Blinding Estimation of Branching Fraction Upper Limit of $\Lambda_c^+ \to p\mu^+\mu^-$

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With the LHCb Run1 data and data collected in 2016, the expected upper limit of branching ratio of rare decay $\Lambda_c^+ \to p\mu^+\mu^-$ is estimated by with extrapolated background in Λ_c^+ mass region after cuts.[1]

1 Methods

The data and MC samples were first preselected by choosing the most efficient trigger lines and a loose cut on Λ_c mass and PID of muons and protons. Then we choose the right sideband of Λ_c^+ mass in data as background and mixture events of Λ_c^+ decay in MC simulations as signal, and use initial MVA discrimination a short list of variables to classify them.
After the cut with initial BDT variable the reduced samples were put into another BDT train with an extended list of parameters. The cuts on the final BDT variables as well as the cuts on ProbNNp(p) and ProbNNmu(μ) were optimized by testing the sensitivity of the cuts with toy MC samples, in order to get the minimized expected upper limit of signal.
The optimized cuts on final BDT variable and PIDs of protons and muons were then applied to the sideband data of Λ_c^+ region to get the number of background events in signal region by extrapolation. With CL_s method we can then estimate the expected upper limit of $\Lambda_c^+ \to p\mu^+\mu^-$ branching ratio if no significant signal is observed.

2 Preselection

In preselection, the most the efficient TOS trigger lines were selected at each trigger level:

- L0
  - Lc_L0MuonDecision_TOS
  - Lc_Hlt1SingleMuonNoIPDecision_TOS
- HLT1
  - Lc_Hlt1TrackMuonDecision_TOS
  - Lc_Hlt1DiMuonLowMassDecision_TOS
  - Lc_Hlt1TrackAllL0Decision_TOS
- HLT2
  - Lc_Hlt2DiMuonDetachedDecision_TOS
  - Lc_Hlt2CharmHadLambdaC2PiPPiWideMassDecision_TOS
  - Lc_Hlt2CharmSemilepD02PiPiMuMuDecision_TOS
  - Lc_Hlt2CharmHadD02HH_D02KKWideMassDecision_TOS
  - Lc_Hlt2TopoMu2BodyBBDTDecision_TOS
  - Lc_Hlt2CharmSemilepD02KPiMuMuDecision_TOS
  - Lc_Hlt2SingleMuonDecision_TOS

The sPlot method is used to correct the the ProbNNp(p) and ProbNNmu(μ) of simulated events. p_V3ProbNNp and mu_V3ProbNNmu were used to for Run1 simulation, p_MC15TuneV1_ProbNNp_Brunel and mu_MC15TuneV1_ProbNNmu_Brunel were used for data in 2016 for sPlot. Then loose rectangular cuts to Λ_c^+ mass, proton momentun, ProbNNp(p), and ProbNNmu(μ) for both MC and data samples:

- $m_{\Lambda_c^+} > 2100 MeV/c^2$
- $proton\ ProbNNp > 0.1$
- $\mu^+, \mu^-\ ProbNNmu > 0.1$
- $10\ GeV/c < p_{proton} < 100 GeV/c$

3 Initial MVA discrimination

After preselection, signals were taken from MC and backgrounds were taken from right sideband $[m_{\Lambda_c^+} + 35, m_{\Lambda_c^+} + 140]$ MeV/c^2 of data and put into the initial BDT discrimination, in order to suppress the background in Λ_c^+ mass region. A k-Folding technique were used to reach better training results with the datasets. The signals and backgrounds were divided into 10 folds respectively, and then 10 independent BDT discrimination was applied, each one use 9 folds to train and 1 fold to test. The ROC curve (background rejection vs signal acceptance) were used to justify the BDT results. A list of MVA variables were chosen for train and test:

- fight distance between the production and decay points
- χ^2 of flight distance
- IP - impact parameter with respect to primary vertex
- χ^2_{IP} - difference in χ^2 when Λ_c^+ candidate is included and excluded from the PV fit
- χ^2_{DTF} - χ^2 of the DecayTreeFitter vertex fit
- p_T - transverse momenta of Λ_c^+

The normalization channel $\Lambda_c^+ \to p\phi(\mu^+\mu^-)$ of data is used to test the background suppression of BDT1 cut. A cut $BDT1 > 0.1$ were applied to accept the majority of signals and reduce the background level.

4 Final MVA discrimination

After the cuts of preselection procedure and BDT1 a second BDT discrimination was applied on the reduced samples of signals from MC and background. The list of variables for training included the parameters of Λ_c^+ decay products:

- the variables for Λ_c^+ used in BDT1
- variables of decay products: p, μ^+, μ^-
    - minimum of χ^2_{IP} of p, μ^+, μ^- wrt primary vertex
    - transverse momenta of p, μ^+, μ^-

- minimum of χ^2_{NDF} of track fit of p, μ^+, μ^-

- isolation variables

  - Λ_c^+ isolation - CDF isolation

  - isolations for p, μ^+, μ^-

5 Optimization

Optimization of BDT2 cut, ProbNNp(p), ProbNNmu(μ) was performed by scanning the cut points of BDT2 variable, ProbNNp(p) and the minimums of ProbNNmu(μ1) and ProbNNmu(μ2) and calculating the expected upper limit of signal at 90% confidence level for the signal and background events remain at each cut points.

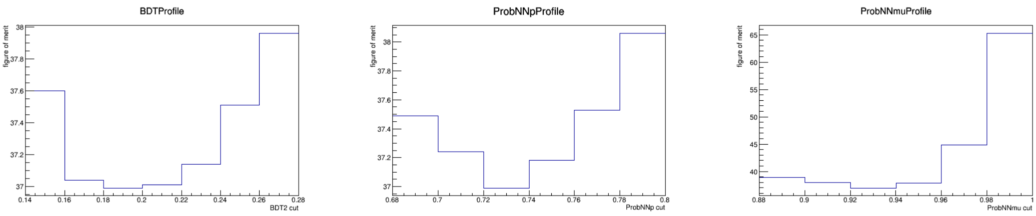
Before the optimization the 3D distributions of BDT2 variable, ProbNNp(p), and ProbNNmu(μ) of MC samples and background after preselection and BDT1 cut were fitted with kernel density estimation (KDE) and the number of background events in signal region is estimated by extrapolation. Then 100 toy MC experiments were performed in which such number of background events and signal events with these 3 variables were generated according to the 3D distribution. The upper limit of these 100 toy experiments were calculated separately, and then the average were calculated to get the best cut point.

The cut points for Run1 and Run2 were chosen as follows:

Variable	Condition for Run1	Condition for Run2
BDT2	>0.18	>0.68
$ProbNNp(p)$	>0.72	>0.93
minimum $ProbNNmu(\mu^{\pm})$	>0.92	>0.5

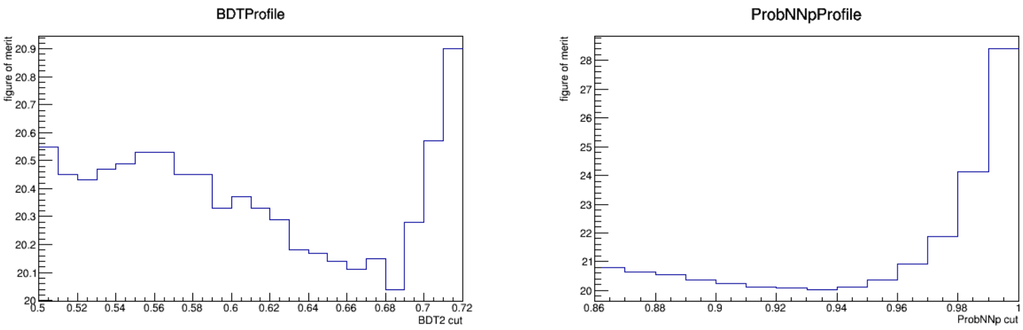
The profiles of expected upper limit about BDT2, $ProbNNp(p)$, $ProbNNmu(\mu^{\pm})$ for Run1 and Run2 is plotted below.

In Run2 analysis the optimization is only performed on BDT2 and ProbNNp, because for the ProbNNmu($\mu^{\pm}$) variable the U.L. decreases with the monotonously with the increase of cut value. In the final cut a loose cut of $ProbNNmu(\mu^{\pm}) > 0.5$ is performed for Run2 data.



(a) U.L. profile on BDT2 (b) U.L. profile on $ProbNNp(p)$ (c) U.L. profile on $ProbNNmu(\mu^{\pm})$

Figure 1: Run1 expected upper limit profiles



(a) U.L. profile on BDT2 (b) U.L. profile on $ProbNNp(p)$

Figure 2: Run2 expected upper limit profiles

6 Expected Upper Limits

With the cut strategy to suppress the background we can now estimate the upper limit of signal with the events remained for normalization channel and its branching ratio. The branching ratio of $\Lambda_c^+ \to p\mu^+\mu^-$ can be derived as follows:
$B(\Lambda_c^+ \to p\mu^+\mu^-) = N_{\Lambda_c^+\to p\mu^+\mu^-}\alpha$, where $\alpha = \frac{B(\Lambda_c^+\to p\phi(\mu^+\mu^-))\epsilon_{\Lambda_c^+\to p\phi(\mu^+\mu^-)}}{N_{\Lambda_c^+\to p\phi(\mu^+\mu^-)}\epsilon_{\Lambda_c^+\to p\mu^+\mu^-}}$ The efficiency of cut for normalize channel and signal channel is calculated from the efficiency of cut for the MC samples of normalize events and signal events.

$\epsilon_{\Lambda_c^+\to p\phi(\mu^+\mu^-)} = N_{MCnormalaftercut}/N_{MCnormalbeforecut}$.

$\epsilon_{\Lambda_c^+\to p\mu^+\mu^-} = N_{MCsignalaftercut}/N_{MCsignalbeforecut}$.

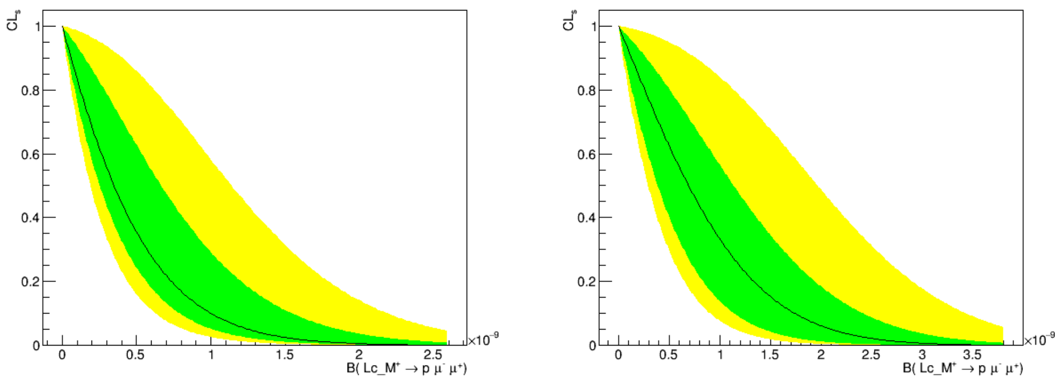
The branching ratio of normalization channel is $B(\Lambda_c^+ \to p\mu^+\mu^-) = B(\Lambda_c^+ \to p\phi)B(\phi \to \mu^+\mu^-)$. $B(\Lambda_c^+ \to p\phi) = (1.04 \pm 0.01) \times 10^{-3}$; $B(\phi \to \mu^+\mu^-) = (2.87 \pm 0.19) \times 10^{-4}$.

With the optimized cut shown in section 5, the number of events before and after cut for MC set is listed below.

events	Run1	Run2
$N_{MCnormalbeforecut}$	405.000 ± 20.0893	316.999 ± 17.7882
$N_{MCnormalaftercut}$	111.000 ± 10.5160	55.0033 ± 7.38922
$N_{MCsignalbeforecut}$	7312.00 ± 85.3949	5765.00 ± 75.7980
$N_{MCsignalaftercut}$	2060.00 ± 45.3235	1021.99 ± 31.7185

The number of events for normalization channel before cut in data is 1058.95 ± 32.5348 for Run1 and 1490.99 ± 38.6003 for Run2 respectively. Then α for Run1 and Run2 is $(2.7421 \pm 0.66126) \times 10^{-10}$ and $(1.9594 \pm 0.51154)^{-10}$.

Using CLs method the upper limit of branching ratio of signal can be determined. The dependence of branching ratio on confidence level is shown below, in which the green area represents 1σ error and the yellow one represents 2σ error.



(a) Run1

(b) Run2

Figure 3: C.L. – $B(\Lambda_c^+ \to p\mu^+\mu^-)$

References

[1] Roel Aaij, Bernardo Adeva, Marco Adinolfi, Ziad Ajaltouni, Simon Akar, Johannes Albrecht, Federico Alessio, Michael Alexander, A Alfonso Albero, Suvayu Ali, et al. Search for the rare decay λ c+ p μ+ μ-. *Physical Review D*, 97(9):091101, 2018.