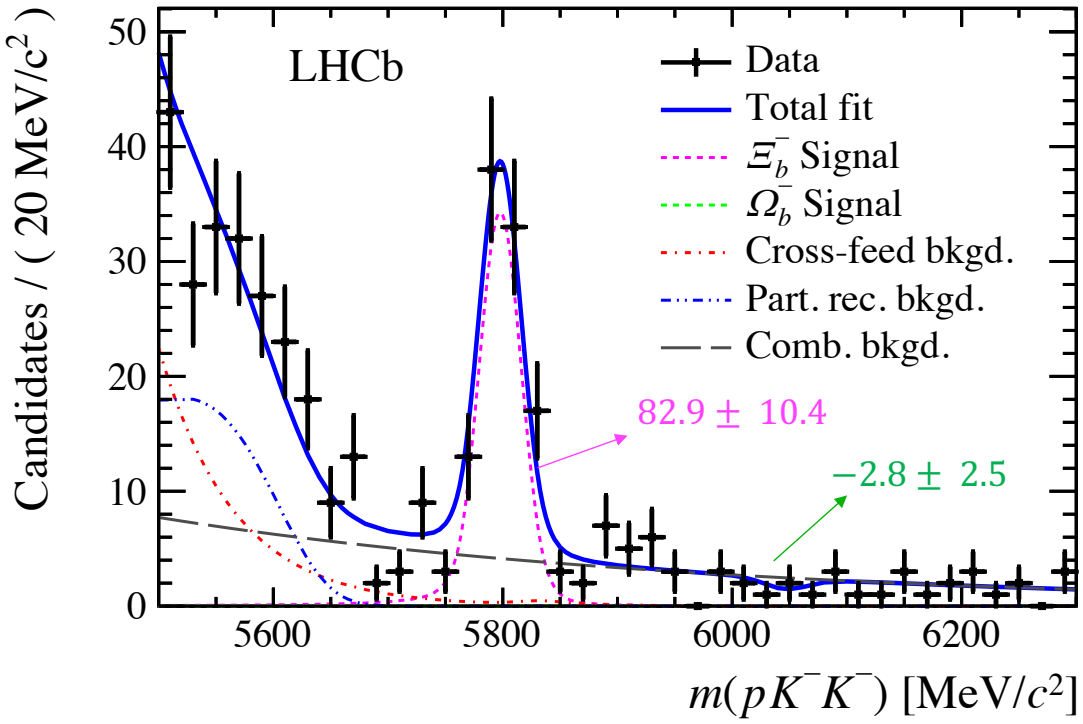


- 77% chance of 5σ observation if $\mathcal{B}(\Lambda_b^0 \to pK\eta')= 4 \times 10^{-6}$
- Analysis in WG review.

Search for CP violation in $\Xi_b^- \to pK^-K^-$ decays.

Overview

- $\Xi_b^- \to pK^-K^-$ was observed for the first time using Run I data [Phys. Rev. Lett. 118, 071801].
- Next step is a search for CPV, possibly using amplitude analysis.



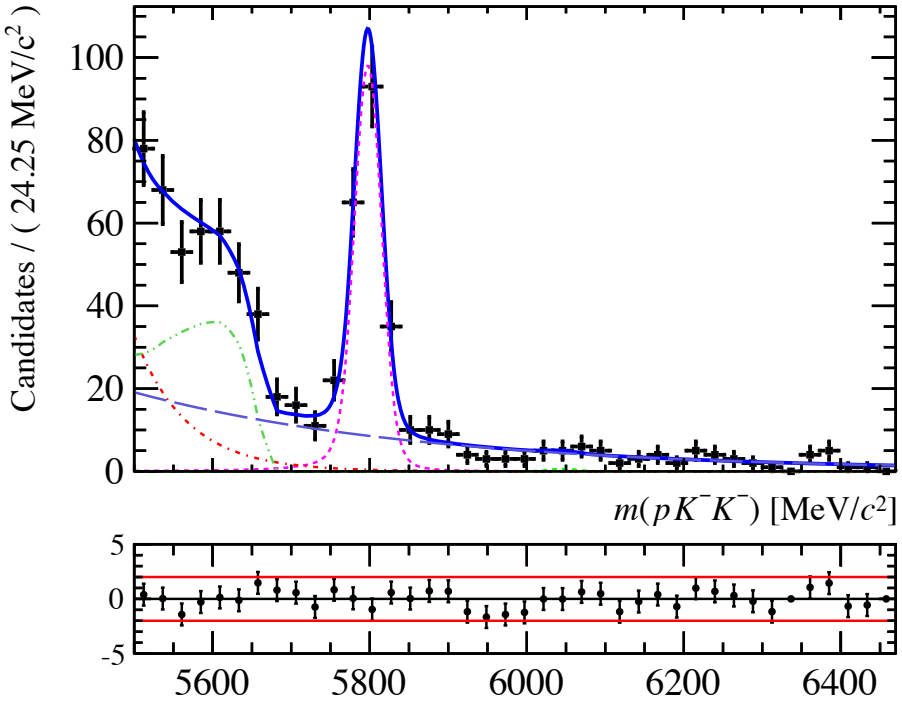
- More events required - Improve selection and add Run II data.

$\Xi_b^- \to pK^-K^-$ Run I improvements

Changes to Run I selection

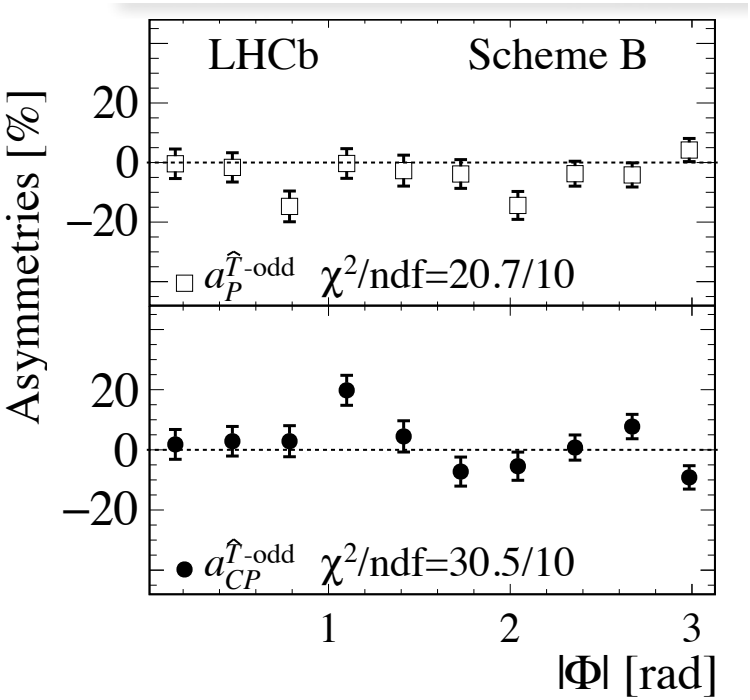
- Switch to using inclusive `Xb2phhLine` stripping line - 15% improvement in stripping efficiency.
- Include PID and isolation variables in MVA, use `xGBoost` algorithm and optimise for signal significance.

- Very preliminary fit to Run I data shows yield of 189 ± 18 events with new selection.
- Plan to include Run II data to search for CPV.

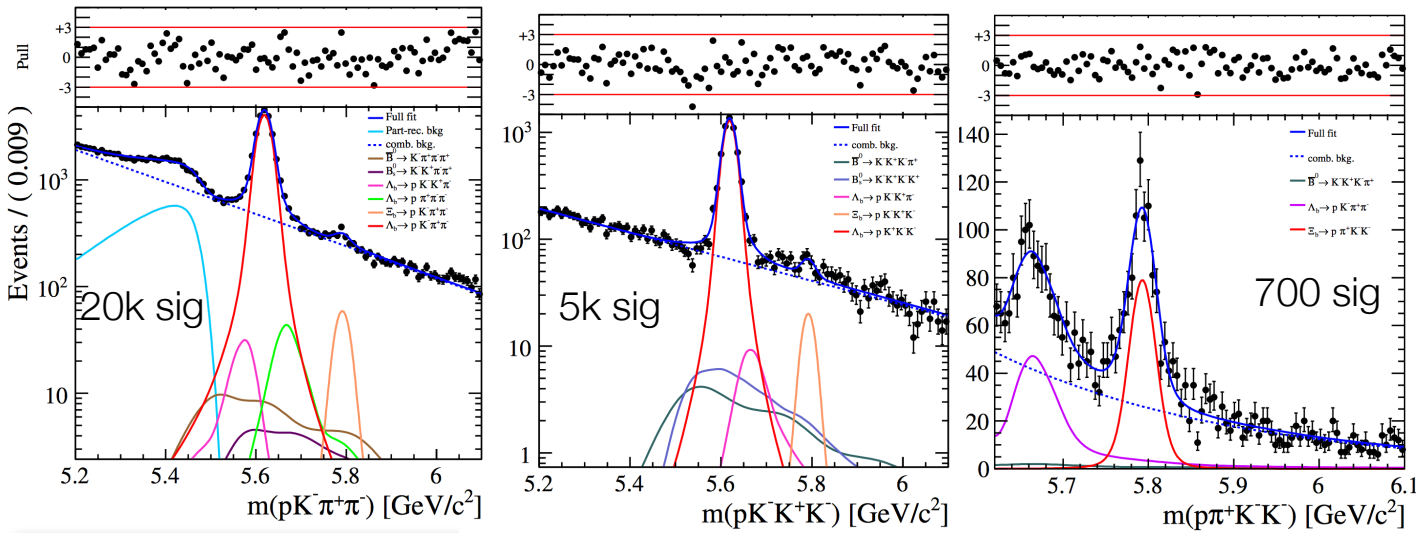


CPV in $\Lambda_b^0/\Xi_b^0 \to phhh$

Current Status



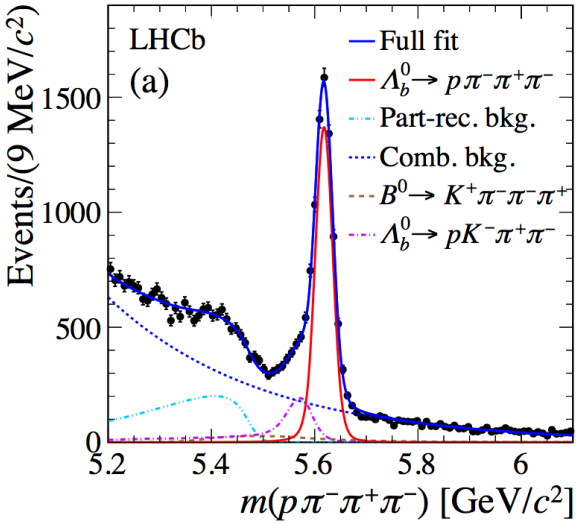
- Using Run I data 3.3σ evidence for CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays was observed.
- Used triple product asymmsetries.
- First evidence for CPV in a baryon decay! Nature Physics 13 (2017)
- More results from other deacy modes in review comittee!



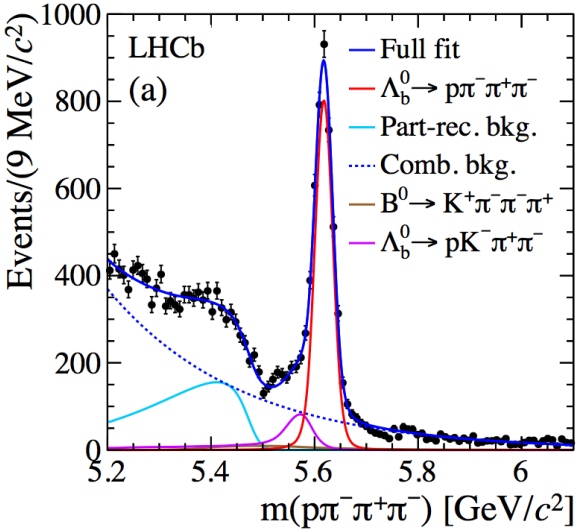
Run II Update

- Run II update of CPV analyses planned.
- Expect factor ~ 3 increase in signal yield with addition of 2016 and 2017 data

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ 7k → 22k sig events



run 1: 6646±105
σ=16.9±0.3 MeV
μ=5618.0 ± 0.3



2016, MD: 3970±78 Magnet down
σ=17.1±0.3 MeV
μ=5618.1 ± 0.3

- First look at 2016 MagDown data shows promising yield - selection not optimised and cross-feed studies needed

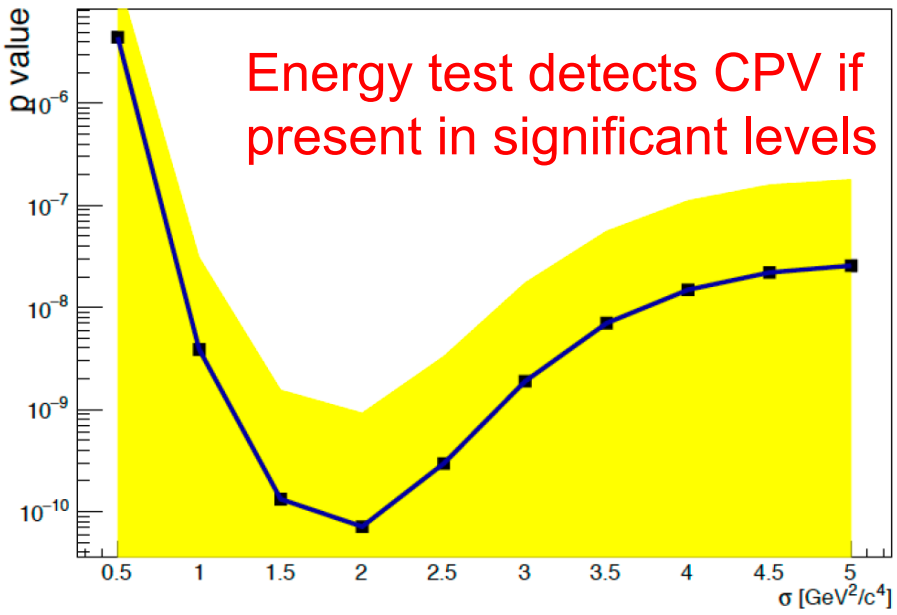
Energy Test

- Work under way to use energy test method to search for both P even and P odd CP violation - arxiv:1612.04705
- Define test statistic based on distances between particles and anti-particles in phase space.

$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\overline{n}} \frac{\psi_{ij}}{\overline{n}(\overline{n}-1)} - \sum_{i,j}^{n,\overline{n}} \frac{\psi_{ij}}{n\overline{n}},$$

$$\psi_{ij} \equiv \psi(d_{ij}) = e^{-d_{ij}^2/2\sigma^2}$$

- Sensitivity studies based on RunI + 2015 +2016 data performed using cocktail of RapidSim samples, CPV artificially introduced by increasing relative fraction of Δ^+ events by 30%.



Summary of $\Lambda_b^0/\Xi_b^0 \to phhh$ CPV searches

- First evidence for CP violation has been seen in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays at level of 3.3σ using Run I data - Run II update planned.
- Run I results for $\Lambda_b^0 \to pK^-\pi^+\pi^-$, $\Lambda_b^0 \to pK^-K^+K^-$ and $\Xi_b^0 \to p\pi^+K^-K^-$ decays still blind and in review comittee.
- Work started on using energy test method to search for CP violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays using Run I + Run II data.
- Further analyses aiming to measure $\mathcal{A}^{CP}$ and BFs for $\Lambda_b^0 \to phhh$ decays are well advanced in the RC.

Conclusions

- Lots of interesting work taking place in BnoC group on wide range of analyses.
- Several analyses in review using Run I data
- Many more analyses using Run II data in preperation e.g:
  - $B_s^0 \to \phi\phi$ (in WG review)
  - $B_c^+ \to K^+ K^- \pi^+$
  - $B_s^0 \to K_S^0 K_S^0$
  - TD CPV in $B_{(s)}^0 \to hh$ decays
  - CPV in $\Lambda_b^0 \to K_S^0 ph$
  - $B \to 3h$ BFs
- Lookout for dedicated talks on $B^+ \to \pi^+\pi^-\pi^+$ (Thursday) and $B_{(s)}^0 \to K_S^0 hh$ (Today).

Backup

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