Testing Lepton Universality in Rare Decays of Λ_b Baryons using LHCb Data

Sean Kirwan, on behalf of the LHCb collaboration

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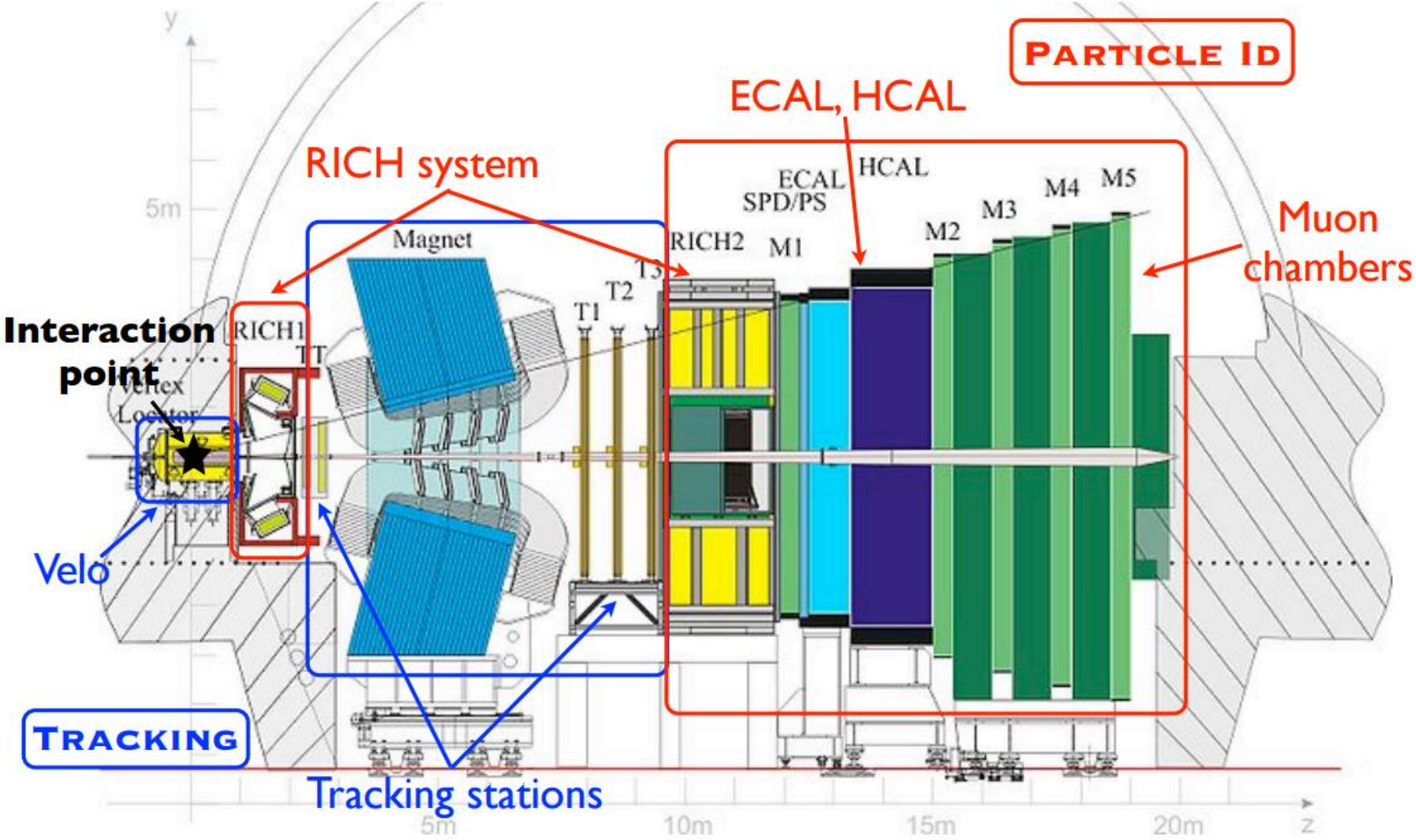
Outline

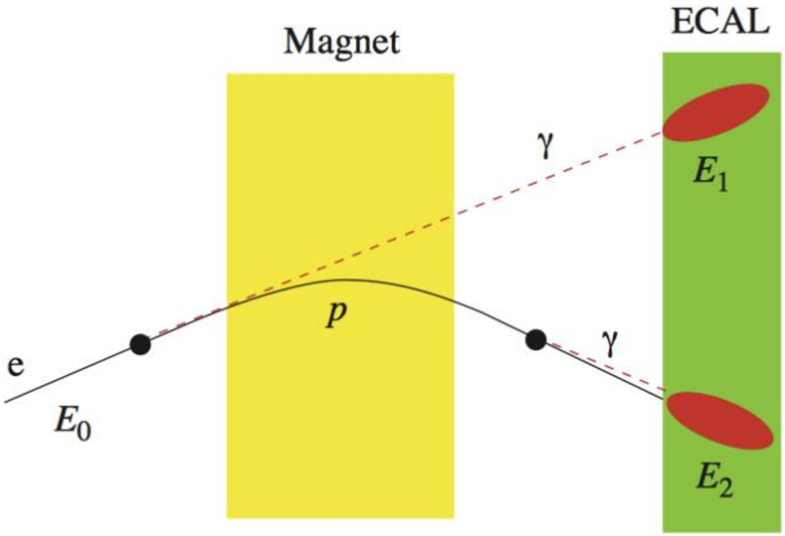
- Theoretical Motivation
- Pre-selection
- Multivariate selection
- Outcome of the current selection
- Status and plans for the analysis

The LHCb Detector



Bremsstrahlung

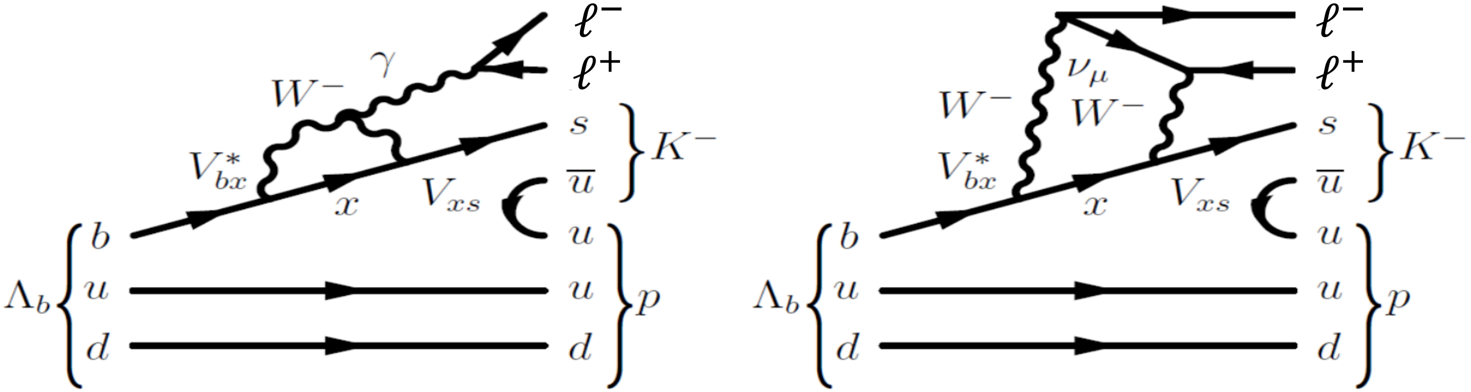
- Electrons suffer very noticeable Bremsstrahlung losses.
- Photon can be emitted before or after the magnet.
- Energy is recovered by looking at photon hits in the ECAL.
- Corrections are useful but not perfect. We have quite a bit of broadening in the electron mode.



- Emission before the magnet – Low density inside magnet region allows photon's path to the ECAL to be described by a simple extrapolation of the electron's original path.
- Emission after the magnet – the Bremsstrahlung photon deposits its energy in the same ECAL cell as the electron and the energy is recovered easily.

Rare Decays

- The rare decay $\Lambda_b^0 \rightarrow pK^-\ell^+\ell^-$ proceeds via the FCNC $b \rightarrow s\ell\ell$, which only occurs in the SM via electroweak penguin and $W^\pm$ box diagrams.



- These processes are suppressed in the SM, but new physics can enter into the loops and increase the amplitudes.

Operator Product Expansion

- The effective Hamiltonian for this decay can be expressed as an operator product expansion.

$$H_{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_{i} [\underbrace{C_i(\mu)O_i(\mu)}_{\textit{left-handed part}} + \underbrace{C_i'(\mu)O_i'(\mu)}_{\substack{\textit{right-handed part} \\ \text{suppressed in SM}}}]$$

- For $b \to s\ell\ell$ transitions it is dominated by the operators O_7, O_9 and O_{10}, along with their respective Wilson coefficients C_7, C_9 and C_{10}.

- New physics may add contributions to the C_i' or introduce new operators O_i' that do not respect lepton universality.

Measuring Lepton Universality

- The parameter

$$R_{pK} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)}$$

is expected to be unity in the SM ($\pm\,\mathcal{O}(10^{-3})$), as electroweak interactions are required to couple equally to all lepton flavours.

JHEP 12 (2007) 040, for similar ratio R_K

- If this ratio deviates from unity, it could be a sign of new physics that does not respect lepton universality.

Why this Λ_b^0 Decay?

- The decay $B^+ \to K^+\ell^+\ell^-$ proceeds via the same FCNC. Its corresponding ratio R_K was measured by LHCb in 2014 and was found to be $0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$.
- This result is 2.6 standard deviations away from the SM prediction.
- A lepton universality measurement involving this FCNC in a new channel is therefore of great interest in the search for new physics.
- LHCb also has measurements of R_{K^*} (underway) and R_{D^*} (published).

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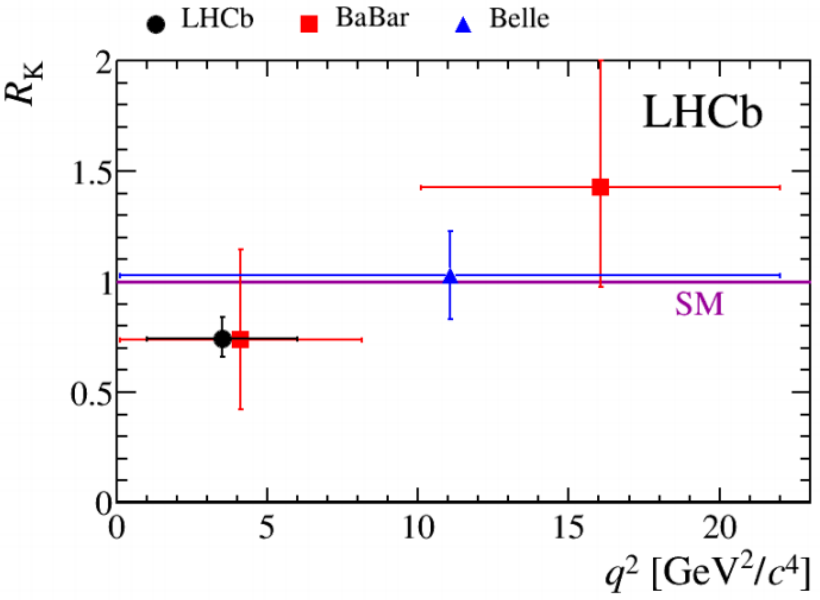
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$



LHCb: PRL 113 (2014) 151601
Babar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801

Data

- This analysis uses the full 3fb^{-1} collected by LHCb in 2011–2012 (1fb^{-1} at $\sqrt{s} = 7$ TeV from 2011 and 2fb^{-1} at $\sqrt{s} = 8$ TeV from 2012).

- Looking at favoured dilepton invariant mass squared (q^2) region $1 < q^2 < 6$ GeV/c^2, with possibility to extend further.

- As part of the analysis, smaller samples of 0.9fb^{-1} for the muon mode and 0.7fb^{-1} for the electron mode are being used for verification with the J/ψ control channel (more on this shortly).

- Before the analysis, the data are subjected to a loose 'stripping' selection to reduce the sample size.

Analysis Strategy

- The analysis seeks to measure R_{pK} using the double ratio

$$R_{pK} = \frac{\left(\frac{\mathcal{B}(\Lambda_b^0 \to pK^- \mu^+ \mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+ \mu^-))}\right)}{\left(\frac{\mathcal{B}(\Lambda_b^0 \to pK^- e^+ e^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to e^+ e^-))}\right)}$$

- This serves to cancel out a lot of the systematic errors arising in the measurement of these branching fractions.

- The decay $\Lambda_b^0 \to pK^- J/\psi(\to \ell^+ \ell^-)$ is also a useful control channel to verify our selection.

The J/ψ Control Channel

- $\Lambda_b^0 \to pK^- J/\psi(\to \ell^+\ell^-)$ has the same final state as the rare mode and has been studied previously.
- PDG gives equal branching fractions for J/ψ decaying to electrons and muons.
- We therefore expect

$$\frac{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-))} = 1$$

- This will be verified as part of the selection procedure.

Pre–selection

- Refers to selection made before the data is passed to the multivariate classifier (more on this shortly).

- Selection criteria imposed on particle identification (PID) and other variables.

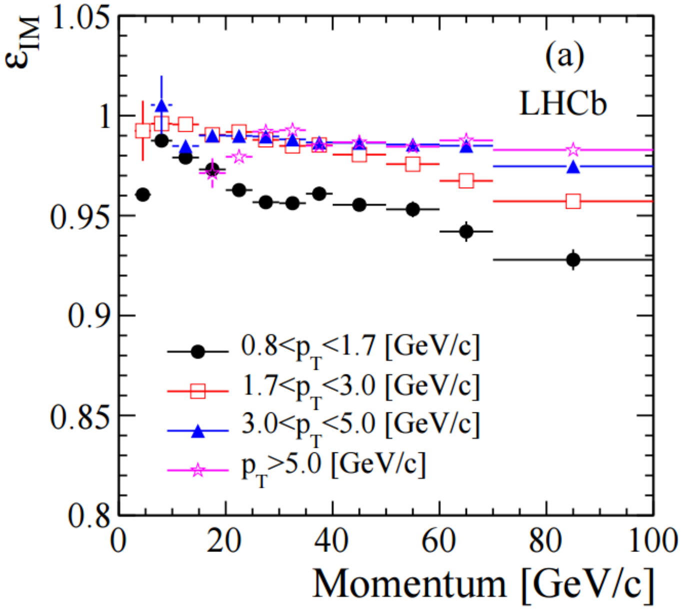
- Vetoes also imposed to remove backgrounds that peak in the $pK\ell\ell$ mass spectrum.

PID and Other Variables

- Information from the particle ID system at LHCb is used to produce variables that describe how likely it is that a given candidate is a proton, kaon, pion, electron or muon.

- Muon identification efficiency at LHCb is ~97%.

- Selection also performed on transverse momenta of final state particles.



JINST 8 (2013) P10020

Peaking Backgrounds

- After PID selection we may still have particles from other decays mis-identified as products of our Λ_b^0 decay.

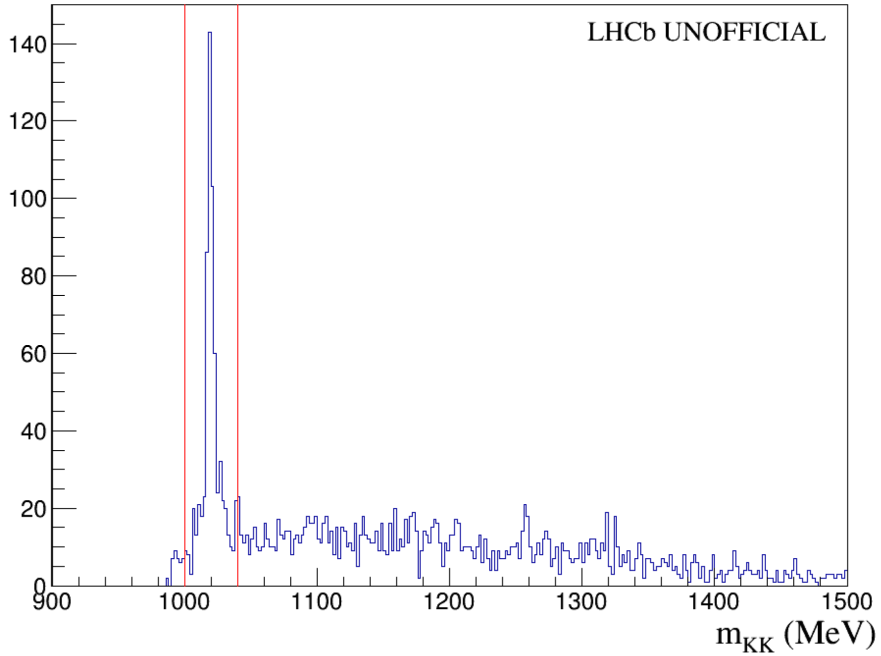
- This causes non-signal peaks in the $m_{pK\mu\mu}$ spectrum. There are two major contributors; removal described on the next slide.

- $\bar{B}^0 \to J/\psi\, \bar{K}^*(\to K^+\pi^-)$ where the either the pion has been misidentified as a proton or both the kaon and pion have been misidentified as a proton and kaon respectively.

- $\bar{B}_s^0 \to J/\psi\, \phi(\to K^+K^-)$ where one of the kaons has been misidentified as a proton.

Peaking Background Removal

- The masses of various daughter particles are assigned to the particles in our final state.
- If a combination produces a peak at the mass of a known particle, this indicates a background decay present in the dataset.
- For example, the figure shows the two-particle mass distribution after the proton candidate has been assigned a kaon mass.



- Clear peak at the Φ mass is removed by rejecting events in the region shown.

Multivariate Selection

- Combinatorial background produced when final state tracks from different Λ_b^0s are reconstructed together.

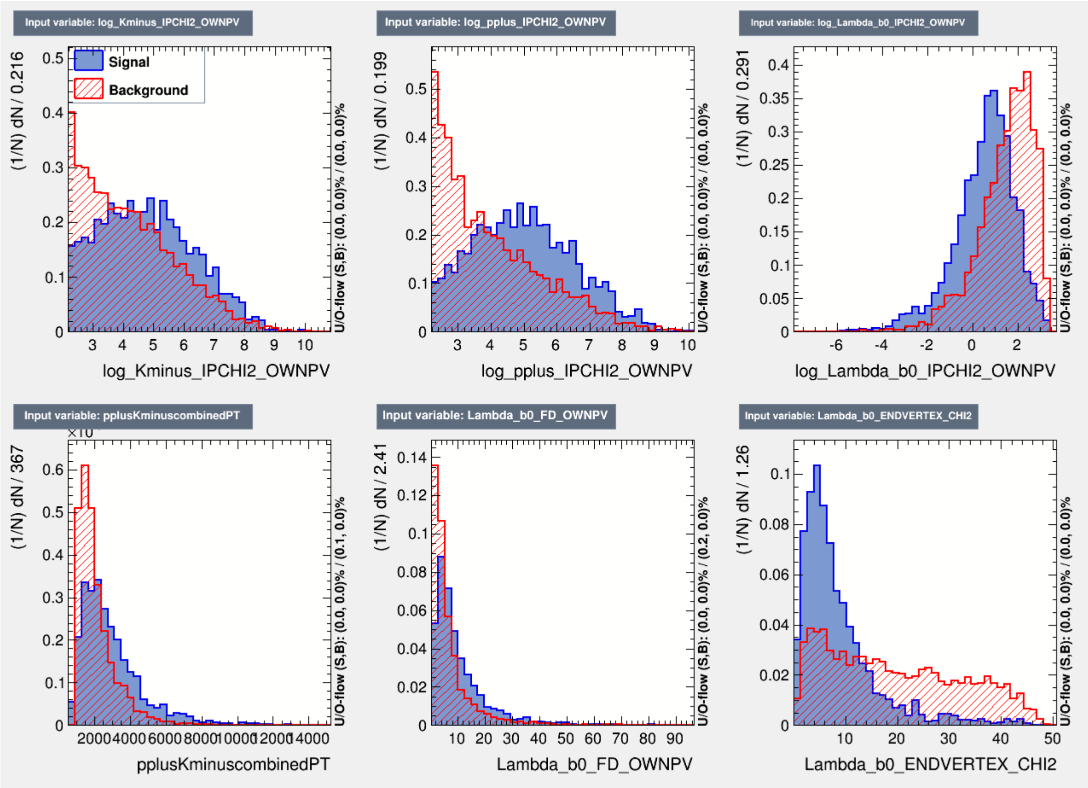
- Removed using a Boosted Decision Tree algorithm (BDT).

- BDT is trained using a Monte Carlo simulated sample to represent the signal and a sample of real data in the upper mass sideband to represent the background.

- A selection of variables is used for training that provides good signal/background separation.

Multivariate Selection Variables

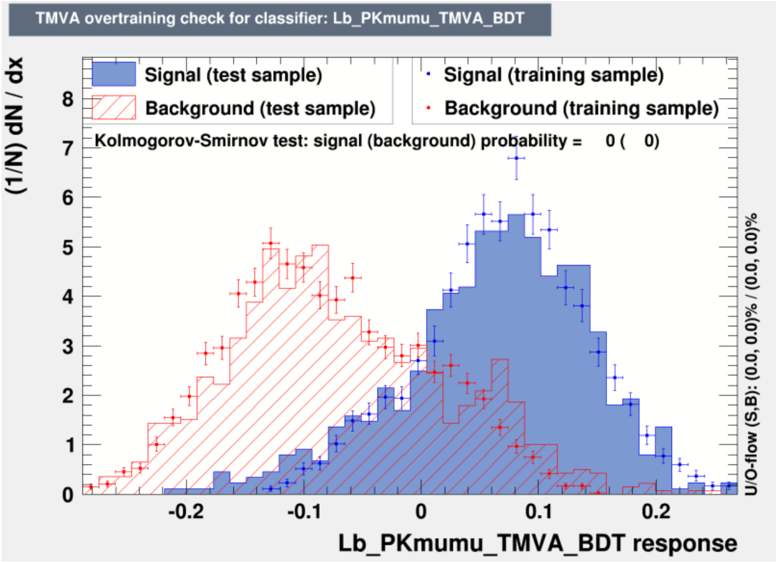
- $\log\left(K^{-}\chi^{2}_{\mathrm{IP}}\right)$
- $\log\left(p\,\chi^{2}_{\mathrm{IP}}\right)$
- $\log\left(\Lambda^{0}_{b}\,\chi^{2}_{\mathrm{IP}}\right)$
- $\mathrm{p}_{\mathrm{PT}} + \mathrm{K}_{\mathrm{PT}}$
- Λ^{0}_{b} flight distance
- $\Lambda^{0}_{b}\,\chi^{2}_{\mathrm{vertex}}$

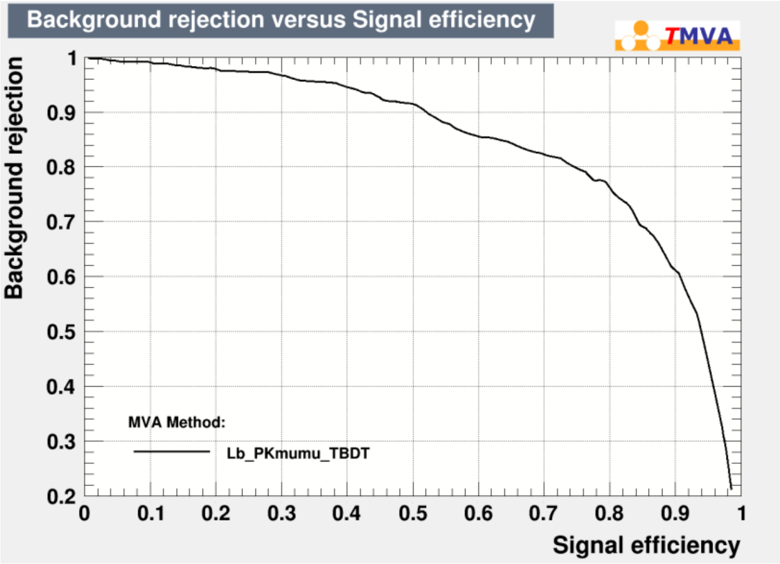


- Figure shows Monte Carlo signal (blue) and upper sideband background (red) distributions of the input variables in the muon mode.

Multivariate Selection

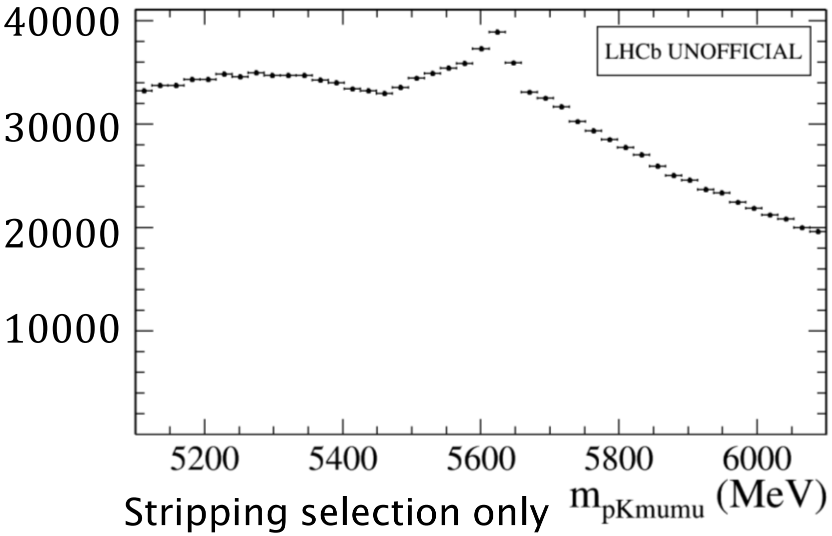
- BDT response shown here for a small sample in muon mode.
- Events tentatively selected for which the response is greater than 0.02.



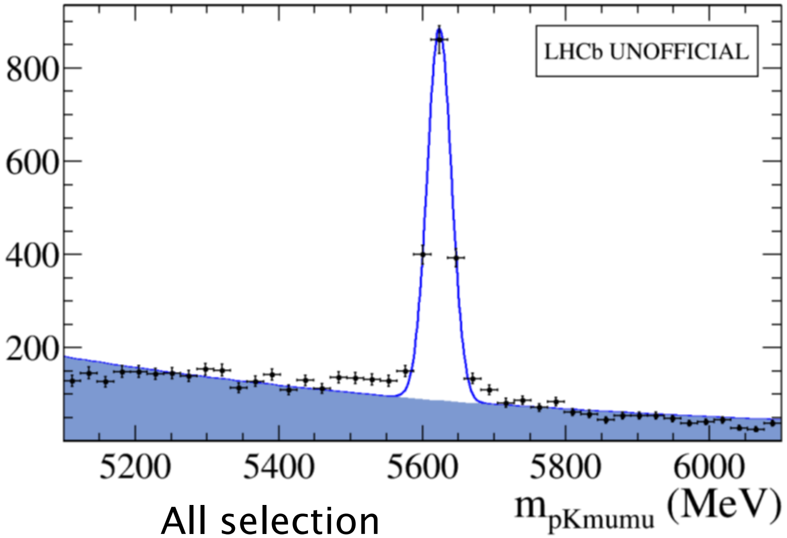


Outcome of Current Selection

- Probability Density Function (PDF) made for the muon mode after all selection has been applied.
- Signal fitted with Crystal Ball function, remaining background approximated by an exponential.
- Work still in progress to refine the model.
- Shown here is a comparison of the data after stripping selection only (top) and after stripping, pre- and multivariate selection (bottom).



Stripping selection only



All selection

A Note on Systematics

- The contributions of the various sources of systematic errors have yet to be worked out, but it is possible to identify some of the sources.

- In the electron mode, an uncertainty is present in the signal model. This is negligible in the muon mode due to excellent dimuon mass resolution at LHCb.

- Some residual uncertainties will not cancel in the double ratio due to different final state kinematics between the control channel and rare modes.

- Selection efficiencies will be calculated using simulated data, which will not perfectly resemble real data.

Conclusion: Status and Plans

- The measurement of R_{pK} is being developed. If the result differs from unity, this could indicate new physics beyond the SM.

- The analysis is a work in progress.

- J/ψ channel is used as a control channel for developing the selections.

- Any remaining physics backgrounds will be modelled with simulated data.

- We expect this to be completed in the coming months.

Backup Slides

Stripping Selection

Particle	Requirement
b hadron	Flight $\chi^2 < 100$ DIRA > 0.9995 Impact Parameter $\chi^2 < 25$ Vertex $\chi^2 < 9$
Dilepton	PT > 0 Flight Distance $\chi^2 > 16$ Impact Parameter $\chi^2 > 0$
$\ell^{\pm}$	Impact Parameter $\chi^2 < 9$ PT > 300
K, p	Impact Parameter $\chi^2 < 9$ PT > 400
$\ell = \mu$	IsMuon = TRUE
$\ell = e$	PIDe = 0

Definitions of PID variables

- Information from the particle ID systems shown on slide 3 is used to create likelihoods that a candidate is a $\pi^{\pm}$, p, K, $e^{\pm}$ or $\mu^{\pm}$.
- The Difference of the Log Likelihoods (DLL) is a logarithm of the ratio between a likelihood to be one particle and the likelihood to be a pion – pion likelihood used as a reference.
- For example $DLL_{e\pi} = \ln L(e) - \ln L(\pi)$ is a measure of how electron-like a particle is compared to a pion.
- This variable is combined with information about the track of the candidate in a neural network to produce another variable called ProbNN.
- For example pplus_ProbNNk is the probability that a proton candidate is a kaon.

Specifics of Pre-selection

Particle	$\boldsymbol{\ell = \mu}$	$\boldsymbol{\ell = e}$
p	ProbNNp > 0.1 ProbNNpi < 0.7 ProbNNk < 0.8	log(ProbNNp) > -1.0 log(ProbNNpi) < -0.4 log(ProbNNk) < -0.2
K^-	ProbNNk > 0.2 ProbNNpi < 0.6	ProbNNk > 0.2 log(ProbNNpi) < -0.4
$\ell^\pm$		ProbNNe > 0.4 log(ProbNNpi) < -0.3

- Table shows requirements imposed on PID variables.
- In both the electron and muon mode, the combined transverse momentum of proton and kaon is required to be >1000 MeV/c.
- In the electron mode only, the transverse momenta of both leptons are required to be between 350 MeV/c and 25000 MeV/c, where the upper limit serves to remove events that are clearly non-signal.

Specifics of Veto Selection

Decay	$\ell = \boldsymbol{\mu}$	$\ell = \boldsymbol{e}$
$\bar{B}^0 \to J/\psi\, \bar{K}^*(\to K^+\pi^-)$	$5250 < m_{\pi K\mu\mu} < 5310$ MeV/c^2 $5250 < m_{K\pi\mu\mu} < 5310$ MeV/c^2	
$B_s^0 \to J/\psi\, \phi(\to K^+K^-)$	$5340 < m_{KK\mu\mu} < 5400$ MeV/c^2	
$\bar{K}^* \to K^+\pi^-$	$880 < m_{K\pi} < 910$ MeV/c^2 $880 < m_{\pi K} < 910$ MeV/c^2	$860 < m_{K\pi} < 930$ MeV/c^2 $860 < m_{\pi K} < 930$ MeV/c^2
$\phi \to K^+K^-$	$1000 < m_{KK} < 1040$ MeV/c^2	$1000 < m_{KK} < 1030$ MeV/c^2

- Table shows mass regions that are vetoed to remove peaking background decays.

- No veto is made on B decays in the electron channel because broadening due Bremsstrahlung corrections means that any meaningful veto results in heavy signal losses.