Testing Lepton Universality with a measurement of R_{pK} in LHCb

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On behalf of the LHCb collaboration

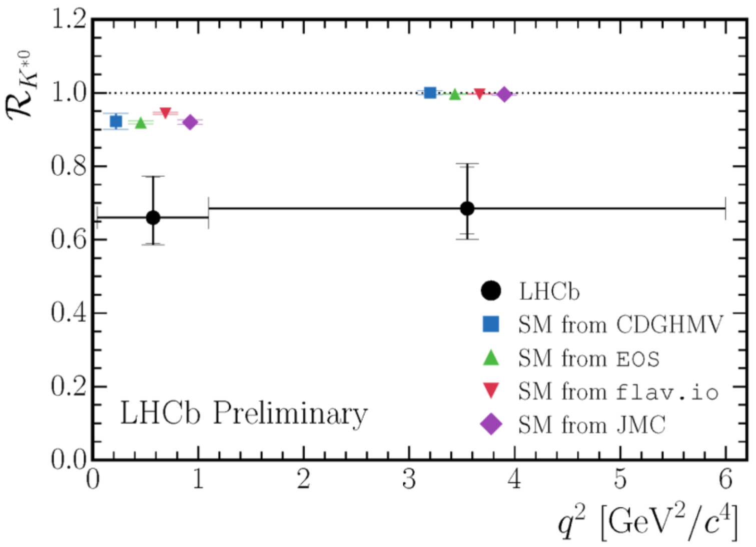
Lepton universality test at the LHCb

- Due to Lepton Universality (LU) the ratios of branching fractions $R_{K^{*0}}$ and R_K, for the decays $B^0 \to K^{*0}\ell^+\ell^-$ and $B^+ \to K^+\ell^+\ell^-$, are predicted to be unity in the $1.1\mathrm{GeV}^2/\mathrm{c}^4 < q^2 < 6GeV^2/c^4$ by the SM [1].

- The measurement of the $R_{K^{*0}}$ (in two q^2 bins) and R_K have found values 2.1-2.3, 2.4-2.5 and 2.6 standard deviations away from SM prediction.

- Hints at New Physics (NP) and the presence of new particle, such as heavy gauge boson Z' or leptoquarks!

- Investigation of similar ratios will provide information on LU-violation.



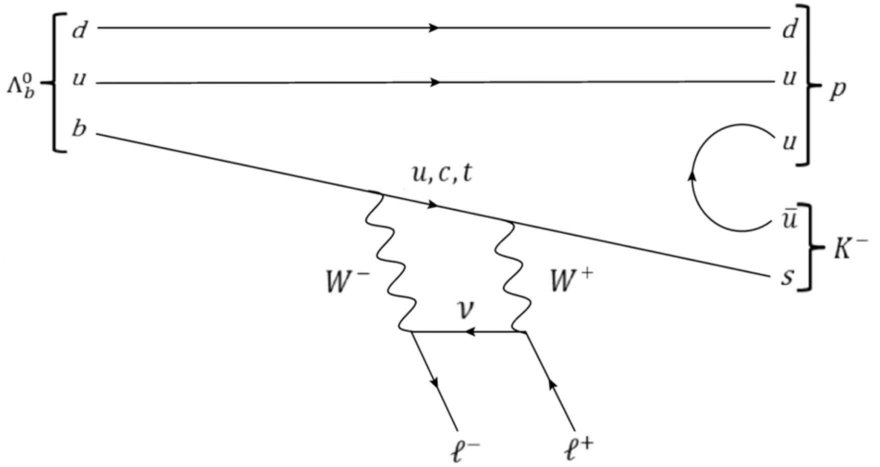
Results from recent LU test [2]

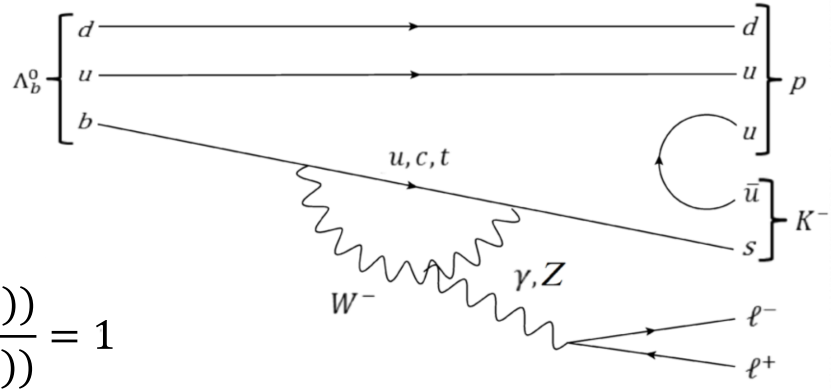
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \qquad R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$

[1] Isidori et al., EPJC 76 (2016)
[2] https://arxiv.org/pdf/1705.05802.pdf

The $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decay

- Flavour changing neutral current decay governed by quark level process $b \to s\ell^+\ell^-$.
- Forbidden at tree level in SM, entering at loop level through electroweak penguin and box diagrams.
- Highly supressed and very sensitive to NP.
- To reduce systematic uncertainties the, well studied [3], control channels $\Lambda_b^0 \to pK^-J/\psi(\to \ell^+\ell^-)$ are used to calculate the double ratio, R_{pK}.
- Since NP is not expected to effect the control channel the ratio, $R_{J/\psi}$, should equal one. This is used to check the validity of the analysis strategy.





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

[3] https://arxiv.org/pdf/1507.03414.pdf

Analysis Strategy: Event Selection

- LHCb Trigger: See backup slides
- **Preselection**: Loose cuts to reduce dataset to manageable size (little loss of signal)
- **Particle identification cuts**: Use variables from neural network to reduce background
- **Peaking background removal**: Vetoing peaking background mass windows
- **Combinatorial background removal**: Multivariate analysis

} Event Selection

$$R_{pK} = \frac{\mathcal{N}(\Lambda_b^0 \to pK^-\mu^+\mu^-)}{\mathcal{N}(\Lambda_b^0 \to pK^-e^+e^-)} \cdot \frac{\epsilon(\Lambda_b^0 \to pK^-e^+e^-)}{\epsilon(\Lambda_b^0 \to pK^-\mu^+\mu^-)} \cdot \frac{\mathcal{N}(\Lambda_b^0 \to pK^-J/\psi(\to e^+e^-))}{\mathcal{N}(\Lambda_b^0 \to pK^-J/\psi(\to \mu^+\mu^-))} \cdot \frac{\epsilon(\Lambda_b^0 \to pK^-J/\psi(\to \mu^+\mu^-))}{\epsilon(\Lambda_b^0 \to pK^-J/\psi(\to e^+e^-))};$$

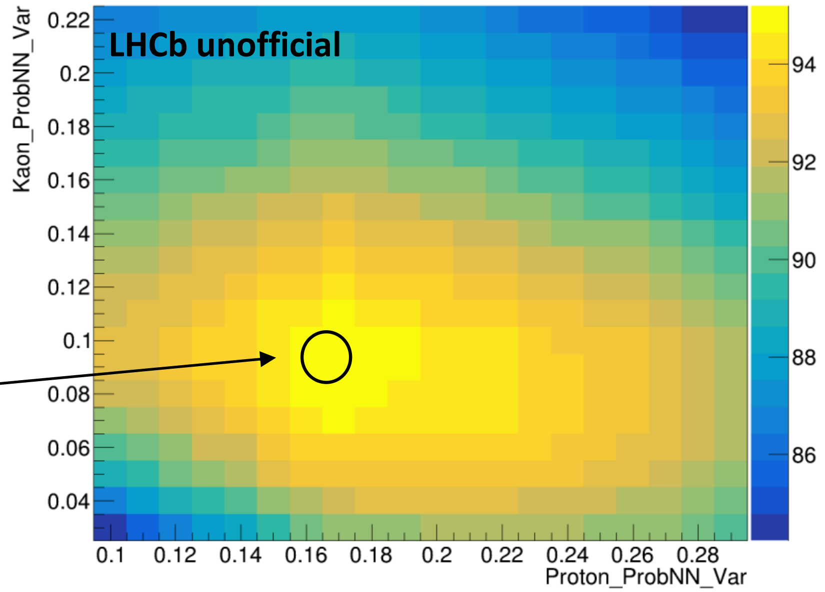
Analysis strategy: Yield Extraction

- **Fit mass distribution** after selection to **extract yields** for control and rare modes
- To **extract** corresponding **branching fraction** must **estimate** the trigger, reconstruction and selection **efficiencies**
- First estimate **branching fraction ratio** for **control channel** to check it is **unity**
- Then develop procedure for rare decay
- Use $3fb^{-1}$ from 2011-2012 and $\sim 2fb^{-1}$ from 2015-2016
- **This presentation** will outline the **selection procedure** and **yield extraction** for both **control channels: $\Lambda_b^0 \rightarrow pK^- J/\psi(\rightarrow \ell^+\ell^-)$.** The data used here corresponds to $\mathbf{762\ pb^{-1}}$ and $\mathbf{638 pb^{-1}}$ of integrated luminosity for muons and electrons respectively.

Particle Identification (PID)

- A neural network takes information from tracking and PID systems to calculate the probability for a track to be a particular particle ($ProbNN$ variables)
- For example $ProbNNK$ is probability to be Kaon.
- Cut values optimized by maximising the figure of merit defined as $FoM = \frac{S}{\sqrt{S+B}}$.
- Find S and B from fits to Λ_b^0 mass distribution after cuts applied.
- Kaon and proton cut optimised simultaneously.

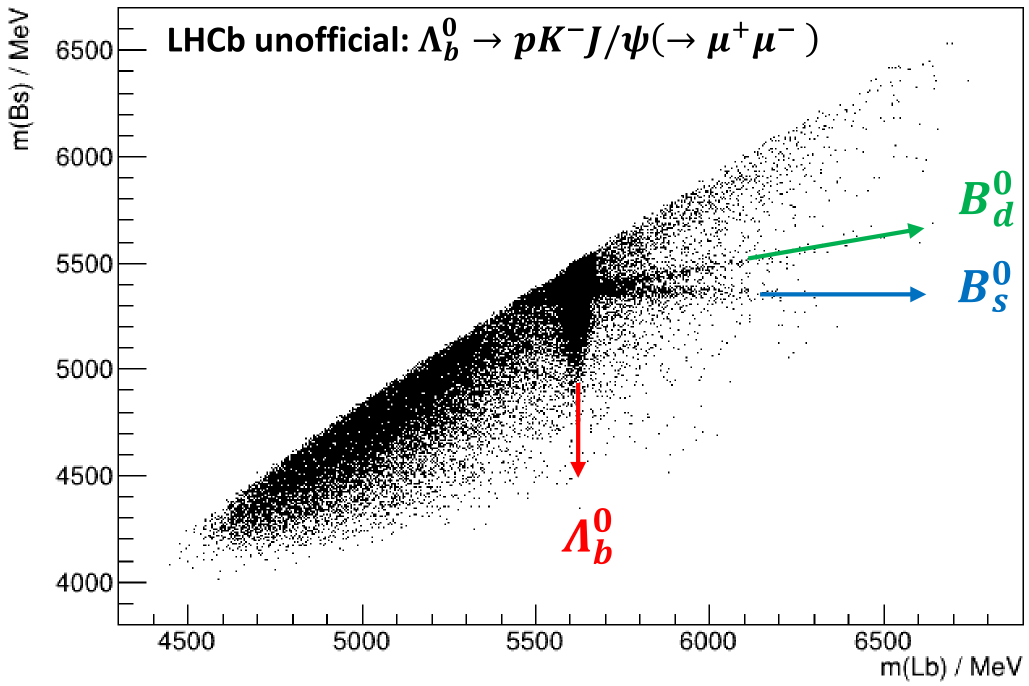
Particle	Cut
p	$ProbNNp \cdot (1 - ProbNNK) \cdot (1 - ProbNN\pi) > 0.16$
K	$ProbNNK \cdot (1 - ProbNNp) > 0.09$
μ	$ProbNN\mu > 0.2$
e	$ProbNNe > 0.2$



Peaking background rejection

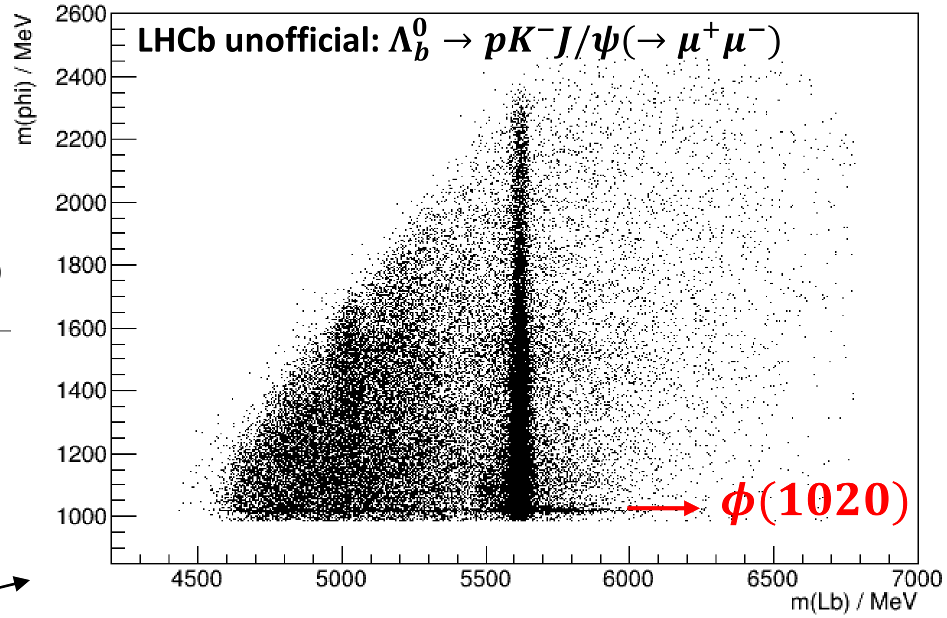
- When PID fails background decays can be reconstructed as signal.
- To search for background assign a final state particle a different mass hypothesis and recalculate parent particle mass.
- Main contributions:
  - $B_s^0 \to K^+K^-J/\psi(\to \ell^+\ell^-)$: Mis-ID $[K \to p]$
  - $B_d^0 \to K\pi J/\psi(\to \ell^+\ell^-)$: Mis-ID $[\pi \to p]$ or $[K \to p, \pi \to K]$
  - $\Lambda_b^0 \to pK^-J/\psi(\to \ell^+\ell^-)$: Mis-ID $[K \to p, p \to K]$
- How to deal with backgrounds:
  1. Veto a known intermediate or mother particles mass window.
  2. Do not place further cuts but instead include in fitting procedure.

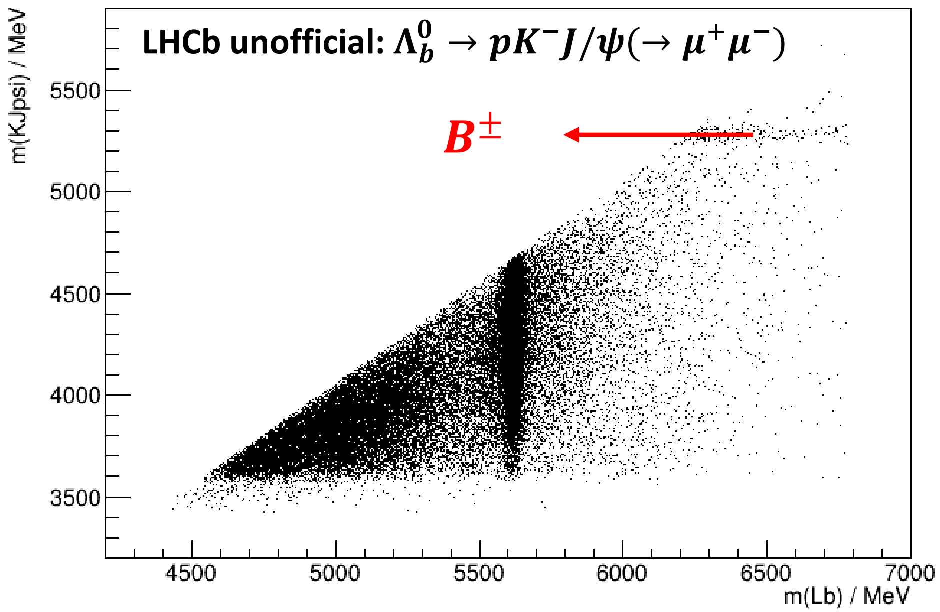
Cuts: PID, Loose BDT



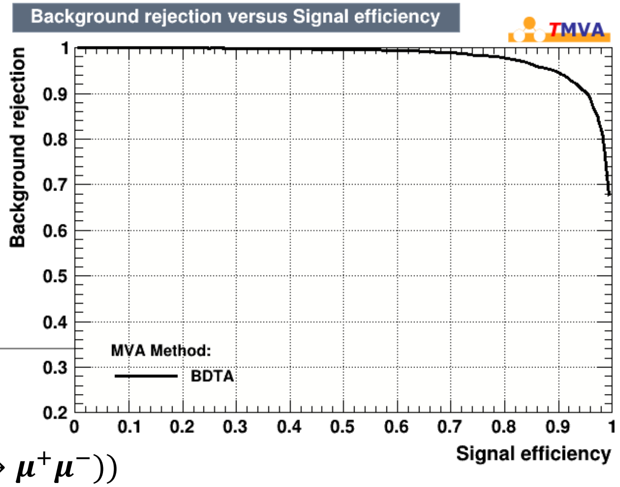
Peaking background vetoes

- Two veto's used in the analysis.
- Main contribution from B_S^0 background have ϕ resonance i.e. $B_S^0 \to \phi(\to K^+K^-)J/\psi$
- Place veto around the $\phi(1020)$ mass:
  - $|m(pK)_{p\to K} - 1020MeV| > 12$MeV
- Also contribution from $B^\pm \to K^\pm J/\psi$
  - $m(K\ell^+\ell^-) < 5200$MeV and $m(p\ell^+\ell^-)_{p\to K} < 5200MeV$
- Contributions from Λ_b^0, B_d^0 and B_s^0 (without ϕ resonance) still remain!
- Peaking backgrounds not removed by mass vetoes will be included in fit, with their shapes obtained from MC



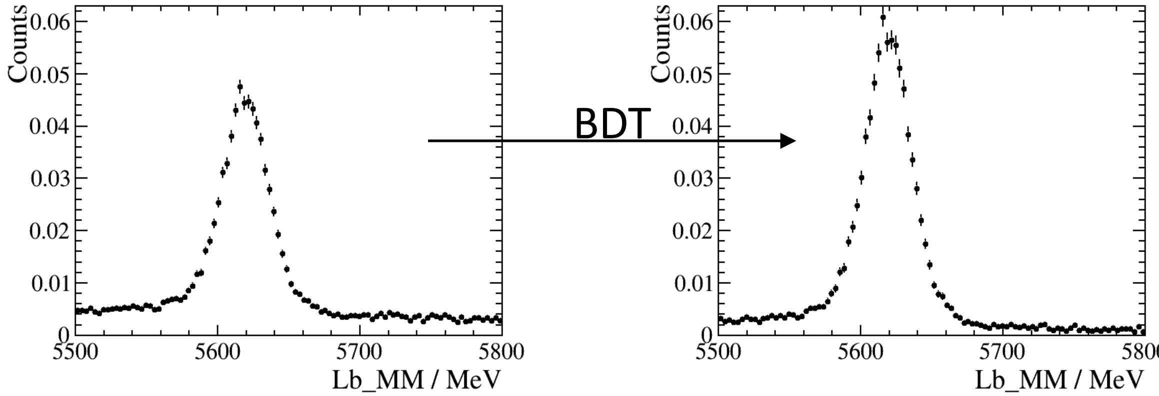


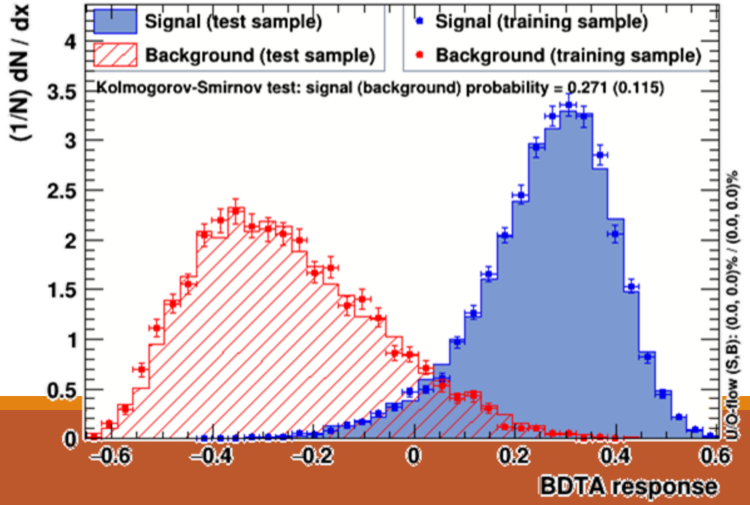
Combinatorial Background



- To reject combinatorial background a multivariate analysis tool is used.
- A Boosted Decision Tree (BDT) is first trained on signal and background proxy events.
- Signal training sample: $\Lambda_b^0 \rightarrow pK^- J/\psi(\rightarrow \ell^+\ell^-)$ reweighted MC events.
- Background training sample: Real data sideband with $m(pK^-\ell^+\ell^-) > 5800 MeV$.
- 21 kinematic variables used.
- Optimal method found by maximising area under ROC curve (top right).
- Cut placed on BDT output

LHCb unofficial: $m(pK^- J/\psi(\rightarrow \mu^+\mu^-))$





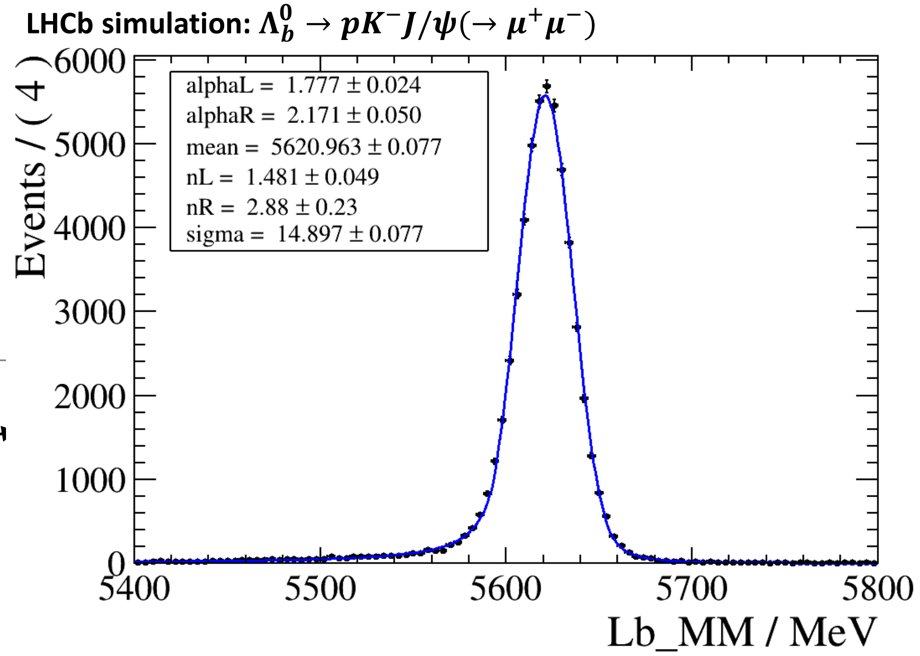
Yield Calculation

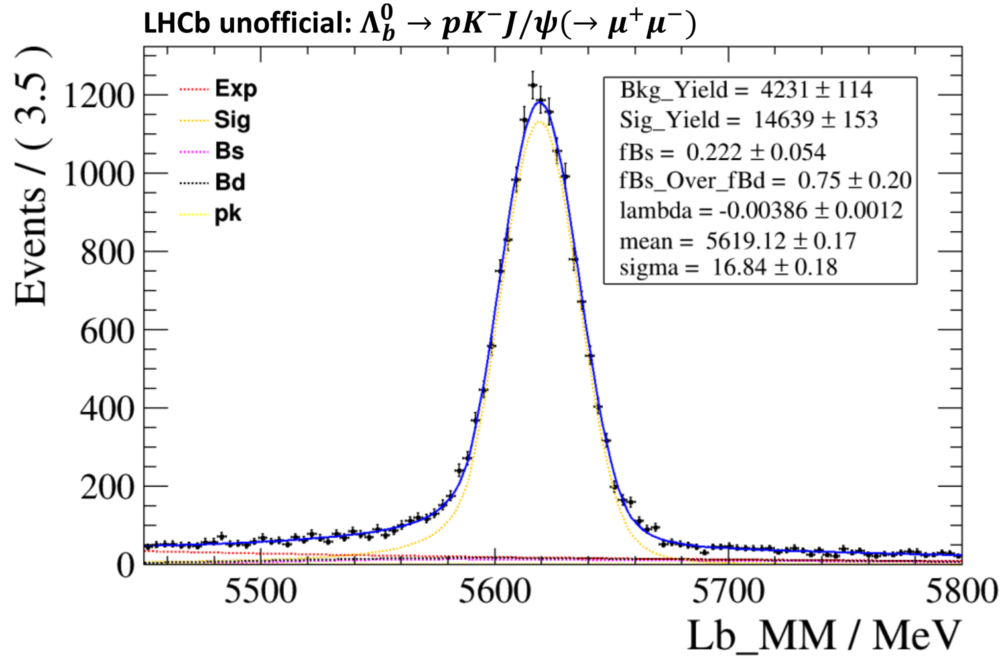
- Calculate yields from maximum likelihood fits to the Λ_b^0 mass spectrum.
- Signal shape constrained from MC
- Shapes included in fits:
  - Muon signal: Double Crystal Ball (CB)
  - Electron: 3CB +2 Gaussians
  - Combinatorial: Exponential
  - B_s^0
  - B_d^0
  - Λ_b^0 $(p \leftrightarrow K)$

Shape obtained from respective MC samples using RooKeysPdf (applies to B_s^0, B_d^0, Λ_b^0 $(p \leftrightarrow K)$)

Muon Fit

- Signal Shape: Bifurcated CB
  - Fix tail parameters from MC
  - width/mean free
- Yield: $\sim 14600\ (762 pb^{-1})$





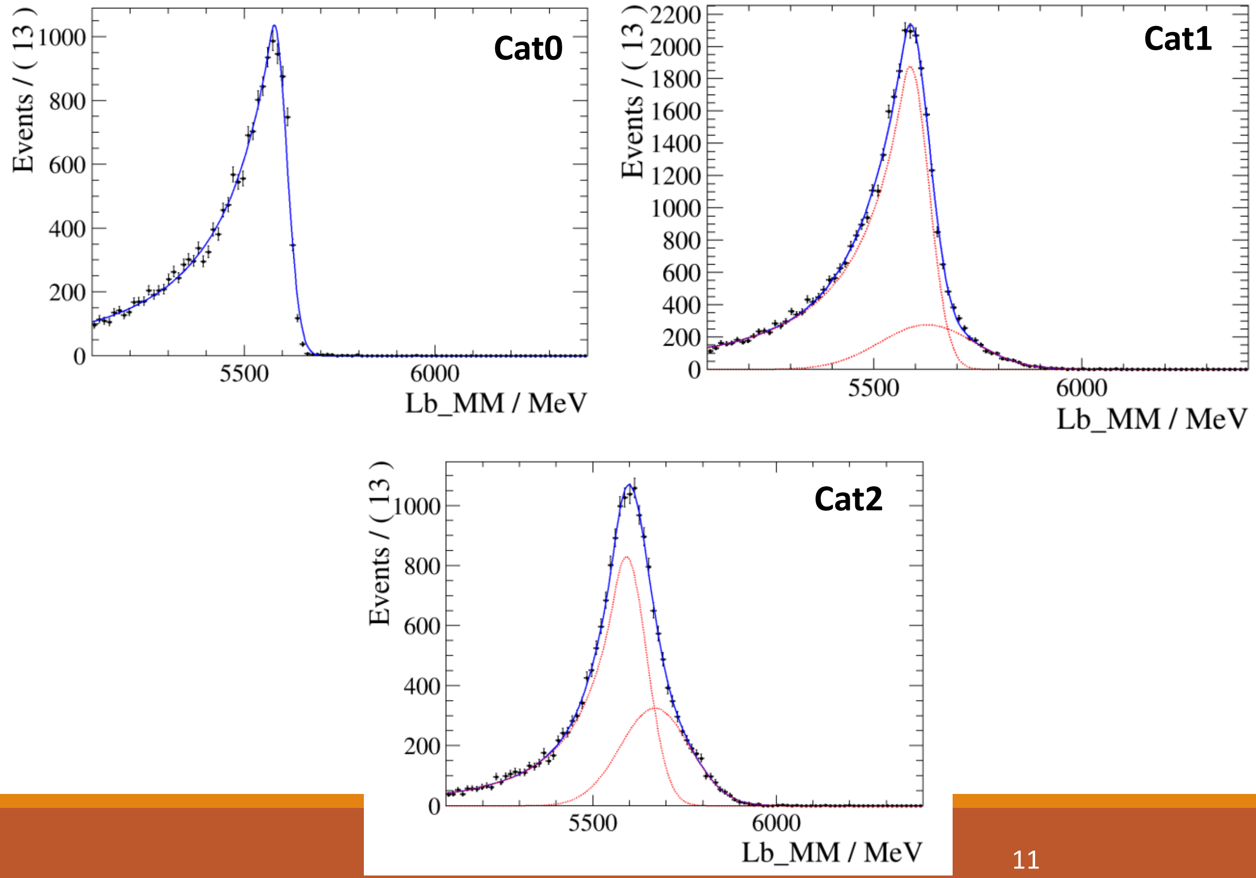
Next steps towards mesurment of $R_{J/\psi}$ with LHCb Run2 data:

- Calculate efficiencies of the selection procedure to obtain efficiency corrected yield
- Study of systematic uncertainties

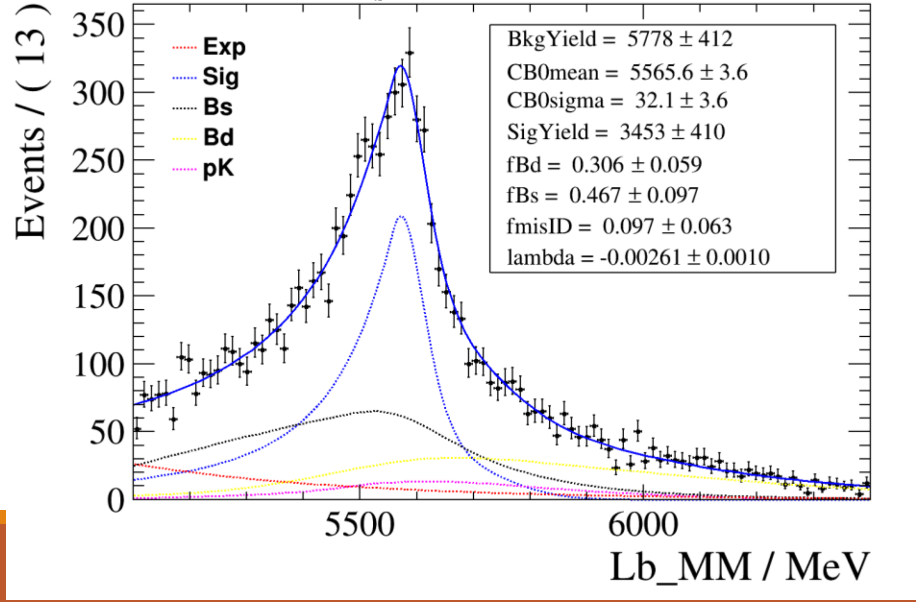
Electron Fit

- Signal shape depends on how many photon used in Bremsstrahlung recovery procedure
  - Cat 0: 0 Bremsstrahlung γ used, Shape: CB
  - Cat 1: 1 Bremsstrahlung γ used, Shape: CBG
  - Cat 2: >2 Bremsstrahlung γ used, Shape: CBG
- Yield: $\sim 3500\ (638 pb^{-1})$

LHCb Simulation: $\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-)$



LHCb unofficial: $\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-)$, 2016 data



CB: Crystal Ball
CBG: Crystal Ball + Gaussian

Summary and next steps

- Previous LU results from LHCb show deviations from SM. Measurement of R_{pK} will provide an additional test to LU
- The control channels are used to establish the analysis procedure and to reduce systematic uncertainties, similar procedure then used for rare mode
- The main sources of background and the rejection procedure for the control channels:
  - mis-ID's.
  - Peaking background.
  - Combinatorial.

  mis-ID's and Peaking background → PID variables & mass vetoes

  Combinatorial → Multivariate analysis (BDT)
- The yield calculation for the control channels. → Λ_b^0 invariant mass fits
- The future work needed:
  - Efficiency calculations
  - Calculation of systematic uncertainties

Thank you for your attention! **Any questions?**

Backup Slides

Trigger

Muons	Electrons
L0Muon = L0MuonDecision || L0DiMuon L0Hadron = L0Hadron && !(L0Muon) L0 = L0Muon || L0Hadron	L0Electron = L1, L2_L0ElectronDecision L0Hadron = Kaon, Proton_HadronDecision && !(L0Electron) L0TIS = L0GlobalTIS && !L0Hadron && !L0Electron
HLT1 = Hlt1TrackMVA, Hlt1TwoTrackMVA, Hlt1TrackMuonMVA, Hlt1TrackMuon, Hlt1SingleMuonHighPT, Hlt1DiMuonLowMass, Hlt1DiMuonHighMass	Hlt1 = Hlt1TrackMVADecision, Hlt1TwoTrackMVADecision
Hlt2 = Not yet applied here due to problems with the data tuple	Hlt2 = Not yet applied here due to problems with the data tuple

Preselection

- Stripping 28r1; lines Bu2LLK_eeLine2 and Bu2LLK_mmLine (CNAF files missing)

Muon	Electron
$p_T(K), > 250MeV\ p_T(P) > 400MeV, p_T(\mu) > 800MeV$	$p_T(K), > 250MeV\ p_T(P) > 400MeV, p_T(\mu) > 450MeV$
$2900 < m(J/\psi) < 3200$	$1000 * \sqrt{6} < m(J/\psi) < 1000 * \sqrt{11}$
Proton_HCAL_region>=0, Kaon_HCAL_region>=0	Proton_HCAL_region>=0, Kaon_HCAL_region>=0

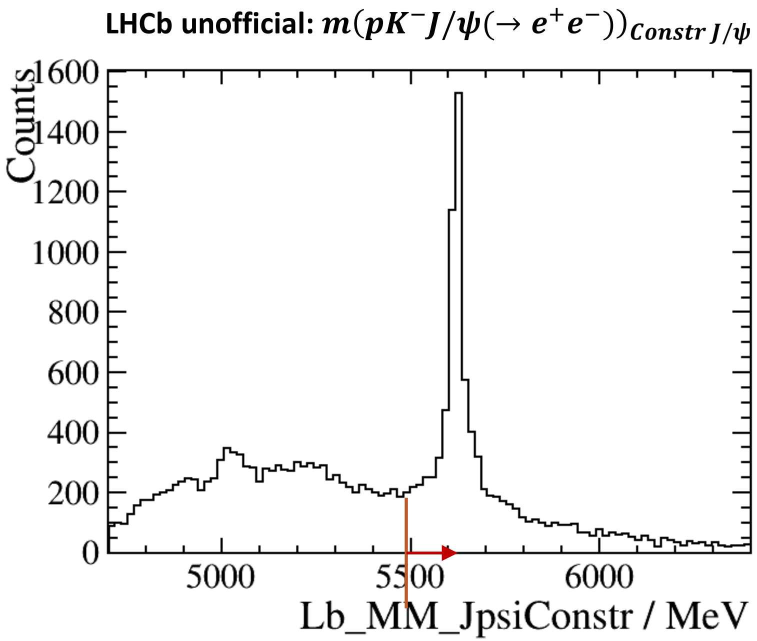
BDT variables

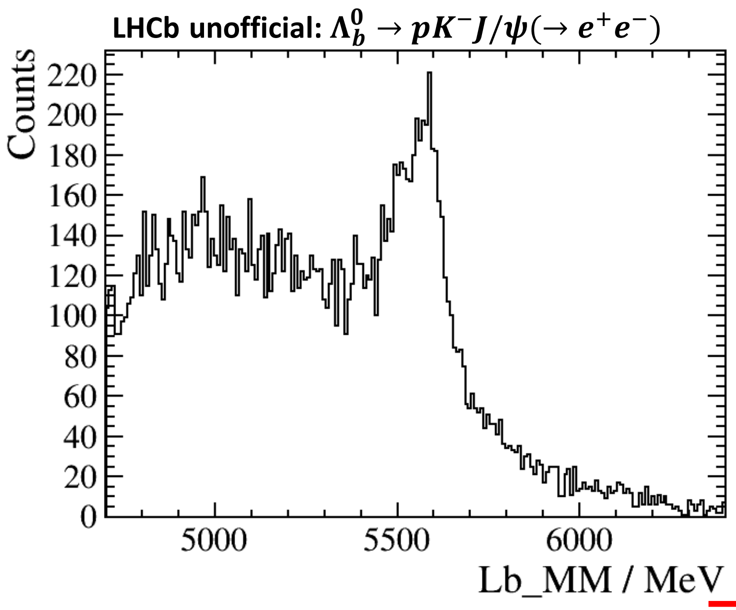
	Λ_b^0	Λ^*	p	K	L1	L2
PT	+	+	Min and sum of two		Min of two	
ETA			Sum of two			
P			+			
IPCHI2	+	+	Min and sum of two		Min and sum of two	
DIRA	+					
FDCHI2	+				dilepton	
LOKI_DTF_CHI2NDOF	+					
ENDVERTEX_CHI2	+	+				

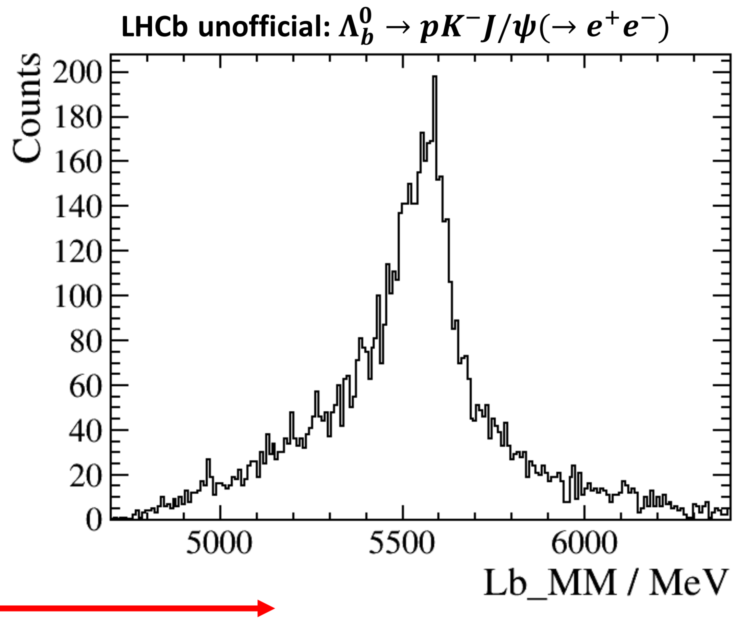
*Also $p_T(dilepton)$, $p_T(\Lambda^*)$, $\frac{p(dilepton)-p(p)-p(K)}{p(dilepton)+p(p)+p(K)}$

Partially reconstructed background

- Partially reconstructed background from $\Lambda_b^0 \to pK^- J/\psi(\to \ell^+\ell^-)X$, where $X = \gamma, \pi^0$ is lost.
- Place cut on $m(pK^- J/\psi(\to e^+e^-))_{Constr\ J/\psi} > 5500 MeV$







$m(pK^- J/\psi(\to e^+e^-))_{Constr} > 5500\text{MeV}$

Bremsstrahlung

- Also reduced resolution of Λ_b^0 mass in electron mode due to Bremsstrahlung radiation.

- Use HOP variables.
- Exploits the fact $\overline{P_T}(pK^-) = -\overline{P_T}(e^+e^-)$ for signal decays.
- $\alpha_{HOP} = \frac{P_T(pK^-)}{P_T(e^+e^-)}$; $\bar{P}^{corr}(e^+e^-) = \bar{P}(e^+e^-)$.
- Recalculate Λ_b^0 mass with corrected electron momentum.
- $m(\Lambda_b^0)_{HOP} > a_1 + a_2 \log(\Lambda_b^0\ Flight\ Distance\ \chi^2)$.
- $a_1 = 3950, MeV\ \ a_2 = 108.$