

**Search for the suppressed
 $\Lambda_c^+ \rightarrow p\mu^+\mu^-$ decay and observation
of the $\Lambda_c^+ \rightarrow p\omega$ decay**



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With M. Jezabek, T. Lesiak, B. Nowak, M. Witek (IFJ PAN)

Tuesday meeting, CERN
September 26, 2017

Yellow pages

⇒ Reviewers: Tom Blake(chair), Harry Cliff, Simon Eydelman(EB)

⇒ Twiki:

<https://twiki.cern.ch/twiki/bin/viewauth/LHCbPhysics/Lc2PMuMu>

⇒ Review start: 31.03.2017

⇒ Fruitfull interactions with the review committee.

⇒ Unblinding: 18.07.2017

⇒ Minor changes to the analysis during the review.

We would like to take this occasion and than Tom, Harry and Simon for fruitful, constructive and smooth review!

Motivation

⇒ SM predictions:

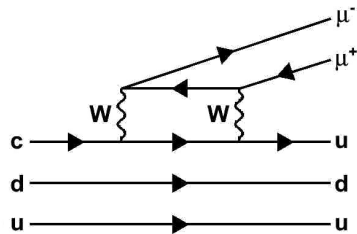
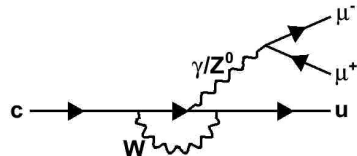
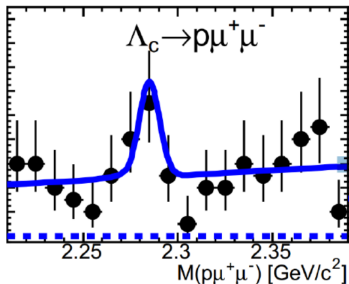
$$\mathcal{O}(10^{-8})$$

⇒ Long distance effects:

$$\mathcal{O}(10^{-6})$$

⇒ Previous measurement done by Babar:

$$\text{Br}(\Lambda_c^+ \rightarrow p\mu^+\mu^-) < 4.4 \cdot 10^{-5} \text{ at 90\% CL}$$



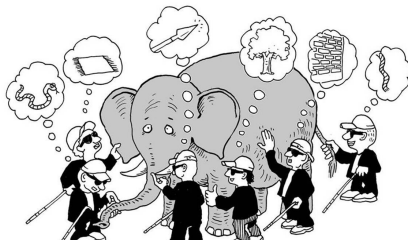
Should be able to improve by a factor of 100!

Analysis strategy

- ⇒ Normalization to $\Lambda_c^+ \rightarrow p\phi(\mu\mu)$.
- ⇒ Typical steps rare decays:
 - Loose stripping selection.
 - BDT1 used for first preselection.
 - BDT2 used to further suppress the background.
 - PID used to fight the peaking background.
- ⇒ Search performed in several dimuon mass windows.
- ⇒ Selection optimized on CL_s .
- ⇒ Unblinding and calculate the UL of BR using CL_s .

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Normalization channel

Use the $\Lambda_c^+ \rightarrow p\phi(\mu\mu)$.

⇒ Same final state, same selection, a lot of systematics cancel.

⇒ The Branching fraction of $\Lambda_c^+ \rightarrow p\phi$ is known with 22 %.

Use the $\Lambda_c^+ \rightarrow pK\pi$.

⇒ More precisely known branching fraction (precision: 6.4 %).

⇒ A lot of additional systematics due to different final states, different selections



We choose the $\Lambda_c^+ \rightarrow p\phi(\mu\mu)$ option

⇒ In the most optimistic scenario where you assume the 22 % systematic to go down to 6.4 % the UL.

In this case the UL gets worse 7.8 %.

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Data sets and Stripping

⇒ 2011+2012 (aka Run1) Stripping 20.

Condition	$\Lambda_c^+ \rightarrow p\mu^+\mu^-$
μ^\pm and p	
p_T	$> 300 MeV/c$
Track χ^2/ndf	< 3
IP χ^2/ndf	> 9
PID μ^\pm	PIDmu > -5 and (PIDmu - PIDK) > 0
PID p	PIDp > 10
Λ_c^+	
Δm	$< 150 MeV/c^2$
Vertex χ^2	< 15
IP χ^2	< 225
$c\tau$	$> 100 \mu m$
Lifetime fit χ^2	< 225

Preselection

⇒ Additional cuts:

Common cuts
$m_{\mu\mu} < 1400 \text{ MeV}/c^2$
proton $ProbNNp > 0.1$
$\mu^+, \mu^- ProbNNmu > 0.1$
$10 \text{ GeV}/c < p_{proton} < 100 \text{ GeV}/c$

⇒ We define couple of dimuon mass regions:

$m(\mu\mu)$ region	MeV/c^2
ϕ region	[985, 1055]
ω region	[759, 805]
<i>non resonant</i>	[210, 747] \cup [817, 980] \cup [1060, 1400]

Trigger

⇒ We require the following triggers (all are TOS):

- L0
 - L0MuonDecision
- HLT1
 - Hlt1TrackMuonDecision
 - Hlt1DiMuonLowMassDecision
 - Hlt1TrackAllL0Decision
- HLT2
 - Hlt2DiMuonDetachedDecision
 - Hlt2CharmSemilep3bodyD2KMuMuDecision
 - Hlt2CharmSemilepD2HMuMuDecision

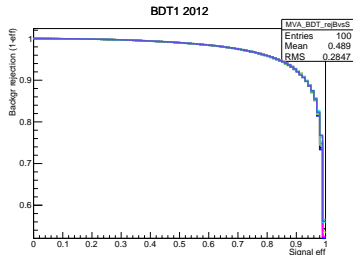
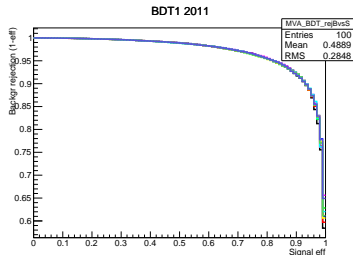
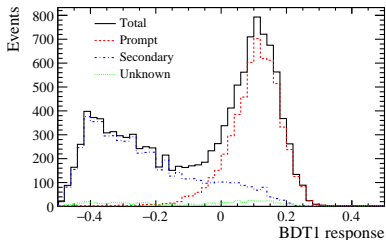
⇒ The TIS increase the signal yield by $< 10\%$ and were asked to be removed at the WG review stage.

BDT1 training

⇒ The normalization channel is also a rather “rare decay”:

$$\text{Br}(\Lambda_c^+ \rightarrow p\phi) \cdot \text{Br}(\phi \rightarrow \mu\mu) = 3.1 \cdot 10^{-7}$$

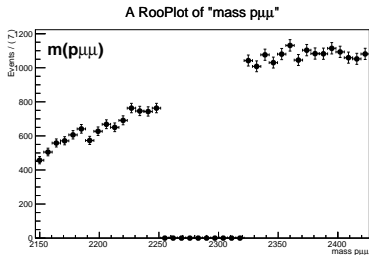
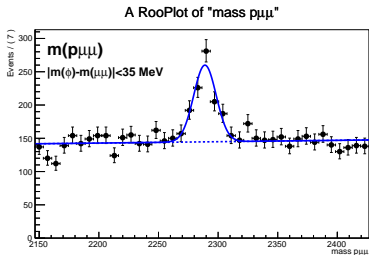
⇒ After the previous preselection a simple BDT is trained using variables that are well simulated in the MC. k-folding used ($k = 10$) ⇒ The BDT1 (not surprisingly) likes the prompt Λ_c rather the secondary ones.



BDT1 selection

- ⇒ The selection based on BDT1 is not optimised.
- ⇒ A loose cut:

$$\text{BDT1} > -0.1$$

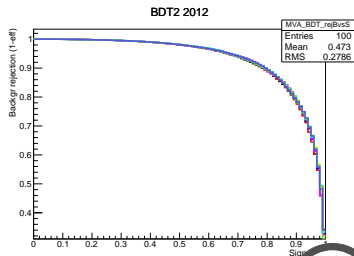
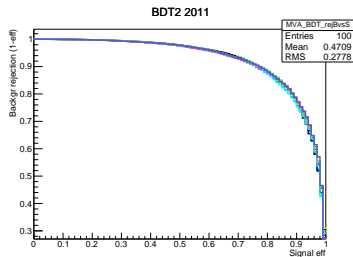


- ⇒ The normalization channel peak is observed.

BDT2 selection

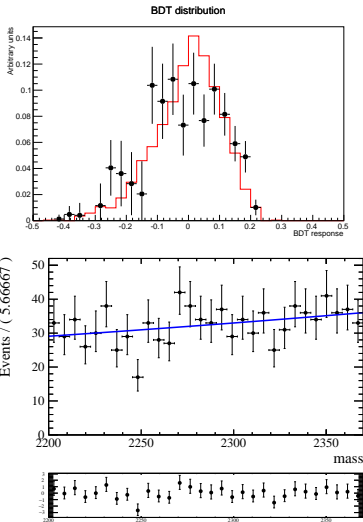
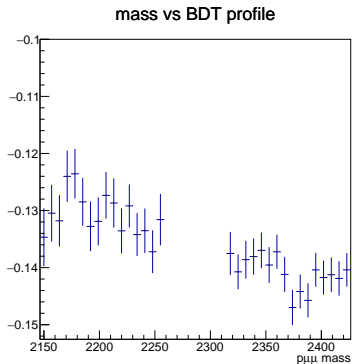
⇒ Variables used:

- flight distance - the one between the production and decay points.
- χ^2 of flight distance,
- transformed decay time - $T = \exp(-1000 \cdot \tau/\text{ns})$,
- IP - impact parameter with respect to primary vertex,
- χ^2 of IP of Λ_c^+
- $\log(\chi_{DTF}^2)$,
- p_T - transverse momentum of Λ_c^+ ,
- minimum of χ^2 of p, μ^+, μ^- w.r.t. primary vertex,
- transverse momenta
- minimum of χ^2/NDF of track fit of p, μ^+, μ^- .



BDT2

- ⇒ After correcting the DATA/MC differences the BDT distribution shows a good DATA/MC agreement.
- ⇒ No mass correlation observed.



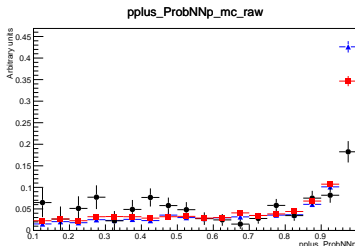
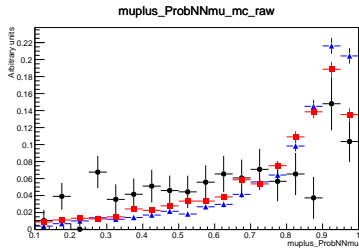
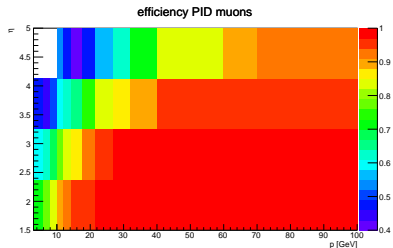
PID

⇒ MC resampling is chosen to correct the PID distributions:

For MC samples the ProbNNp and ProbNNmu are drawn from the PIDCalib distributions.

⇒ The PIDCalib doesn't cover the low p_T region for muons (10%).

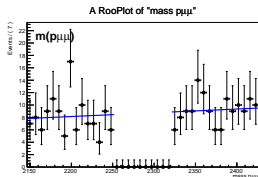
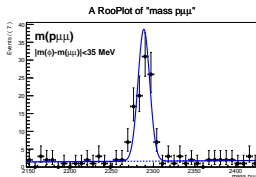
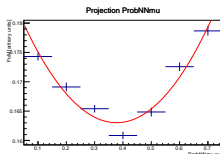
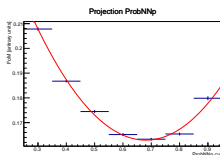
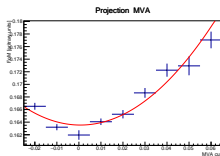
⇒ Decided to use for them the $D_s \rightarrow \phi(\mu\mu)$ sample.



Selection optimization

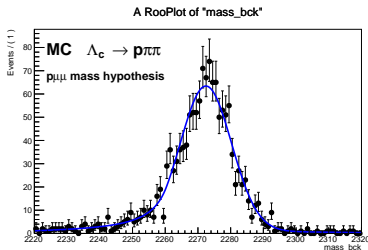
- ⇒ The final selection of the analysis is optimized!
- ⇒ CL_s method used.
- ⇒ Toy experiment used to find the optimum.

Variable	Condition
BDT	> 0.0
$ProbNNp(p)$	> 0.68
minimum $ProbNNmu(\mu^\pm)$	> 0.38

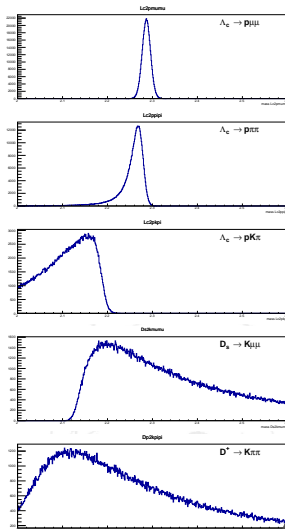


Peaking backgrounds

- ⇒ The tight PID cuts essentially kill the peaking bkg!
- ⇒ The only bkg left is the $\Lambda_c^+ \rightarrow p\pi\pi$.



- ⇒ Estimated contamination:
 1.96 ± 1.13 ⇒ assigned as systematic



Normalization

⇒ The gold equation:

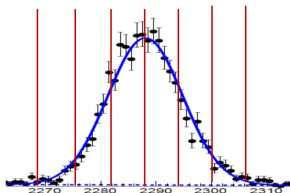
$$\frac{\mathcal{B}(\Lambda_c^+ \rightarrow p\mu^+\mu^-)}{\mathcal{B}(\Lambda_c^+ \rightarrow p\phi(\mu\mu))} = \frac{\epsilon_{\text{norm}}^{\text{TOT}}}{\epsilon_{\text{sig}}^{\text{TOT}}} \times \frac{N_{\text{sig}}}{N_{\text{norm}}},$$

⇒ We take advantage of the cancellation that:

$$\frac{\epsilon_{\text{norm}}^{\text{TOT}}}{\epsilon_{\text{sig}}^{\text{TOT}}} = \frac{\epsilon_{\text{norm}}^{\text{STRIP}}}{\epsilon_{\text{sig}}^{\text{STRIP}}} \times \frac{\epsilon_{\text{norm}}^{\text{COMM}}}{\epsilon_{\text{sig}}^{\text{COMM}}} \times \frac{\epsilon_{\text{norm}}^{\text{SPEC}}}{\epsilon_{\text{sig}}^{\text{SPEC}}}, \quad \frac{\epsilon_{\text{norm}}^i}{\epsilon_{\text{sig}}^i} \simeq 1$$

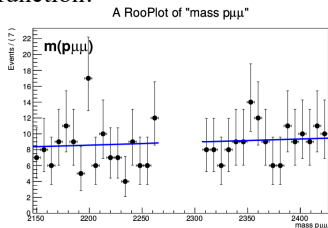
⇒ In addition we have added 6 mass bins to increase the sensitivity.

⇒ Signal is modelled by a double Crystall Ball.

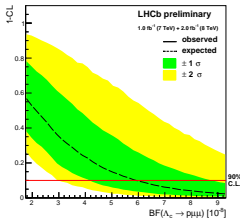
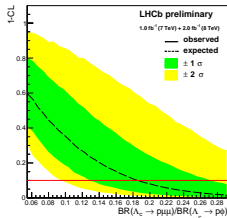


Expected background

⇒ Background modelled with a linear function.



bin	no events
bin1	8.56136 ± 0.540302
bin2	8.60318 ± 0.536917
bin3	8.64582 ± 0.536561
bin4	8.6887 ± 0.539208
bin5	8.7304 ± 0.544752
bin6	8.77226 ± 0.553162

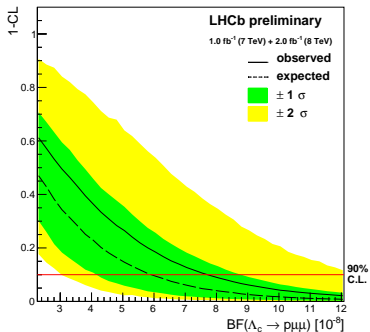
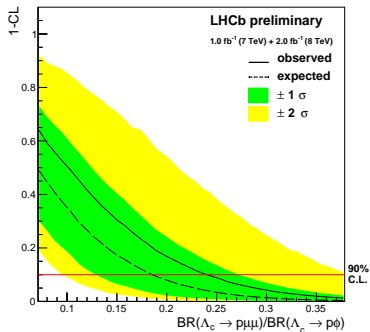
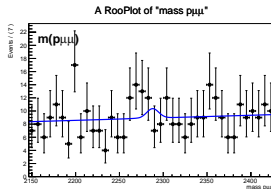


⇒ Expected upper limits:
 $\mathcal{B}(\Lambda_c^+ \rightarrow p\mu^+\mu^-) <$
 5.91×10^{-8} at 90 % CL

Observed Upper limits

⇒ After the green light from RC we have unblinded; no significant excess of events have been observed. ⇒ We have set an UL:

$$\mathcal{B}(\Lambda_c^+ \rightarrow p\mu^+\mu^-) < 7.68 \times 10^{-8} \text{ at } 90\% \text{ CL}$$



By product :)

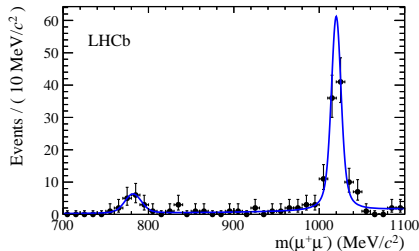
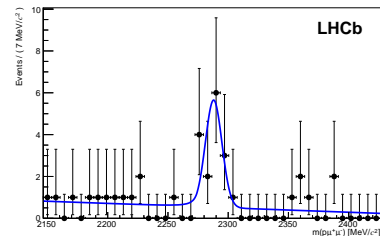
⇒ We also looked at the ω dimuon region.

We observed an excess
Using Wilks theorem we have
calculated the significance to be
 5.0σ !

⇒ This is the first observation of
this decay!!!

$$\mathcal{B}(\Lambda_c^+ \rightarrow p\omega) = (7.6 \pm 2.6 (stat) \pm 0.9 (syst1) \pm 3.1 (syst2)) \times 10^{-4}$$

A RooPlot of "mass $p\mu\mu$ "



Conclusion

- Improved the UL for $\mathcal{B}(\Lambda_c^+ \rightarrow p\mu^+\mu^-)$ by two orders of magnitude!

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- First time observed the decay $\Lambda_c^+ \rightarrow p\omega$!!
- Paper is beeing prepared, aiming PRL
- We would like to ask the collaboration for approving this analysis.

