Search for excited doubly charmed baryons

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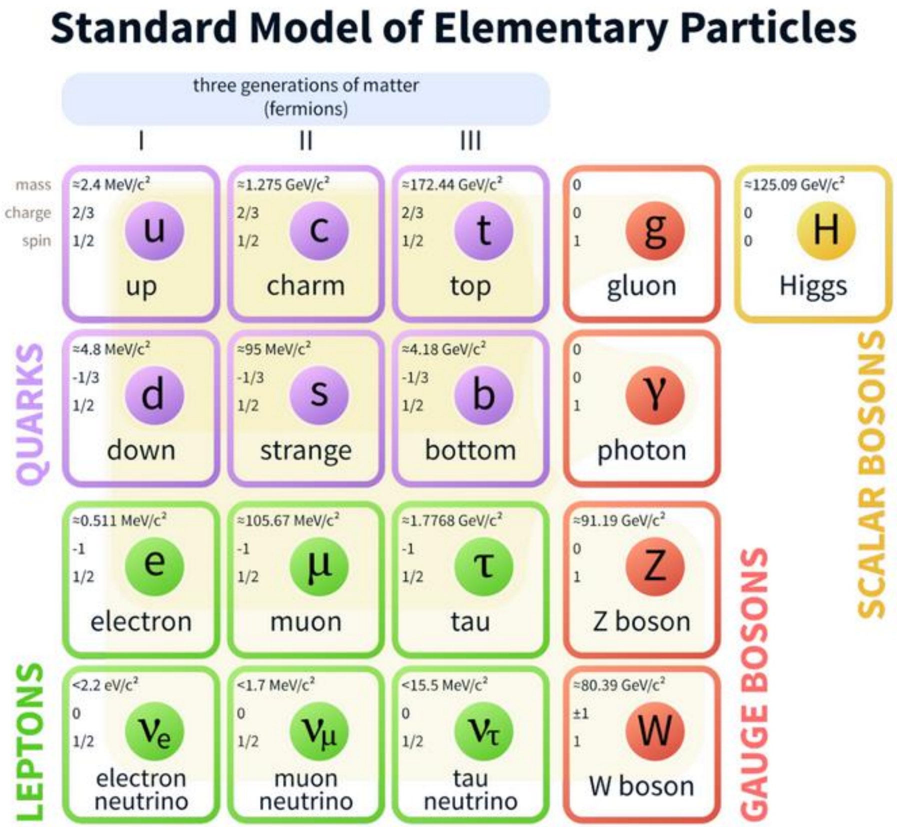
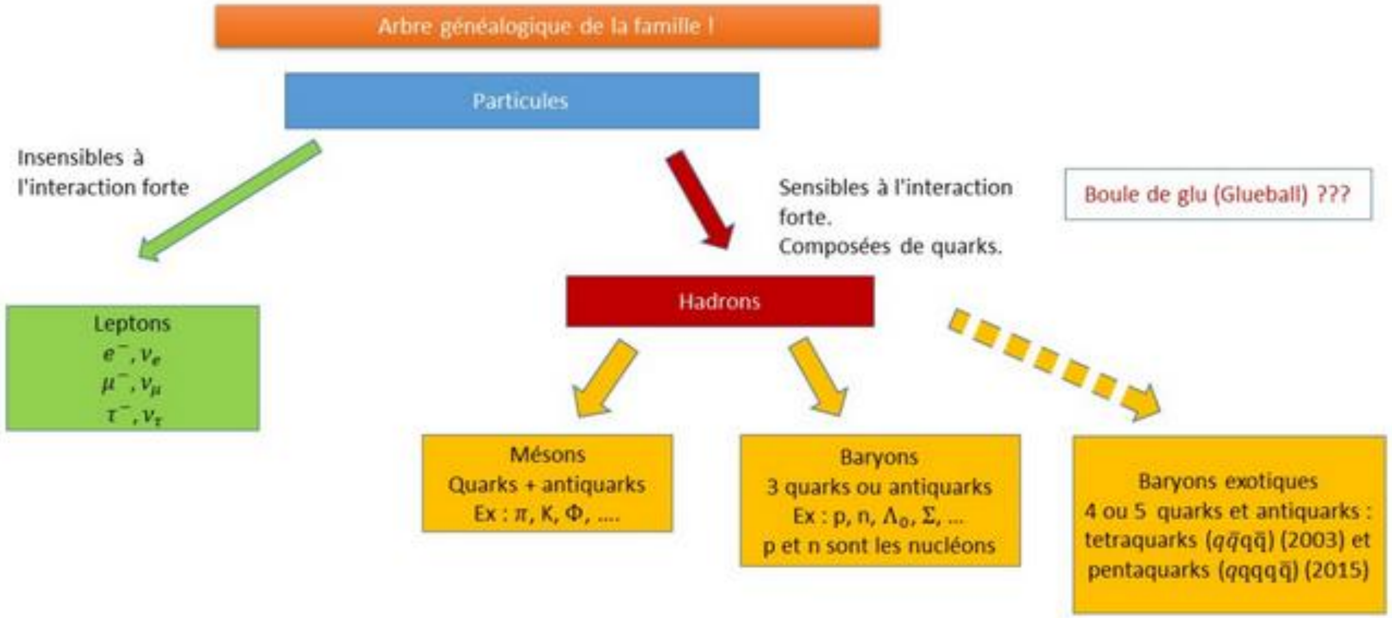
Particles physics





Large Hadron Collider (LHC)

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator

- 27 kilometres in circumference
- from 50 to 175 metres underground
- 4 interaction points
- 13.6 TeV total collision energy
- 40 MHz bunching rates

LHCb

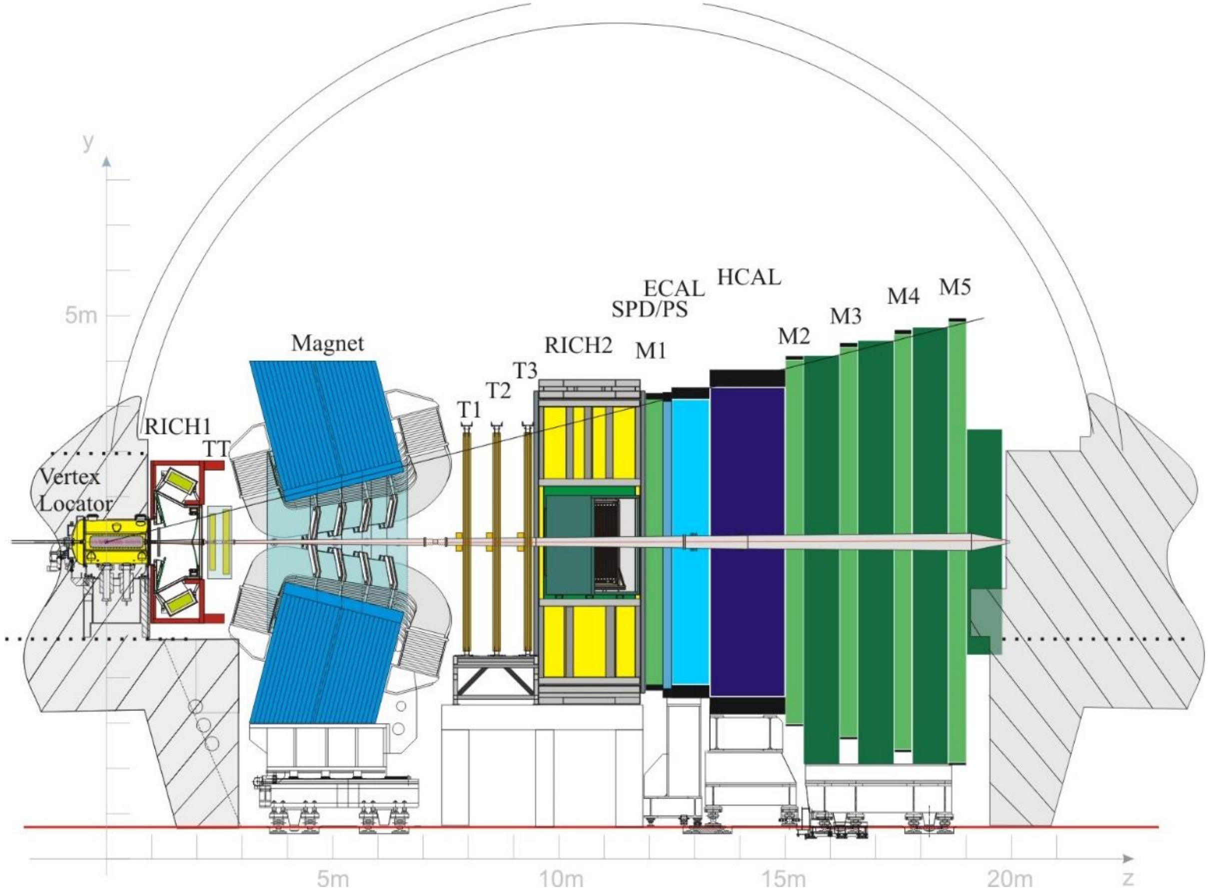
The LHCb collaboration, who built, operate and analyse data from the experiment, is composed of approximately 1650 people from 95 scientific institutes, representing 22 countries.

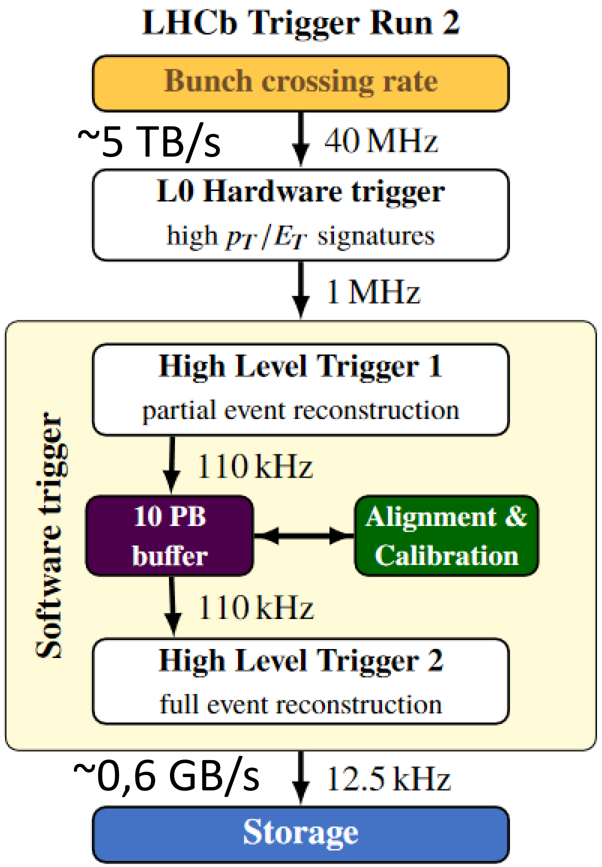
LHCb is a specialized b-physics experiment :

- Measurements of the parameters of CP violation in the interactions of b-hadrons (heavy particles containing a bottom quark)
- Measurements of production cross sections
- Exotic hadron spectroscopy
- Charm physics
- Electroweak physics in the forward region

LHCb detector

40 MHz of bunch crossings with an average of 2 proton-proton interactions (events) per bunch crossing, and about 30 particles produced per interaction

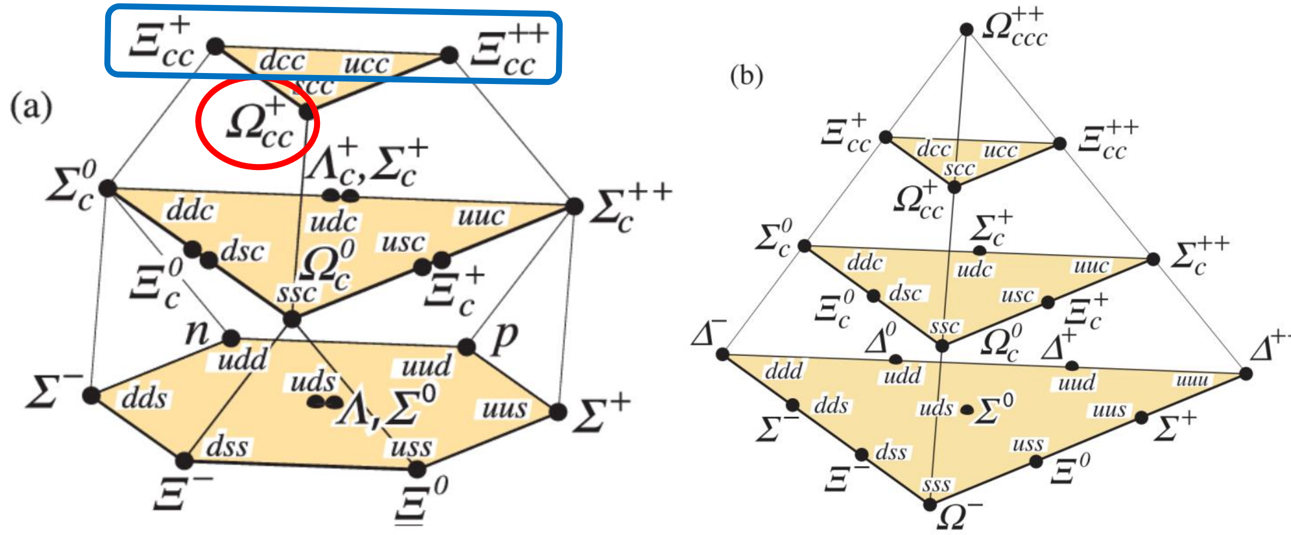




Doubly Charmed Baryons

Three weakly decaying doubly charmed baryons are expected:

- Ξ_{cc} isodoublet (ccu, ccd)
  - $\rightarrow$ Similar masses (isospin symmetry)
- Ω_{cc} isosinglet (ccs)

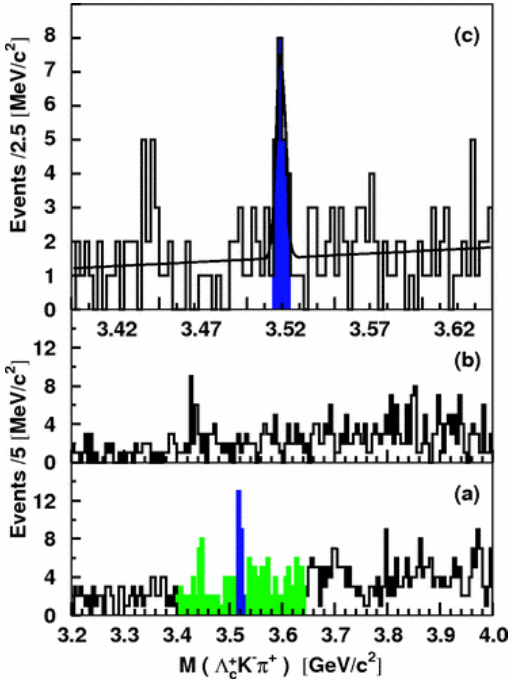


SU(4) 20-plets of baryons made of u, d, s, and c quarks with (a) $J^P = 1/2^+$ and (b) $J^P = 3/2^+$.

Experimental status

- SELEX in 2002

$\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+}$



FERMILAB-Pub-02/183-E

First Observation of the Doubly Charmed Baryon Ξ_{cc}^{+}

M. Mattson[3], G. Alkhazov[11], A.G. Atamantchouk[11,*], M.Y. Balatz[8,*], N.F. Bondar[11], P.S. Cooper[5], L.J. Dauwe[17], G.V. Davidenko[8], U. Dersch[9,†], A.G. Dolgolenko[8], G.B. Dzyubenko[8], R. Edelstein[3], L. Emediato[19], A.M.F. Endler[4], J. Engelfried[13,5], I. Eschrich[9,‡], C.O. Escobar[19,§], A.V. Evdokimov[8], I.S. Filimonov[10,*], F.G. Garcia[19,5], M. Gaspero[18], I. Giller[12], V.L. Golovtsov[11], P. Gouffon[19], E. Gülmez[2], He Kangling[7], M. Iori[18], S.Y. Jun[3], M. Kaya[16], J. Kilmer[5], V.T. Kim[11], L.M. Kochenda[11], I. Konorov[9,¶], A.P. Kozhevnikov[6], A.G. Krivshich[11], H. Krüger[9,∥], M.A. Kubantsev[8], V.P. Kubarovsky[6], A.I. Kulyavtsev[3,5], N.P. Kuropatkin[11,5], V.F. Kurshetsov[6], A. Kushnirenko[3], S. Kwan[5], J. Lach[5], A. Lamberto[20], L.G. Landsberg[6], I. Larin[8], E.M. Leikin[10], Li Yunshan[7], M. Luksys[14], T. Lungov[19,**], V.P. Maleev[11], D. Mao[3,††], Mao Chensheng[7], Mao Zhenlin[7], P. Mathew[3,‡‡], V. Matveev[8], E. McCliment[16], M.A. Moinester[12], V.V. Molchanov[6], A. Morelos[13], K.D. Nelson[16,§§], A.V. Nemitkin[10], P.V. Neoustroev[11], C. Newsom[16], A.P. Nilov[8], S.B. Nurushev[6], A. Ocherashvili[12,¶¶], E. Oliveira[4], Y. Onel[16], E. Ozel[16], S. Ozkorucuklu[16], A. Penzo[20], S.V. Petrenko[6], P. Pogodin[16], M. Procario[3,***], V.A. Prutskoi[8], E. Ramberg[5], G.F. Rappazzo[20], B.V. Razmyslovich[11,†††], V.I. Rud[10], J. Russ[3], P. Schiavon[20], J. Simon[9,‡‡‡], A.I. Sitnikov[8], D. Skow[5], V.J. Smith[15], M. Srivastava[19], V. Steiner[12], V. Stepanov[11,†††], L. Stutte[5], M. Svoiski[11,†††], N.K. Terentyev[11,3], G.P. Thomas[1], L.N. Uvarov[11], A.N. Vasiliev[6], D.V. Vavilov[6], V.S. Verebryusov[8], V.A. Victorov[6], V.E. Vishnyakov[8], A.A. Vorobyov[11], K. Vorwalter[9,§§§], J. You[3,5], Zhao Wenheng[7], Zheng Shuchen[7], R. Zukanovich-Funchal[19]

(SELEX Collaboration)

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(August 9, 2002)

We observe a signal for the doubly charmed baryon Ξ_{cc}^{+} in the charged decay mode $\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+}$ in data from SELEX, the charm hadro-production experiment at Fermilab. We observe an excess of 15.9 events over an expected background of 6.1 ± 0.5 events, a statistical significance of 6.3σ. The observed mass of this state is 3519 ± 1 MeV/c^2. The Gaussian mass width of this state is 3 MeV/c^2, consistent with resolution; its lifetime is less than 33 fs at 90% confidence.

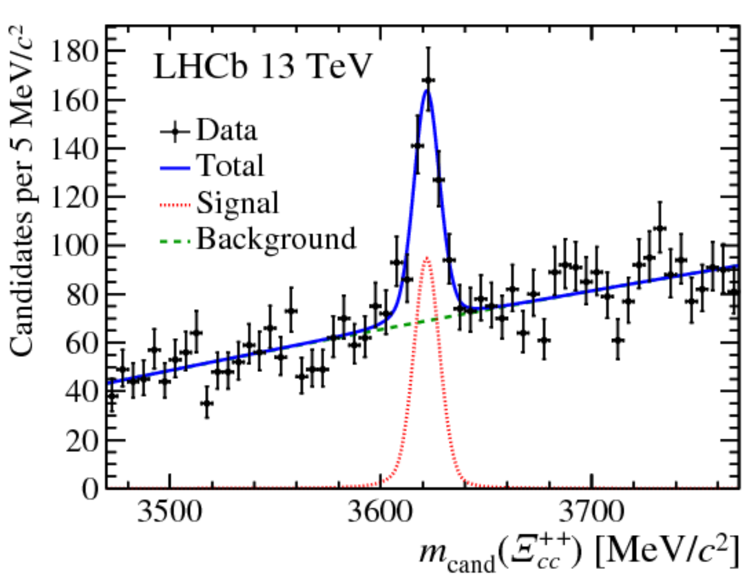
PACS numbers: 14.20.Lq, 13.30.Eg

1

Experimental status

- SELEX in 2002
- First observation in 2017 by LHCb

$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2017-156
LHCb-PAPER-2017-018
12 September 2017

LHCb-PAPER-2017-018

Observation of the doubly charmed baryon Ξ_{cc}^{++}

LHCb collaboration†

Abstract

A highly significant structure is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, where the Λ_c^+ baryon is reconstructed in the decay mode $pK^-\pi^+$. The structure is consistent with originating from a weakly decaying particle, identified as the doubly charmed baryon Ξ_{cc}^{++}. The difference between the masses of the Ξ_{cc}^{++} and Λ_c^+ states is measured to be $1334.94 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst})$ MeV/c^2, and the Ξ_{cc}^{++} mass is then determined to be $3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14\,(\Lambda_c^+)$ MeV/c^2, where the last uncertainty is due to the limited knowledge of the Λ_c^+ mass. The state is observed in a sample of proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 1.7 fb^{-1}, and confirmed in an additional sample of data collected at 8 TeV.

Published in Phys. Rev. Lett. 119 (2017) 112001

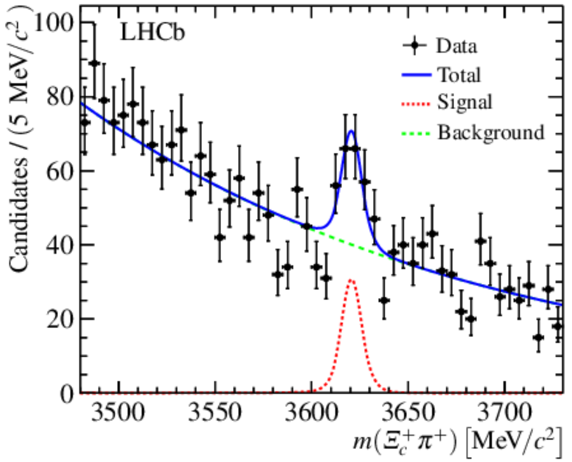
†Authors are listed at the end of this paper.

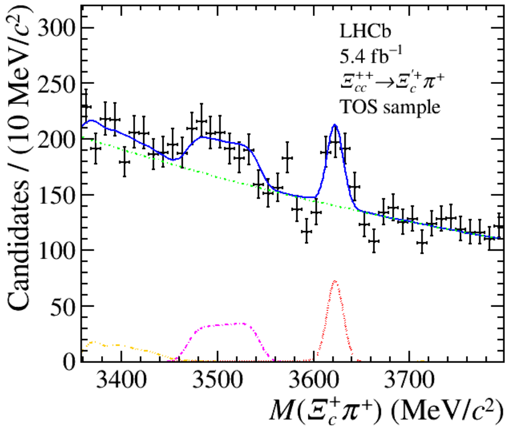
Experimental status

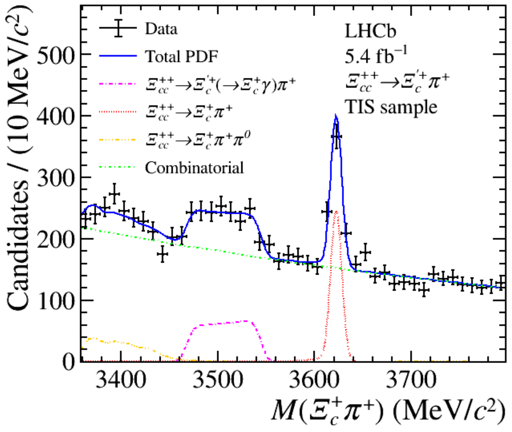
- SELEX in 2002
- First observation in 2017 by LHCb
- Observation of other decay modes

$\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ (LHCb-PAPER-2018-026)

$\Xi_{cc}^{++} \rightarrow \Xi_c^{\prime +} \pi^+$ (LHCb-PAPER-2021-052)

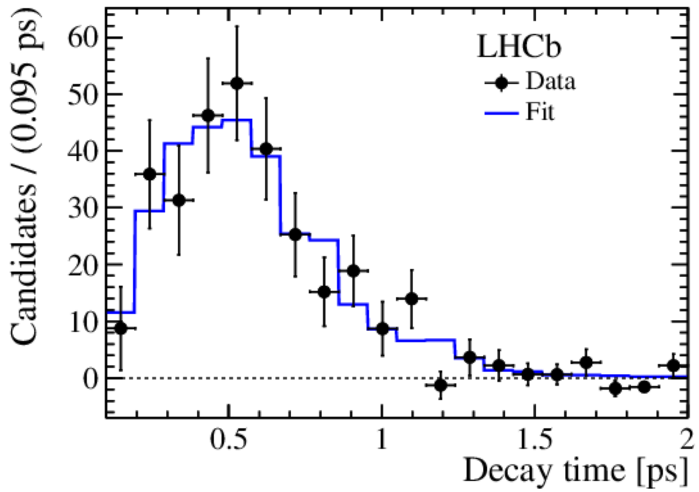




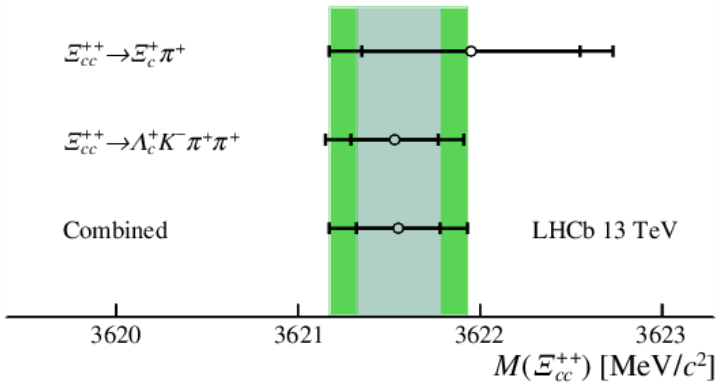


Experimental status

- SELEX in 2002
- First observation in 2017 by LHCb
- Observation of other decay modes
- Mass, lifetime and production measurements



LHCb-PAPER-2018-019



LHCb-PAPER-2019-037

Ξ_{cc}^{++}	Value	(stat)	(syst)
Mass (MeV/c^2)	3621.55	± 0.23	± 0.30
Lifetime (ps)	0.256	± 0.024	± 0.014
$\boldsymbol{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)/\sigma(\Lambda_c^+)}$ $(\times 10^{-4})$ (LHCb-PAPER-2017-018)	2.22	± 0.27	± 0.29

Experimental status

- SELEX in 2002
- First observation in 2017 by LHCb
- Observation of other decay modes
- Mass ,lifetime and production measurements
- Search for other doubly charmed baryon decays

- $\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+}$
LHCB-PAPER-2013-049
LHCb-PAPER-2019-029

- $\Xi_{cc}^{+} \rightarrow \Xi_c^{+} \pi^{-} \pi^{+}$
LHCb-PAPER-2021-019

- $\Omega_{cc}^{+} \rightarrow \Xi_c^{+} K^{-} \pi^{+}$
LHCb-PAPER-2021-011

- $\Xi_{cc}^{++} \rightarrow \Xi_c^{0} \pi^{+} \pi^{+}$
LHCb-ANA-2022-031
(last week presentation)

- $\Xi_{cc}^{++} \rightarrow D^{+} p K^{-} \pi^{+}$
LHCb-PAPER-2019-011

Search for excited doubly charmed baryons

We study the following two spectra:

- $\Xi_{cc}^{**+} \rightarrow \Xi_{cc}^{++}\,\pi^{-}$
- $\Omega_{cc}^{**+} \rightarrow \Xi_{cc}^{++}\,K^{-}$

where the Ξ_{cc}^{++} is reconstructed via:

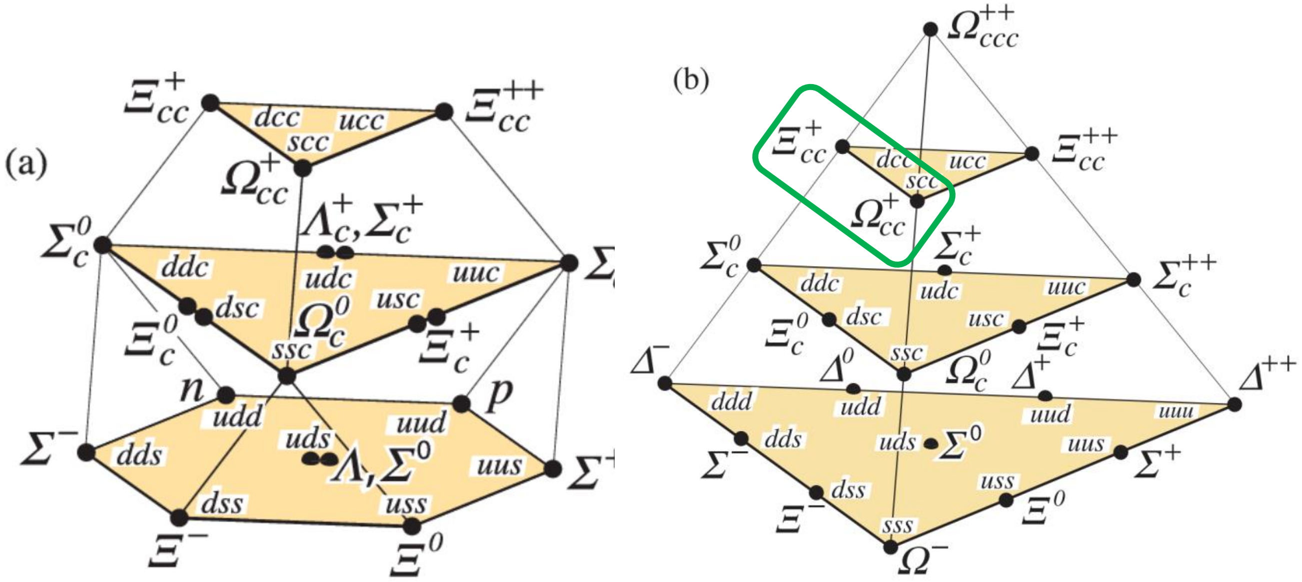
- $\Xi_{cc}^{++} \rightarrow \Lambda_c^{+}\,K^{-}\,\pi^{+}\,\pi^{+}$

First search for excited states

$\rightarrow$ some Ξ_{cc}^{++} must be from an excited state

$\Xi_{cc}^{**+} \rightarrow \Xi_{cc}^{++}\,\pi^{-}$: 30% i.e. 450 expected candidates

$\Omega_{cc}^{**+} \rightarrow \Xi_{cc}^{++}\,K^{-}$: 3% i.e. 45 expected candidates



SU(4) 20-plets of baryons made of u, d, s, and c quarks with (a) $J^P = 1/2^+$ and (b) $J^P = 3/2^+$.

Analysis strategy

1. Reconstruct Ξ_{cc}^{++} candidates from the exclusive Ξ_{cc}^{++} TURBO line (Persistence Reco not available. Used only as a starting point)
   - *Hlt2CharmHadXiccpp2LcpKmPipPip_Lcp2PpKmPipTurbo*

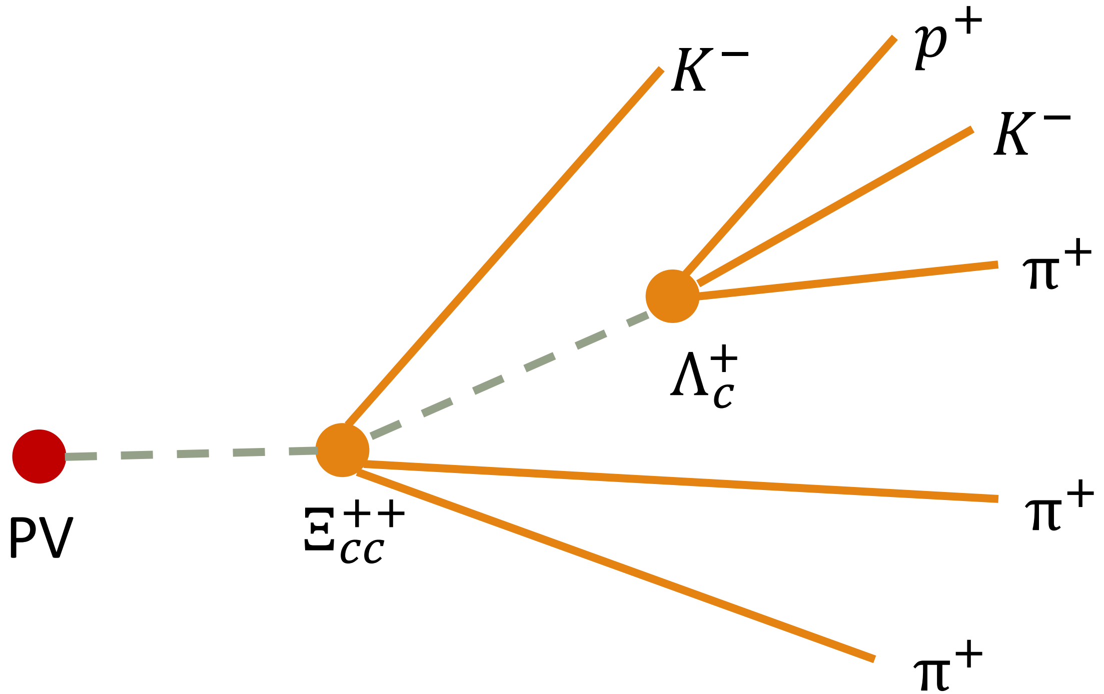
2. Reconstruct Ξ_{cc}^{++} candidates from the inclusive Λ_c^+ TURBO line (Persistence Reco in 2016. Selective Persistence in 2017&2018)
   - *Hlt2CharmHadLcpToPpKmPipTurbo*

3. Combine the candidates from (2) to a π^-/K^- (Right Sign) and π^+/K^+(Wrong Sign). The latter used for background studies

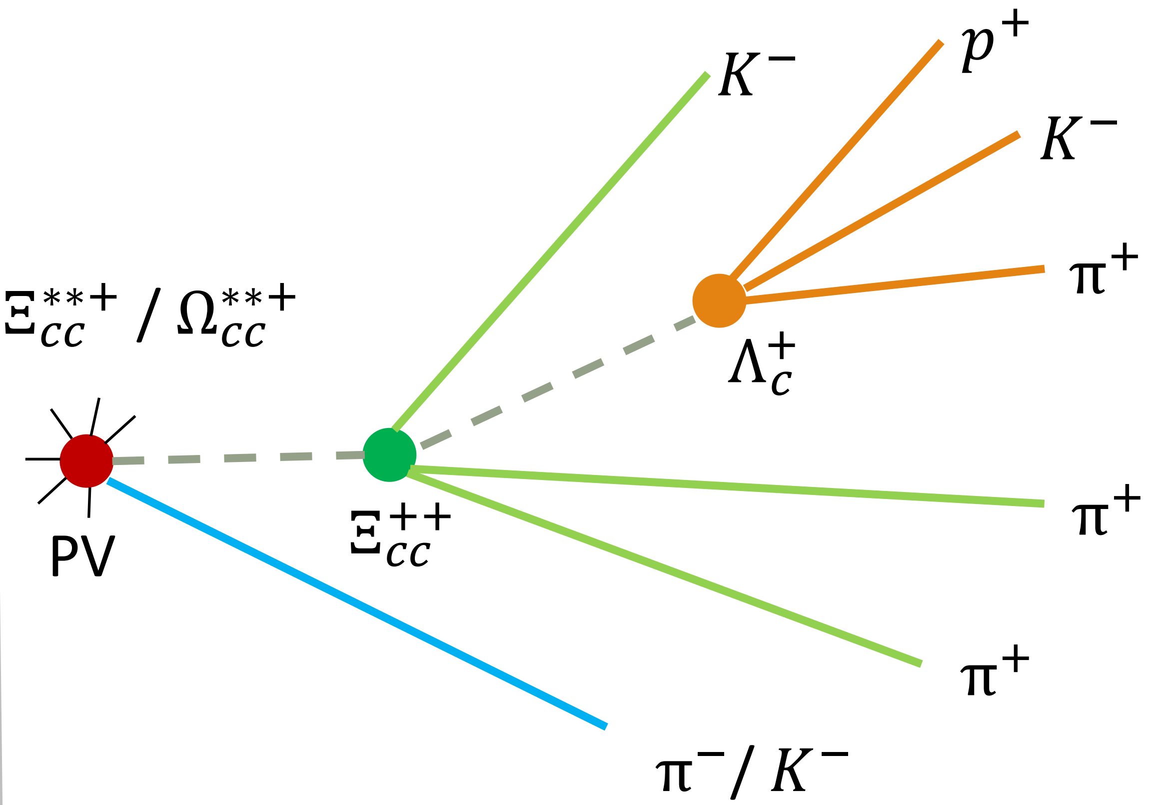
Analysis strategy for each step

1. Events are filtered and candidates are reconstructed and selected centrally through the trigger
2. A cut-based pre-selection is applied
3. Candidates are required to lie inside a Λ_c^+ mass window of 2270 < m(Λ_c^+) < 2306 MeV/c^2
4. A multivariate selection is applied
5. Clone and duplicated candidates are removed

Reconstruction of Ξ_{cc}^{++}



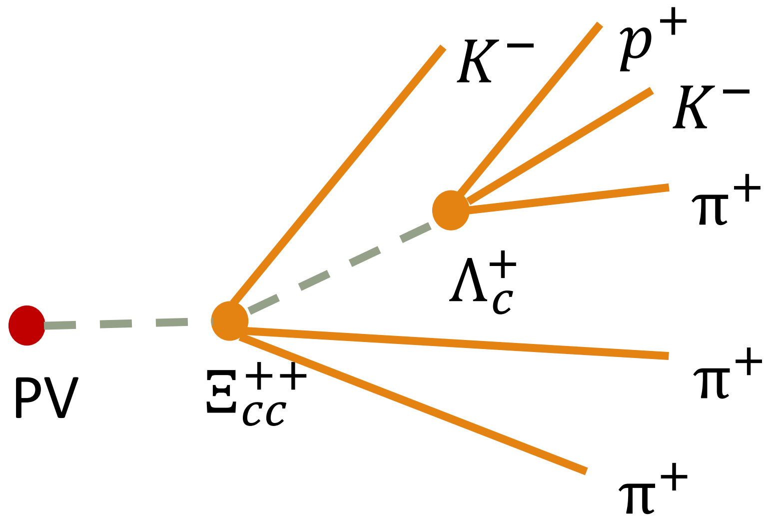
Ξ_{cc}^{++} Turbo line



Λ_c^+ Turbo line

Step 1: Reconstruction from the exclusive Ξ_{cc}^{++} line

- Selection applied on the data:



Ξ_{cc}^{++} Turbo line

Particles	Variable	Cuts
Daughters of Λ_c^+	Track quality	$\chi^2/ndf < 3$
	Momentum	$p > 1\,\mathrm{GeV}/c$
	Transverse momentum	$p_T > 0.2\,\mathrm{GeV}/c$
	Arithmetic sum of daughter	$> 3\,\mathrm{GeV}/c$
	Impact parameter significance	$\chi^2_{IP} > 6$
	p momentum	$p > 10\,\mathrm{GeV}/c$
	p particule ID	$\mathrm{DLL}_{p\pi} > 5$, $\mathrm{DLL}_{pK} > 5$
	K particule ID	$\mathrm{DLL}_{K\pi} > 5$
	π particule ID	$\mathrm{DLL}_{K\pi} < 5$
	Maximum p_T	$> 1\,\mathrm{GeV}/c$
	Second maximum p_T	$> 0.4\,\mathrm{GeV}/c$
	Maximum χ^2_{IP}	> 16
	Second maximum χ^2_{IP}	> 9
Λ_c^+	Vertex quality	$\chi^2_{vtx}/ndf < 10$
	Cosine of decay angle (DIRA)	$> cos(0.01)$
	Decay time	$\tau > 0.15\,\mathrm{ps}$
	Mass	$M \pm 75\,\mathrm{MeV}/c^2$
Daughters of Ξ_{cc}^{++}	Track quality	$\chi^2/\mathrm{ndf} < 3$
	Momentum	$p > 1\,\mathrm{GeV}/c$
	Transverse momentum	$p_T > 0.5\,\mathrm{GeV}/c$
	K particule ID	$\mathrm{DLL}_{K\pi} > 10$
	π particule ID	$\mathrm{DLL}_{K\pi} < 0$
Ξ_{cc}^{++}	Vector sum of daughter	$> 2\,\mathrm{GeV}/c$
	Vertex quality	$\chi^2_{\mathrm{vtx}}/\mathrm{ndf} < 60$
	Λ_c^+ vertex displacement w.r.t. Ξ_{cc}^{++}	$z_{\Lambda_c^+} - z_{\Xi_{cc}^{++}} > 0.01mm$
	Distance of closest approach	$< 10mm$

Step 1: Reconstruction from the exclusive Ξ_{cc}^{++} line

- Follow the strategy of LHCb-PAPER-2017-018:

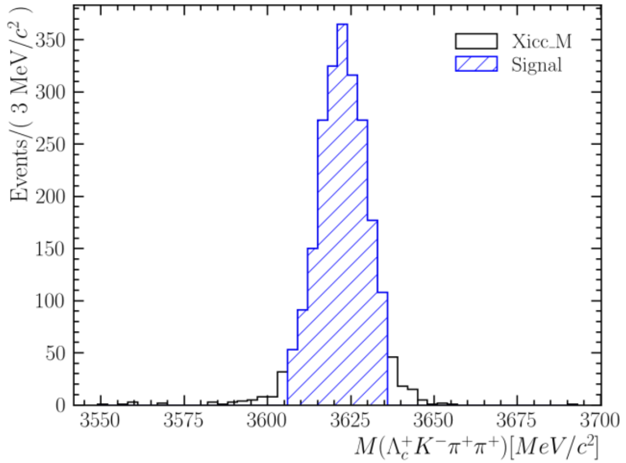
TMVA training:

- Signal: 2016 MC (Monte Carlo) samples (EventType 26266050)
- Background: 2016 Upper sideband (3800-3900 MeV/c^2)

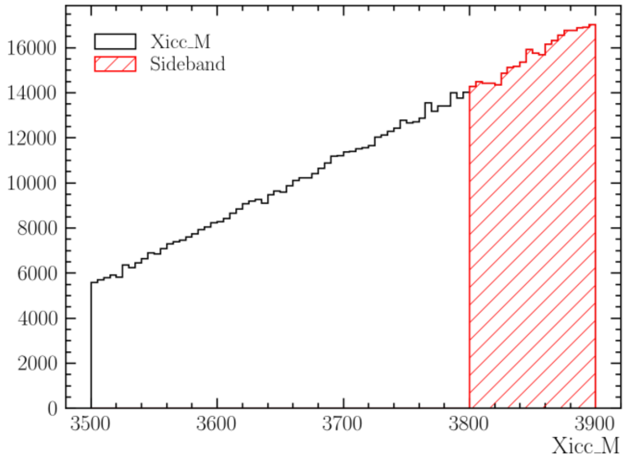
Same variables as the previous analysis:

1.	$\log(\chi^2_{IP})$ of Ξ_{cc}^{++} to its PV
2.	$\cos^{-1}$(DIRA) of Ξ_{cc}^{++} from its PV
3.	$\log(\mathrm{FD}\chi^2)$ of Ξ_{cc}^{++} from its PV
4.	χ^2_{vtx}/ndf of the Λ_c^+ vertex fit
5.	χ^2_{vtx}/ndf of the Ξ_{cc}^{++} vertex fit (non-DTF)
6.	χ^2_{vtx}/ndf of the Ξ_{cc}^{++} vertex fit (DTF, with the PV constraint)
7.	Smallest $\log(\chi^2_{IP})$ among the daughters (Λ_c^+, K^-, π^+ and π^+) of Ξ_{cc}^{++}
8.	Scalar p_T sum of the daughters (Λ_c^+, K^-, π^+ and π^+) of Ξ_{cc}^{++}
9.	Smallest p_T among the daughters (Λ_c^+, K^-, π^+ and π^+) of Ξ_{cc}^{++}
10.	Smallest p_T among the final daughters of the Λ_c^+

(Input variable PDFs in backup)



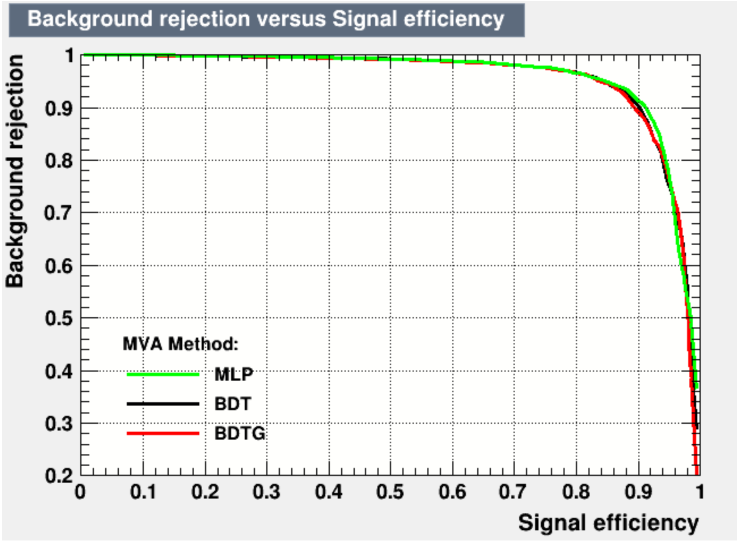
Ξ_{cc}^{++} candidates TURBO MC 2016

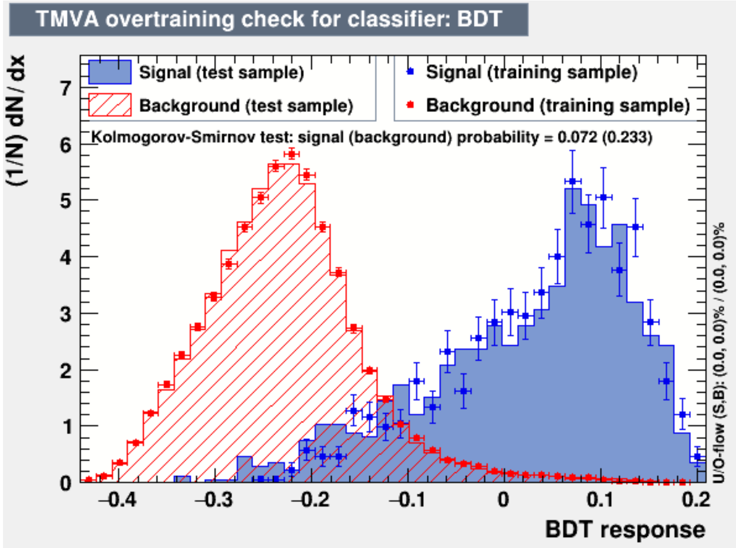


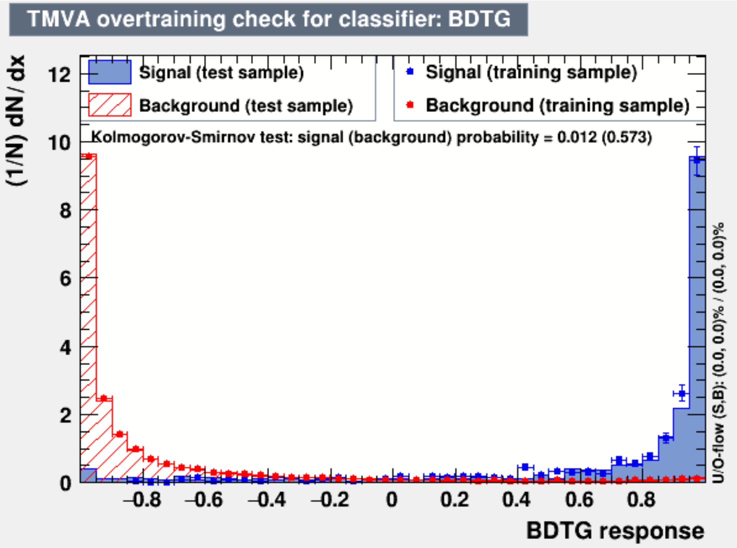
Ξ_{cc}^{++} candidates after selection 2016

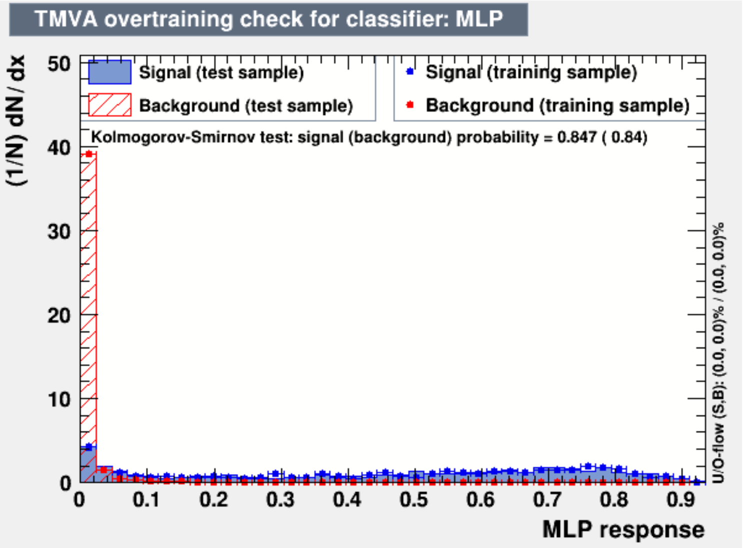
Overtraining check

MVA: BDT, BDTG and MLP are compared









MVA optimization

Cut optimization:

- Cut point is determined by optimizing $S/\sqrt{S+B}$
- S nb of MC signal candidates scaled to 2016 data

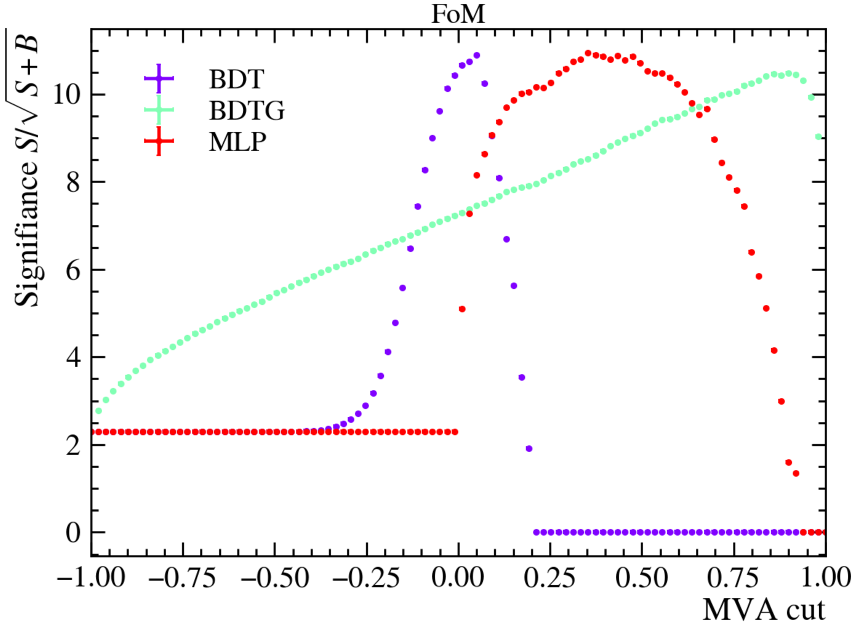
$$S = \frac{\varepsilon_{MC} S_{0,MC}}{C_{MC-Data}}$$

  - $C_{MC-Data} = \frac{yield\ in\ MC}{yield\ in\ data}$ for BDT>0.05

- B nb of background candidates from sideband scaled to the mass window (30 MeV/c^2)

$$B = \frac{\varepsilon_{bkg} B_{0,bkg}}{C_{window}}$$

  - $C_{window} = \frac{100}{30}$



Selector	Optimal cut	Signal efficiency	Significance
BDT	0.050	0.51	10.89 σ
BDTG	0.899	0.59	10.49 σ
$\boxed{\text{MLP}}$	0.353	0.64	10.94 σ

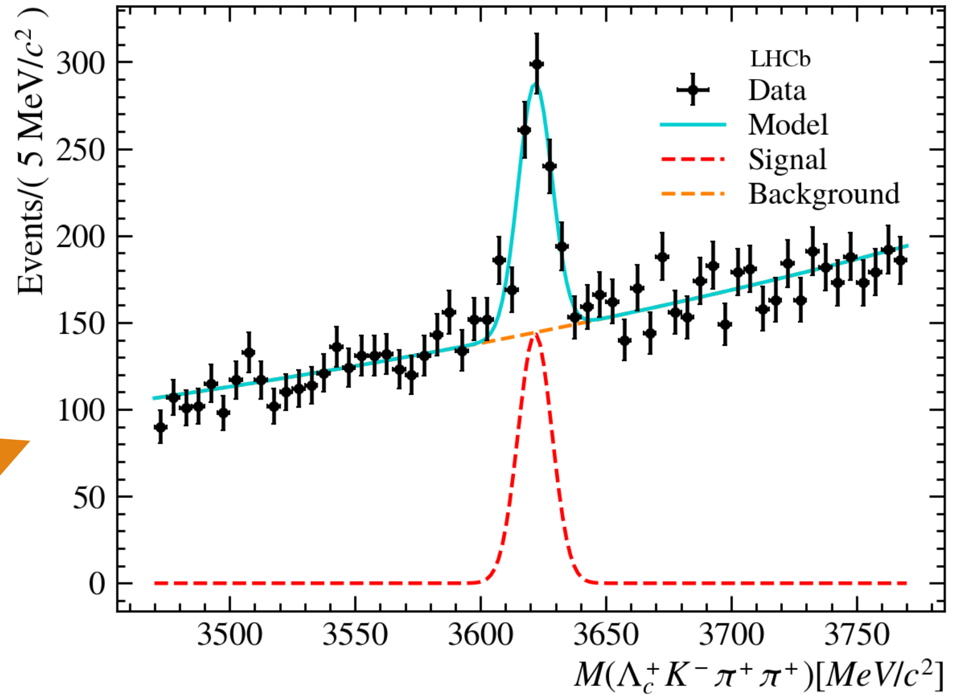
FoM response and optimal cut for the different selectors

Mass fit

Simple fit model:

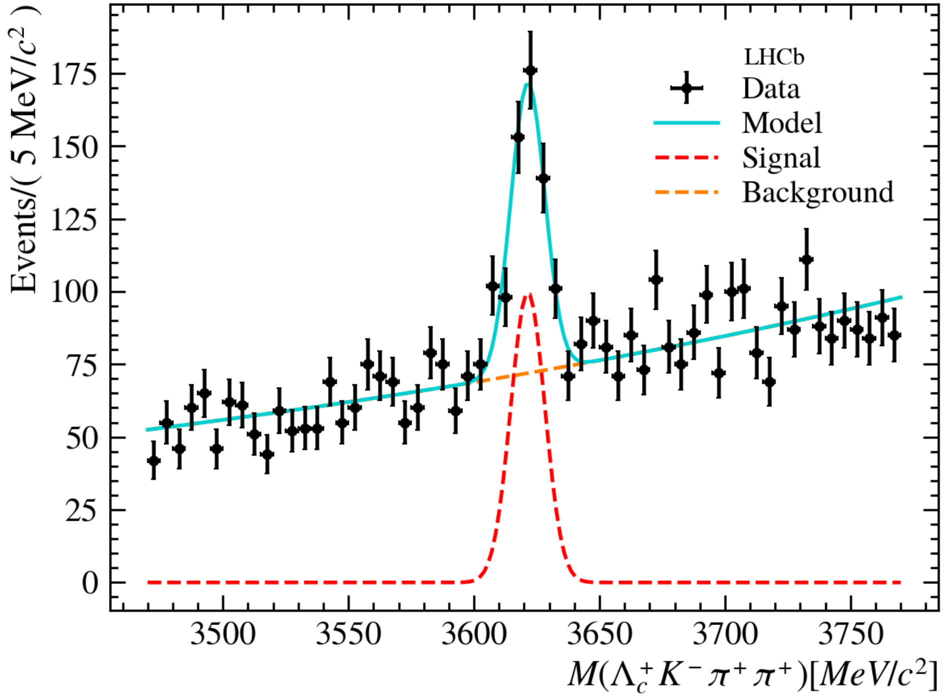
- Signal → Gaussian
- Background → exponential

MVA Cut	Signal yield	Background yield	Significance
BDT > 0.050	329.8	438.1	11.9 σ
BDTG > 0.899	423.7	789.2	12.2 σ
MLP > 0.353	485.4	973.4	12.7 σ

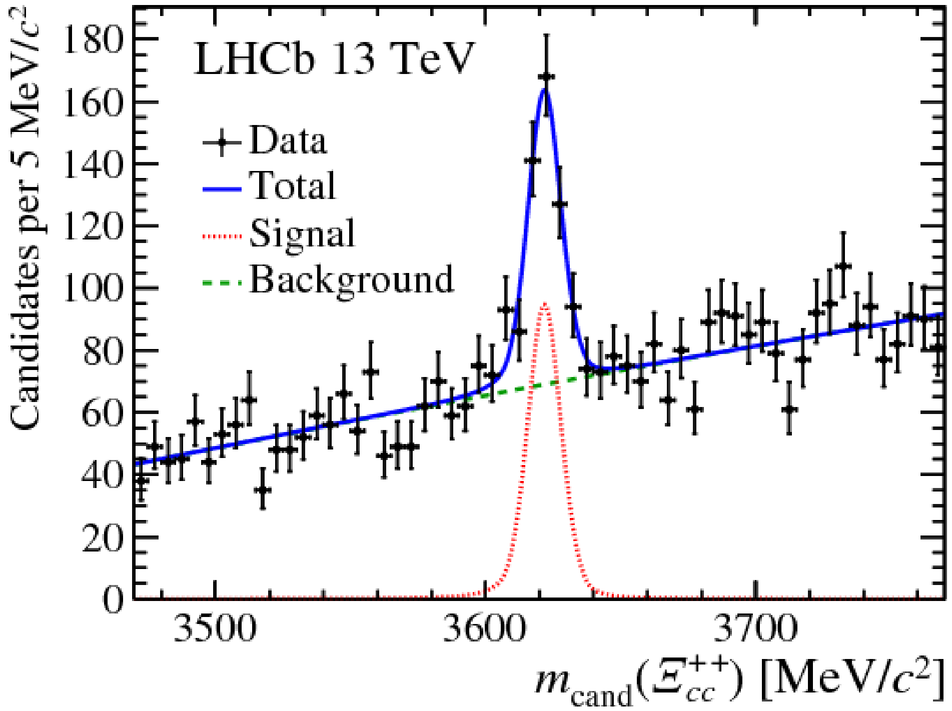


Fit result for MLP>0.353 (2016 Data)

Results comparison



Fit for MLP>0.5

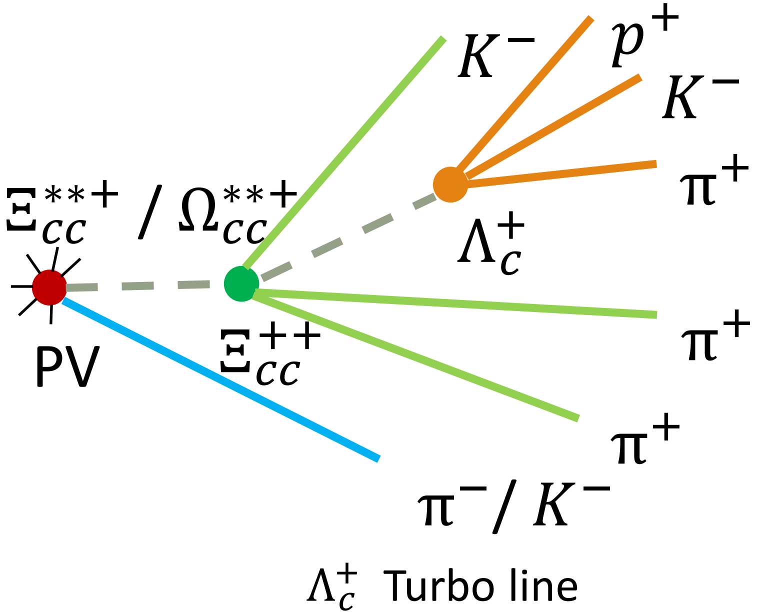


LHCb-PAPER-2017-018

Step 2: Reconstruction from the inclusive Λ_c^+ line

- Follow the strategy from LHCb-PAPER-2019-037 for 2016 Data
- The Λ_c^+ trigger line (*Hlt2CharmHadLcpToPpKmPipTurbo)* have switched from Persist Reco to Selective Persistence
- Examine the case of 2017 and 2018:

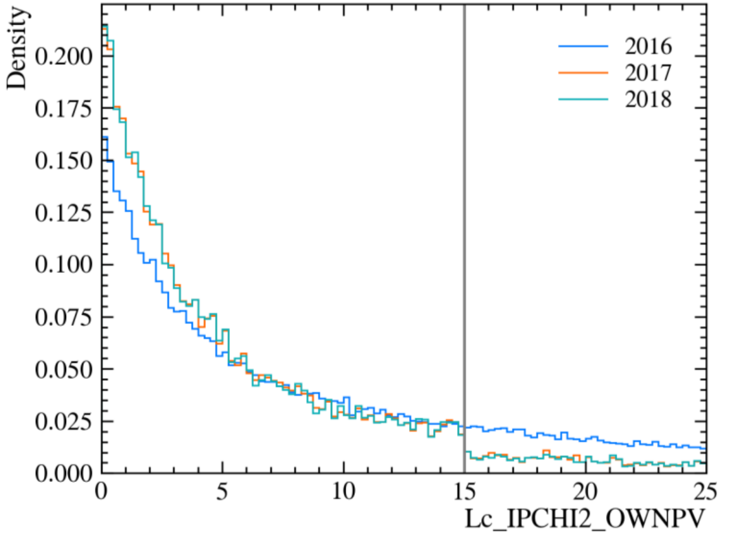
- The paper used other trigger lines due to 'problems'
    - 2017 : *Hlt2CharmHadXiccpp2LcpKmPipPip_Lcp2PpKmPipTurbo*
    - 2018 : *Hlt2CharmHadInclLcpToKmPpPipBDTTurbo*

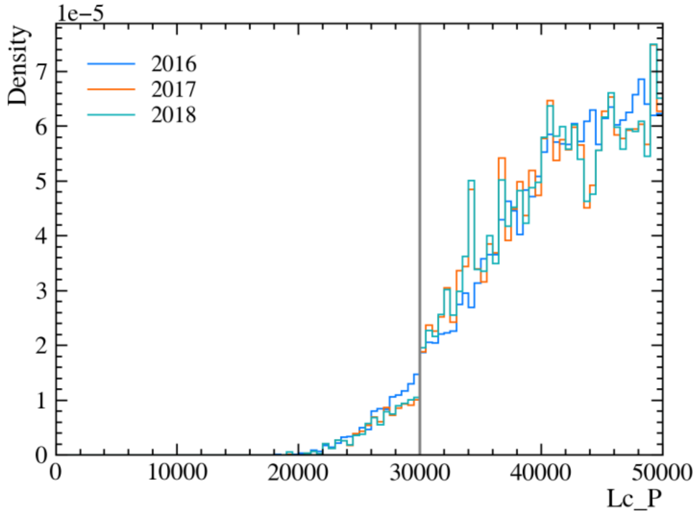


The case of 2017 and 2018

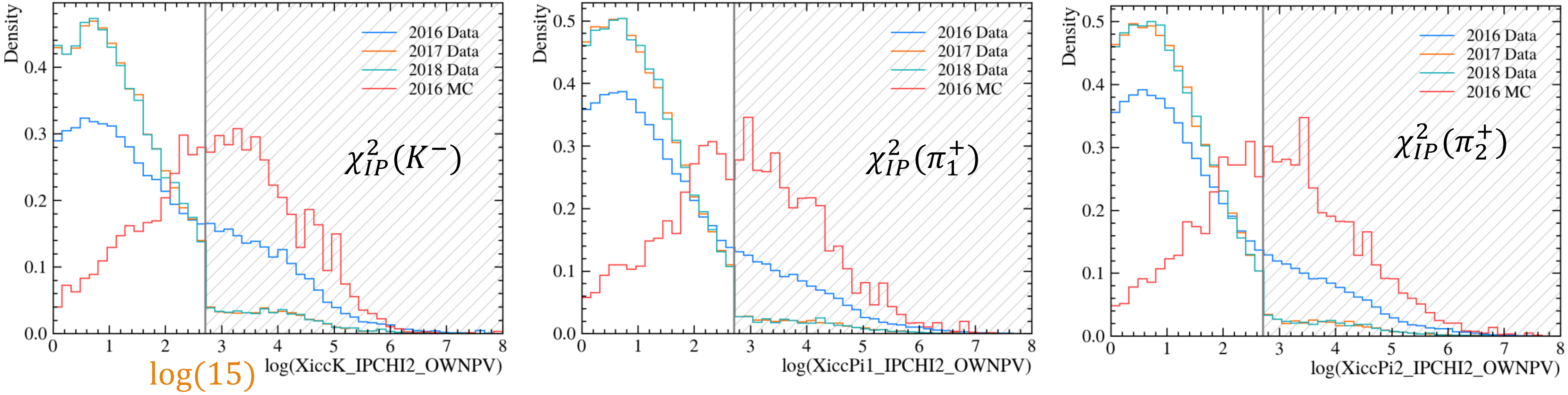
- Few changes in Λ_c^+ trigger line in 2017 and 2018
- Selective Persistence cuts

Particules	Variable	Cuts
Λ_c^+	Impact parameter significance	$\chi^2_{IP} < 15$
	Decay time	$\tau > 0.30\,\mathrm{ps}$
	Momentum	$p > 30\,\mathrm{GeV}/c$
	Transverse momentum	$p_T > 2\,\mathrm{GeV}/c$
Companion tracks	Track quality	$\chi^2/ndf < 3$
	Ghost probabilty	$GhostProb < 0.4$
	Impact parameter significance	$\chi^2_{IP} < 15$
	Momentum	$p > 1\,\mathrm{GeV}/c$
	Transverse momentum	$p_T > 0.2\,\mathrm{GeV}/c$





The case of 2017 and 2018



- The cut $\chi^2_{IP} < 15$ removes a sizeable fraction of the Ξ_{cc}^{++} signal
- No alternative for 2017
  - We will use the inclusive Λ_c^+ trigger despite the low efficency
- 2018 alternative:
  - *Hlt2CharmHadInclLcpToKmPpPipBDTTurbo* (PersistReco)

MVA Training

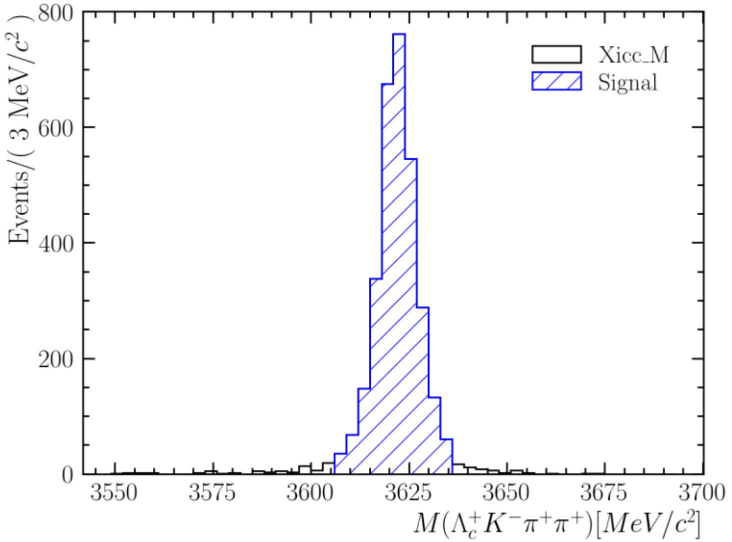
Data:

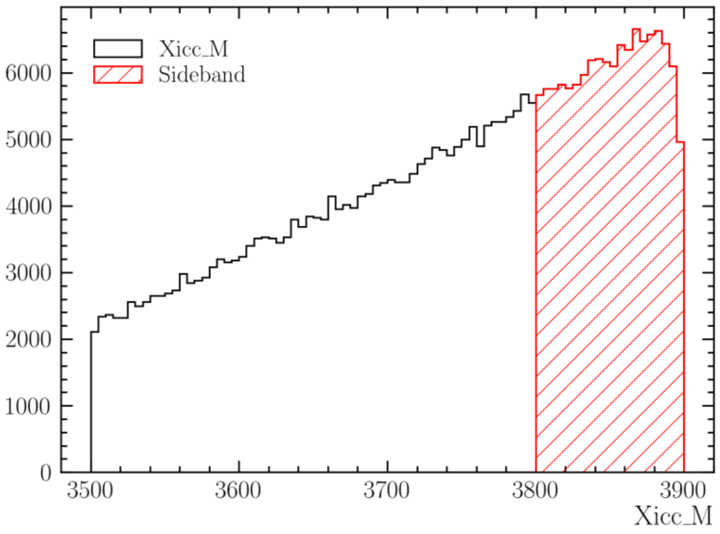
- Signal: Run2 MC samples (EventType 26266052)
- Background: 2016 Upper sideband (3800-3900 MeV/c^2)

Same set of MVA variables as LHCb-PAPER-2019-037 apart for few changes:

- varPi1 & varPi2 → varPi1+varPi2 & | varPi1-varPi2 |

1. $\log(\chi^2_{\rm IP})$ of $\Xi_{\rm cc}^{++}$ to its PV
2. $\cos^{-1}$(DIRA) of $\Xi_{\rm cc}^{++}$ from its PV
3. $\log(\chi^2_{\rm FD})$ of $\Xi_{\rm cc}^{++}$ from its PV
4. $\chi^2_{\rm vtx}$/ndf of the $\Lambda_{\rm c}^{+}$ vertex fit
5. $\log(\chi^2_{\rm vtx}/{\rm ndf})$ of the $\Xi_{\rm cc}^{++}$ vertex fit (non-DTF)
6. $\log(\chi^2_{\rm vtx}/{\rm ndf})$ of the $\Xi_{\rm cc}^{++}$ vertex fit (DTF, with the PV constraint)
7. PID$_p$ of the p from $\Lambda_{\rm c}^{+}$
8. PID$_K$ of the K$^-$ from $\Lambda_{\rm c}^{+}$
9. PID$_K$ of the π^+ from $\Lambda_{\rm c}^{+}$
10. PID$_K$ of the K$^-$ from $\Xi_{\rm cc}^{++}$
11. ~~PID$_K$ of the first π^+ from $\Xi_{\rm cc}^{++}$~~
12. ~~PID$_K$ of the second π^+ from $\Xi_{\rm cc}^{++}$~~ (old)
11. Sum of PID$_K$ of the two π^+ from $\Xi_{\rm cc}^{++}$ (new)
12. Absolute difference of PID$_K$ of the two π^+ from $\Xi_{\rm cc}^{++}$
13. Smallest p_T among the daughters ($\Lambda_{\rm c}^{+}$, K$^-$, π^+ and π^+) of $\Xi_{\rm cc}^{++}$
14. Scalar p_T of $\Lambda_{\rm c}^{+}$
15. ~~Scalar p_T of the first π^+ from $\Xi_{\rm cc}^{++}$~~
16. ~~Scalar p_T of the second π^+ from $\Xi_{\rm cc}^{++}$~~ (old)
15. Sum of p_T of the two π^+ from $\Xi_{\rm cc}^{++}$ (new)
16. Absolute difference of p_T of the two π^+ from $\Xi_{\rm cc}^{++}$
17. Scalar p_T of the K$^-$ from $\Xi_{\rm cc}^{++}$
18. $\log(\chi^2_{\rm IP})$ of $\Lambda_{\rm c}^{+}$
19. $\log(\chi^2_{\rm IP})$ of the K$^-$ from $\Xi_{\rm cc}^{++}$
20. ~~$\log(\chi^2_{\rm IP})$ of the first π^+ from $\Xi_{\rm cc}^{++}$~~
21. ~~$\log(\chi^2_{\rm IP})$ of the second π^+ from $\Xi_{\rm cc}^{++}$~~ (old)
20. log sum of $\chi^2_{\rm IP}$ of the two π^+ from $\Xi_{\rm cc}^{++}$
21. log absolute difference $\chi^2_{\rm IP}$ of the two π^+ from $\Xi_{\rm cc}^{++}$ (new)





Ξ_{cc}^{++} MC signal candidates and background candidates from Λ_c^+ TURBO Run2

MVA optimization

MVA training:

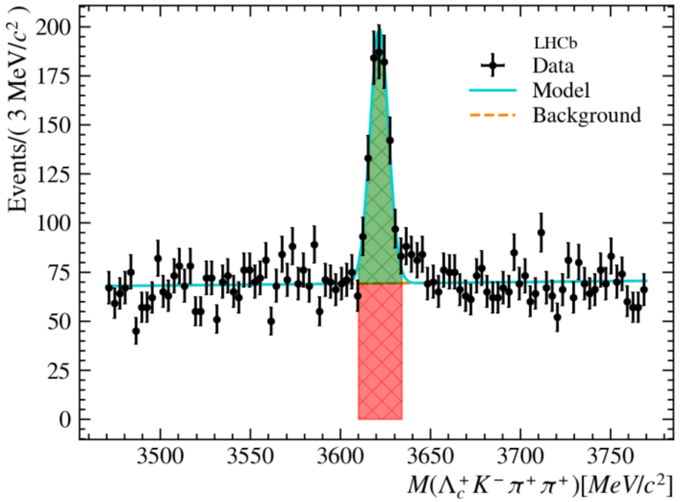
- BDT, BDTG and MLP are compared (in backup)

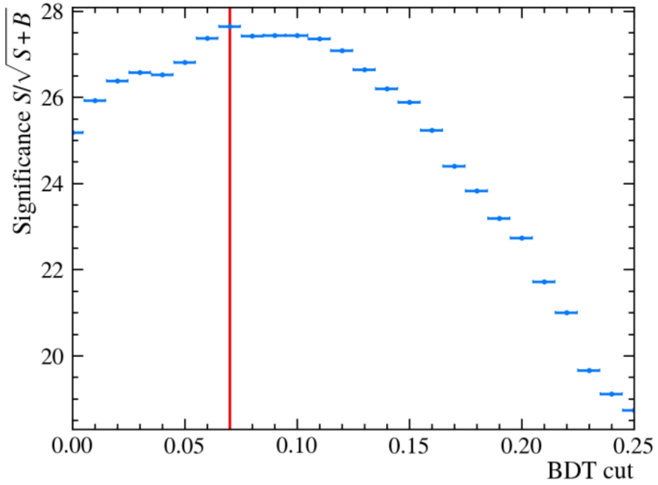
Cut optimization:

- Cut point is determined by optimizing $S/\sqrt{S+B}$
- Significance $S/\sqrt{S+B}$ computed by fitting the Ξ_{cc}^{++} mass spectrum in Run2 data
- S nb of signal events (green)
- B nb of background events in ±2.5σ mass window (red)

Optimal cut:

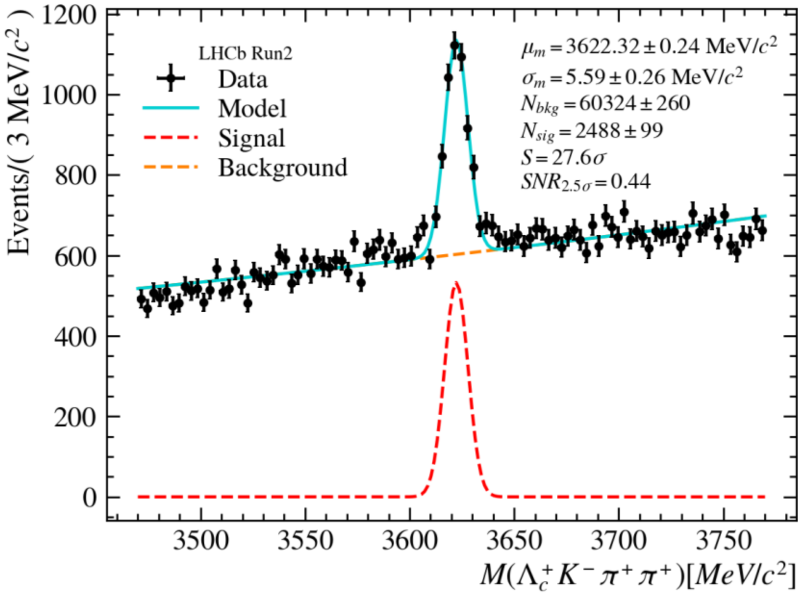
- BDT>0.07



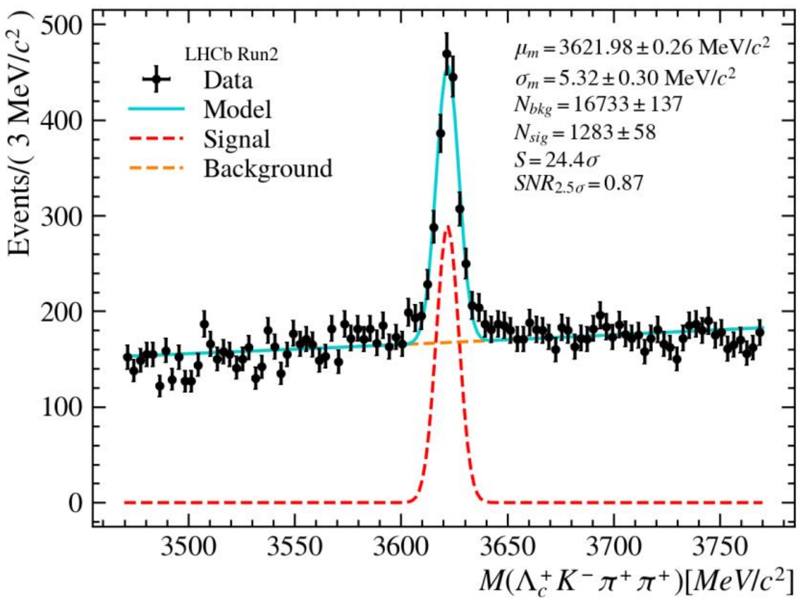


FoM curve from Data (BDT)

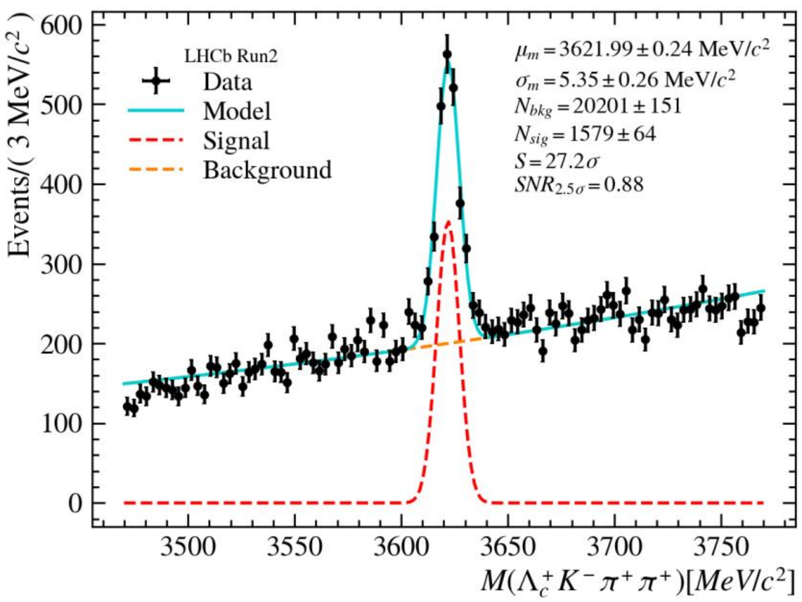
Results comparison



BDT > 0.07 (Loose)



BDT > 0.17 (Tight)



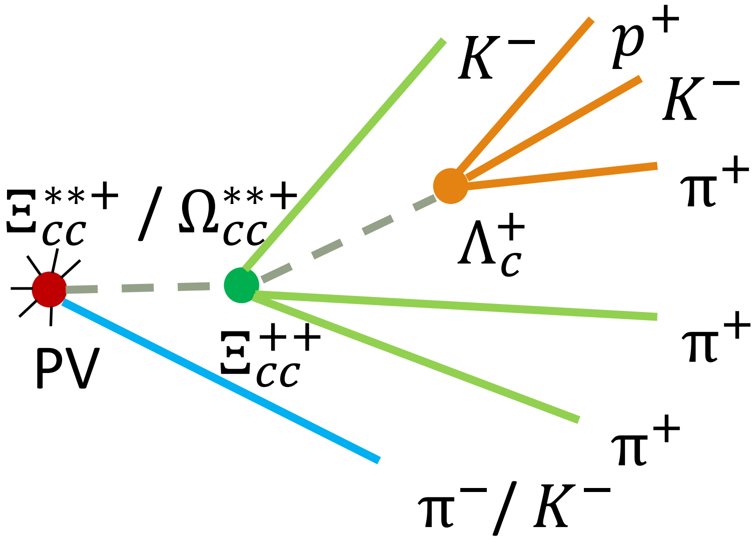
LHCb-PAPER-2019-037

Because of the use of a less efficiency trigger line in 2017, yields are the smaller with the same SNR.

Step 3: Reconstruction of doubly charmed baryons

The Ξ_{cc}^{++} candidates are combined to a prompt π^- and K^- to look for excited doubly baryons

- $\Xi_{cc}^{**+} \rightarrow \Xi_{cc}^{++}\,\pi^-$
- $\Omega_{cc}^{**+} \rightarrow \Xi_{cc}^{++}\,K^-$



Selection :

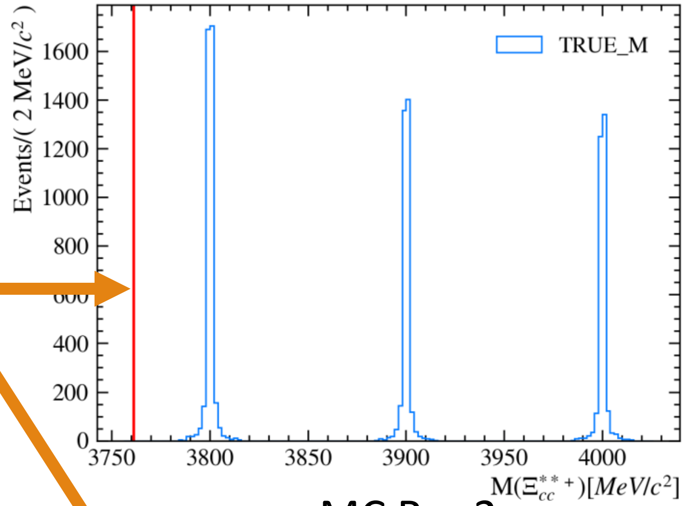
Particles	Variable	Cuts
Ξ_{cc}^{++}	BDT	BDT>0.07 (Loose) or BDT>0.17 (Tight)
	Mass	$M \pm 15\,\mathrm{MeV}/c^2$
π^-/ K^-	Track quality	$\chi^2/ndf < 3$
	Impact parameter	$\chi^2_{IP} < 16$
	Transverse momentum	$p_T > 0.2\,\mathrm{GeV}/c$
	π particle ID	$ProbNNpi > 0.1$
	K particle ID	$ProbNNk > 0.1$
Ξ_{cc}^{**+}/ Ω_{cc}^{**+}	Vertex quality	$\chi^2_{vtx}/ndf < 25$

MC Samples

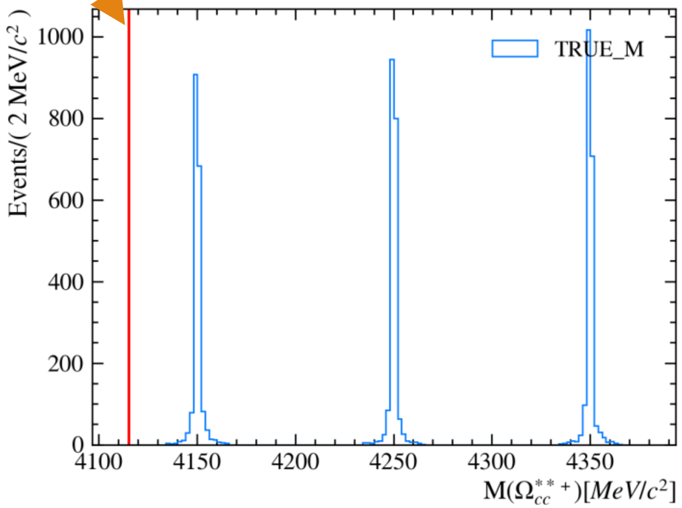
(1M events per year/per polarity/per EventType)

$\Xi_{cc}^{**+} \to \Xi_{cc}^{++}\pi^-$	$\Omega_{cc}^{**+} \to \Xi_{cc}^{++}K^-$
26167051	26167054
26167052	26167055
26167053	26167056

kinematic thresholds



MC Run2



ParticleValue: "Xi_cc+ 502 4412 1.0 3.8 6.58e-22 Xi_cc+ 4412 0.",
"Xi_cc~- 503 -4412 -1.0 3.8 6.58e-22 anti-Xi_cc- -4412 0. "

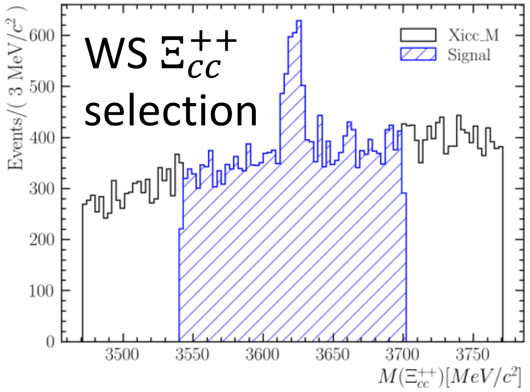
Natural width of 1 MeV/c^2 → lifetime of 6.58×10^{-22}s

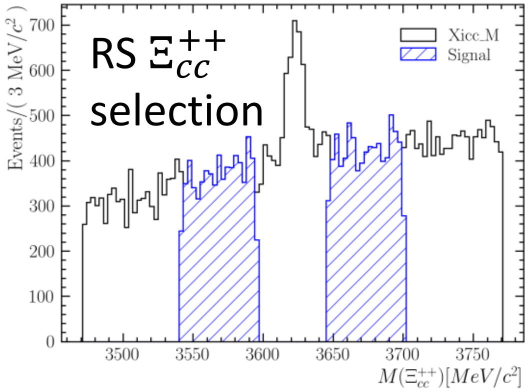
→ Fixed a "bug" in GenXicc to customize the natural width

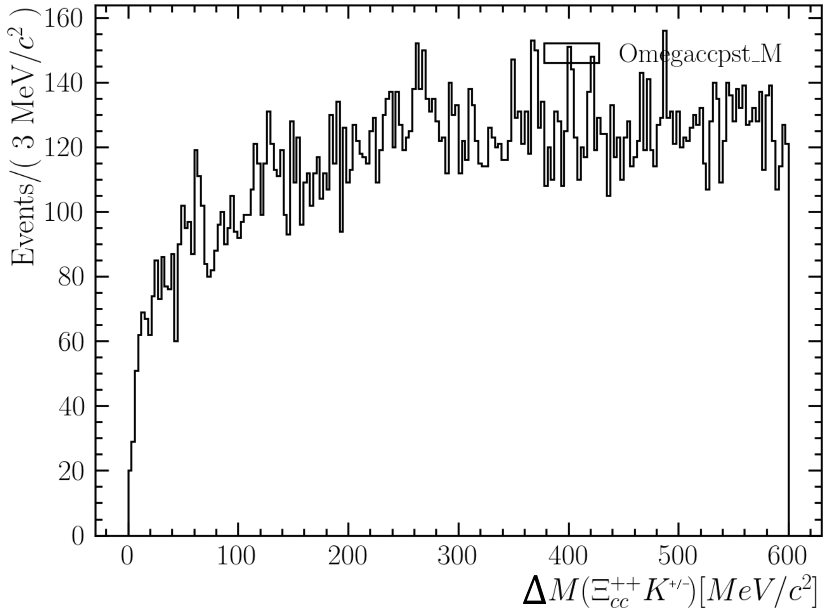
MVA Training

Data:

- Signal: Run2 MC samples (3 mass hypothesis combined)
- Background: Run2 WS + RS (Ξ_{cc}^{++} sidebands) Data ($m(\Xi_{cc}^{++}\mathrm{K}^+) - m(\Xi_{cc}^{++}) - m(\mathrm{K}^+)$ < 500 MeV/c^2)





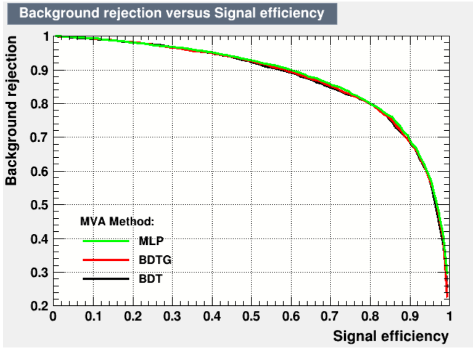


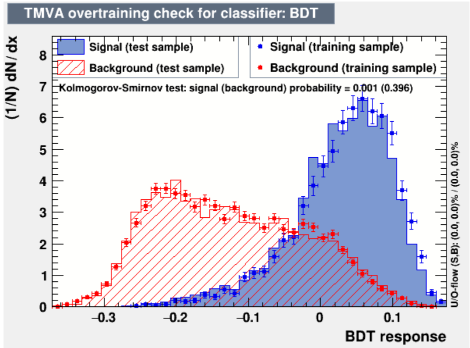
Resulting background used for the training

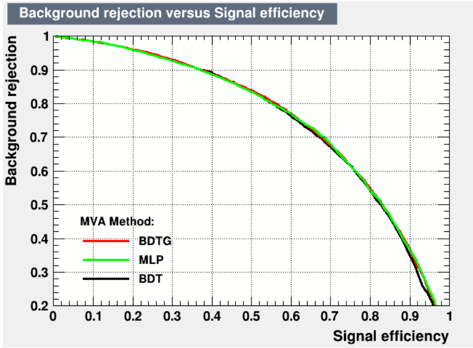
$\log(\chi^2_{\mathrm{IP}})$ of $\Xi_{cc}^{**+}/\Omega_{cc}^{**+}$ to its PV
Transverse momentum p_T of $\Xi_{cc}^{**+}/\Omega_{cc}^{**+}$
$\log(\chi^2_{\mathrm{IP}})$ of π^-/K^-
ProbNNpi/k of π^-/K^-
Transverse momentum p_T of π^-/K^-

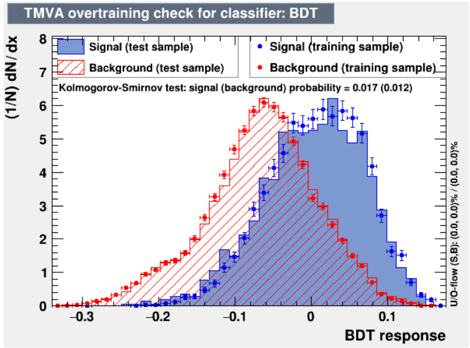
Overtraining check

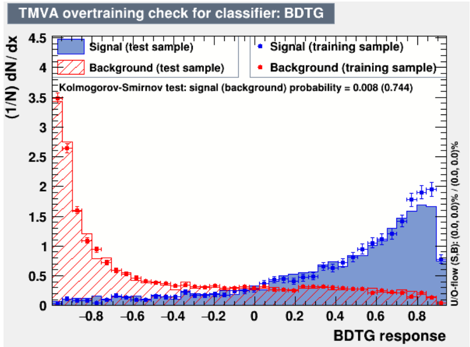
MVA: BDT, BDTG and MLP are compared

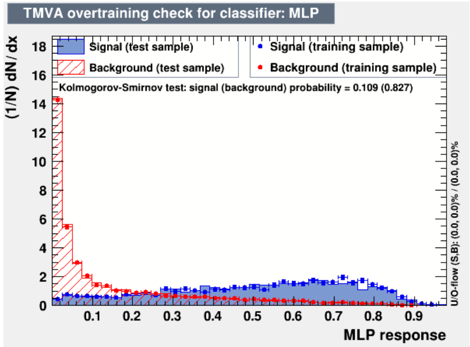


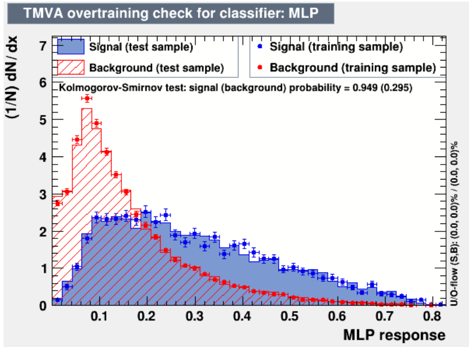


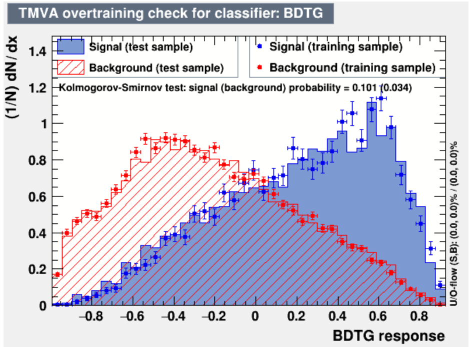












MVA optimization

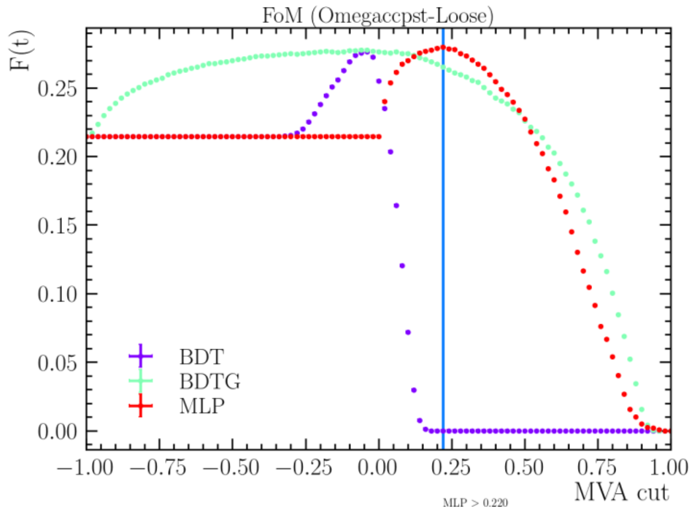
Cut optimization:

- Cut point is determined by optimizing :

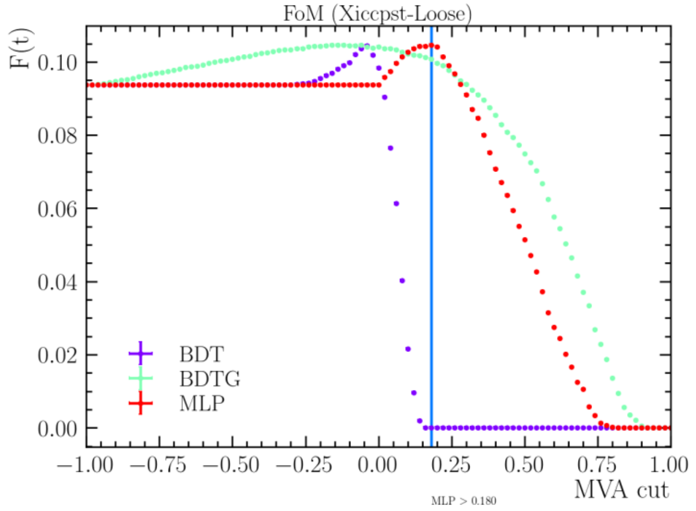
$$FoM_{PUNZI} = \frac{\varepsilon_{sig}}{\frac{a}{2} + \sqrt{B}}$$

  - ε_{sig} is the efficiency of the cuts on the signal
  - a is the desired significance (3σ)
  - B is the expected number of background candidates

Ω_{cc}^{**+}



Ξ_{cc}^{**+}



Mass fit

Fit models :

- Signal → Double Sided Crystal Ball

$$f(x;\mu,\sigma,\alpha_L,n_L,\alpha_R,n_R) = \begin{cases} A_L \cdot (B_L - \frac{x-\mu}{\sigma})^{-n_L}, & \text{for } \frac{x-\mu}{\sigma} < -\alpha_L \\ \exp(-\frac{(x-\mu)^2}{2\sigma^2}), & -\alpha_L \leqslant \text{for } \frac{x-\mu}{\sigma} \leqslant \alpha_R \\ A_R \cdot (B_R - \frac{x-\mu}{\sigma})^{-n_R}, & \text{for } \frac{x-\mu}{\sigma} > \alpha_R \end{cases}$$

$$A_{L/R} = \left(\frac{n_{L/R}}{|\alpha_{L/R}|}\right)^{n_{L/R}} \cdot \exp\left(-\frac{|\alpha_{L/R}|^2}{2}\right)$$

$$B_{L/R} = \frac{n_{L/R}}{|\alpha_{L/R}|} - |\alpha_{L/R}|$$

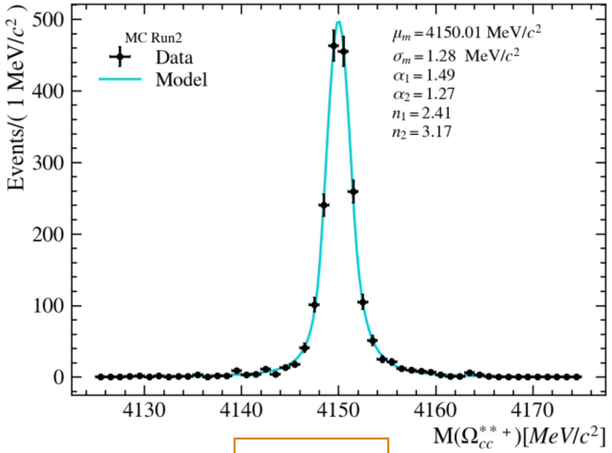
- Background → custom function :

$$f(\Delta M; a, b) = \Delta M^a \times \exp(-b.\Delta M)$$

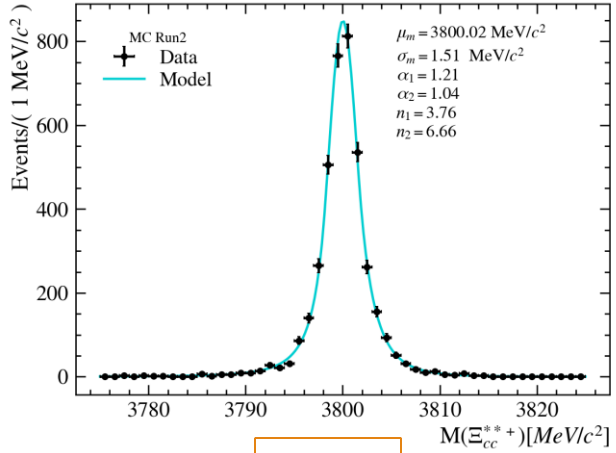
$$\Delta M = m(\Omega_{cc}^{+}) - m(\Xi_{cc}^{++}) - m(K^{-})$$

or

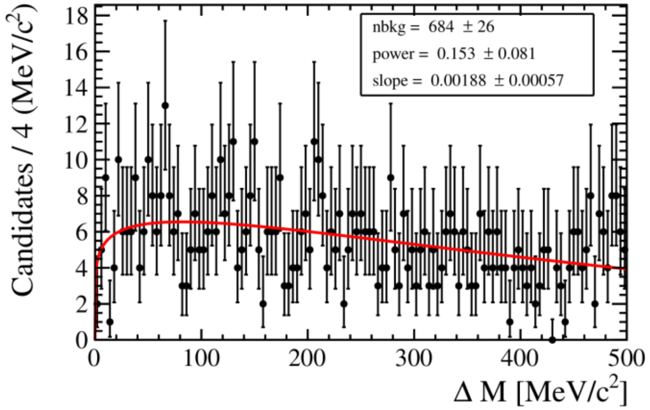
$$\Delta M = m(\Xi_{cc}^{+}) - m(\Xi_{cc}^{++}) - m(\pi^{-})$$

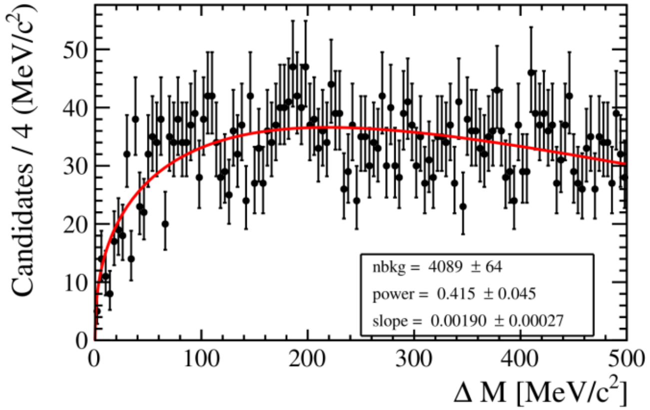


Ω_{cc}^{**+}



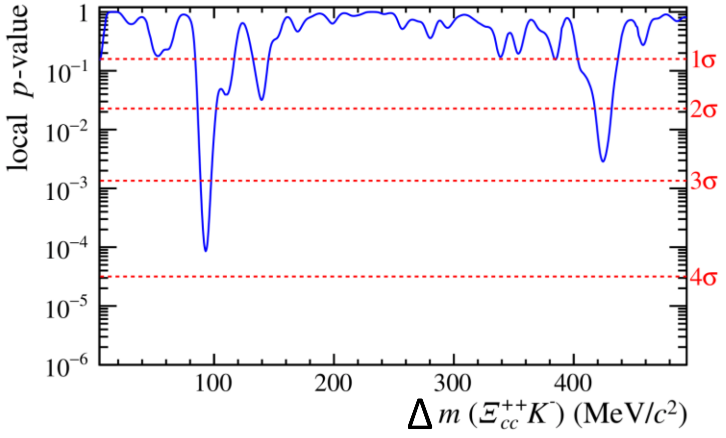
Ξ_{cc}^{**+}



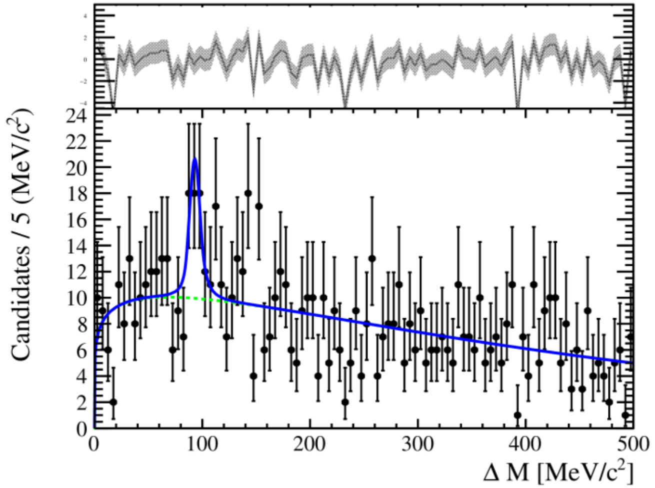


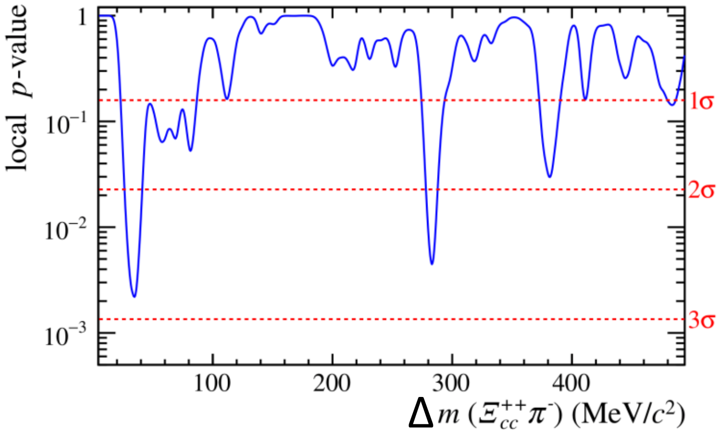
Significance

- The local p-value is determined as a function of the mass in steps of 1 MeV/c^2
- The local p-values are determined from the test statistics q±, which are based on the ratio of likelihoods of the fit under the background-only and signal-plus-background hypothese.
- Ξ_{cc}^{++} Loose selection (not enough statistics to use the Tight one).

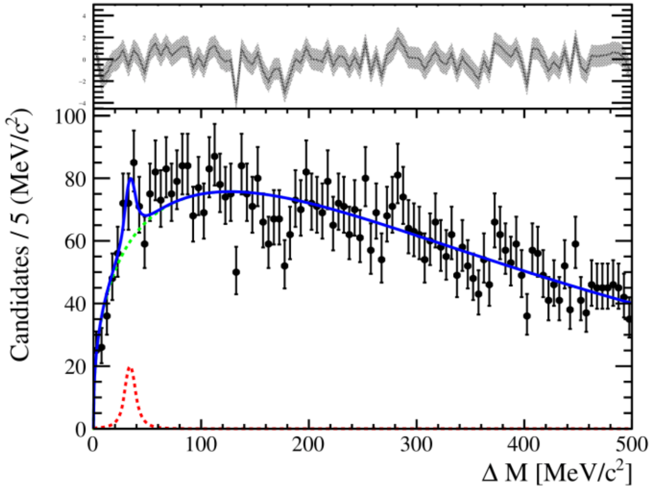


Ω_{cc}^{**+}





Ξ_{cc}^{**+}



Summary

- Reproduced the results of LHCb-PAPER-2017-018
- Reproduced the results of LHCb-PAPER-2019-037
  - Understood why efficicency of Λ_c^+ trigger line is lower in 2017 and 2018 data
- GenXicc updated to generate resonances with sizeable natural width
- Reconstructed two decays modes
  - Generated MC samples
  - MVA training and optimization
  - Mass fit
  - P-value scan
- No significant signal is observed in the mass range of 0 to 500 MeV from the mass threshold.

Future work

- Future searches by the LHCb experiment with upgraded detectors, improved trigger conditions, additional Ξ_{cc}^{**+} and Ω_{cc}^{**+} decay modes, and larger data samples will further increase Ξ_{cc}^{**+} and Ω_{cc}^{**+} signal sensitivity
- Measure lifetimes, masses, quantum numbers and production cross sections of all states
- LHCb aims to build an accurate and concise picture of doubly charmed baryons as a whole

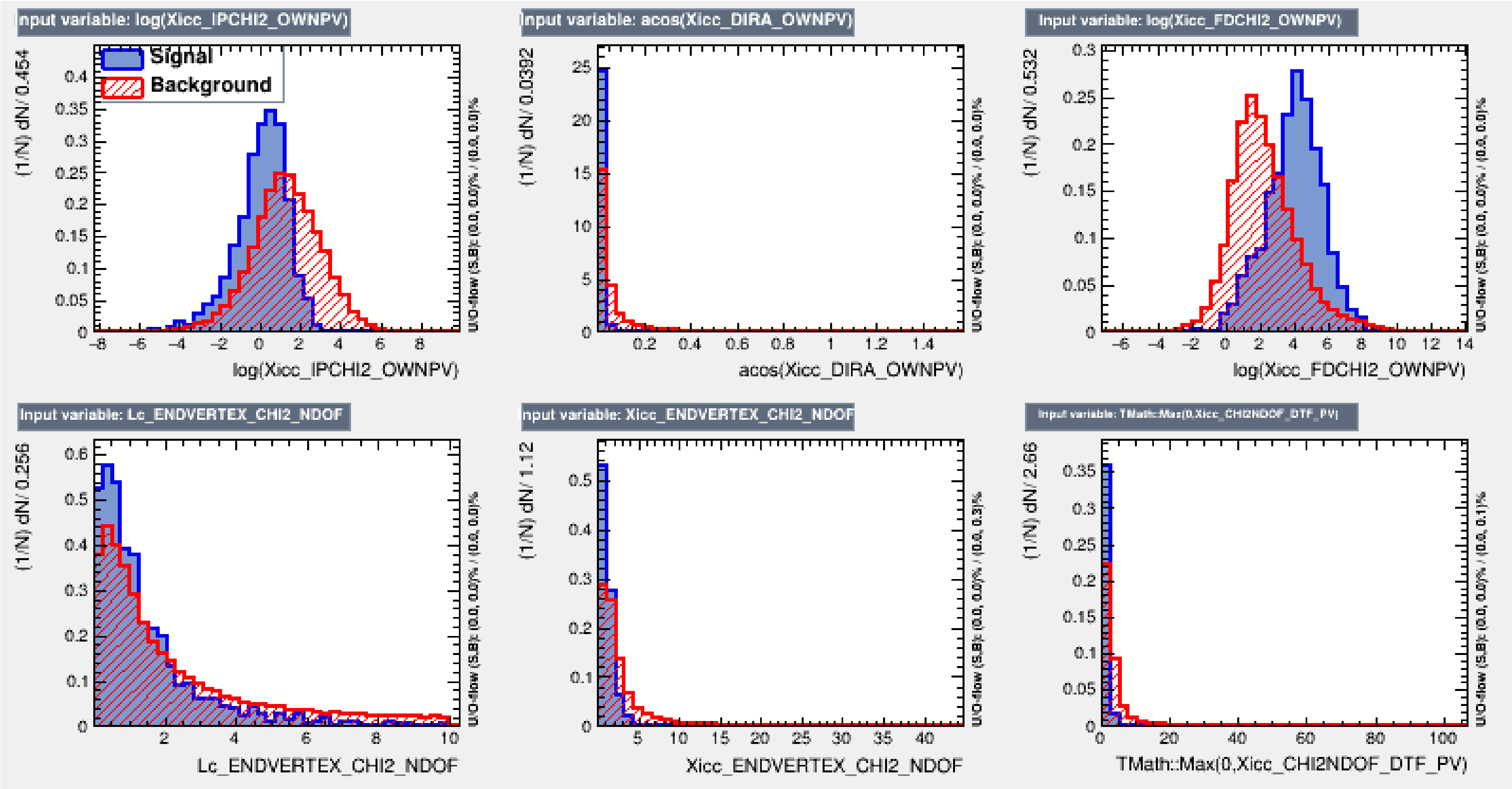
Thank you !

Backup

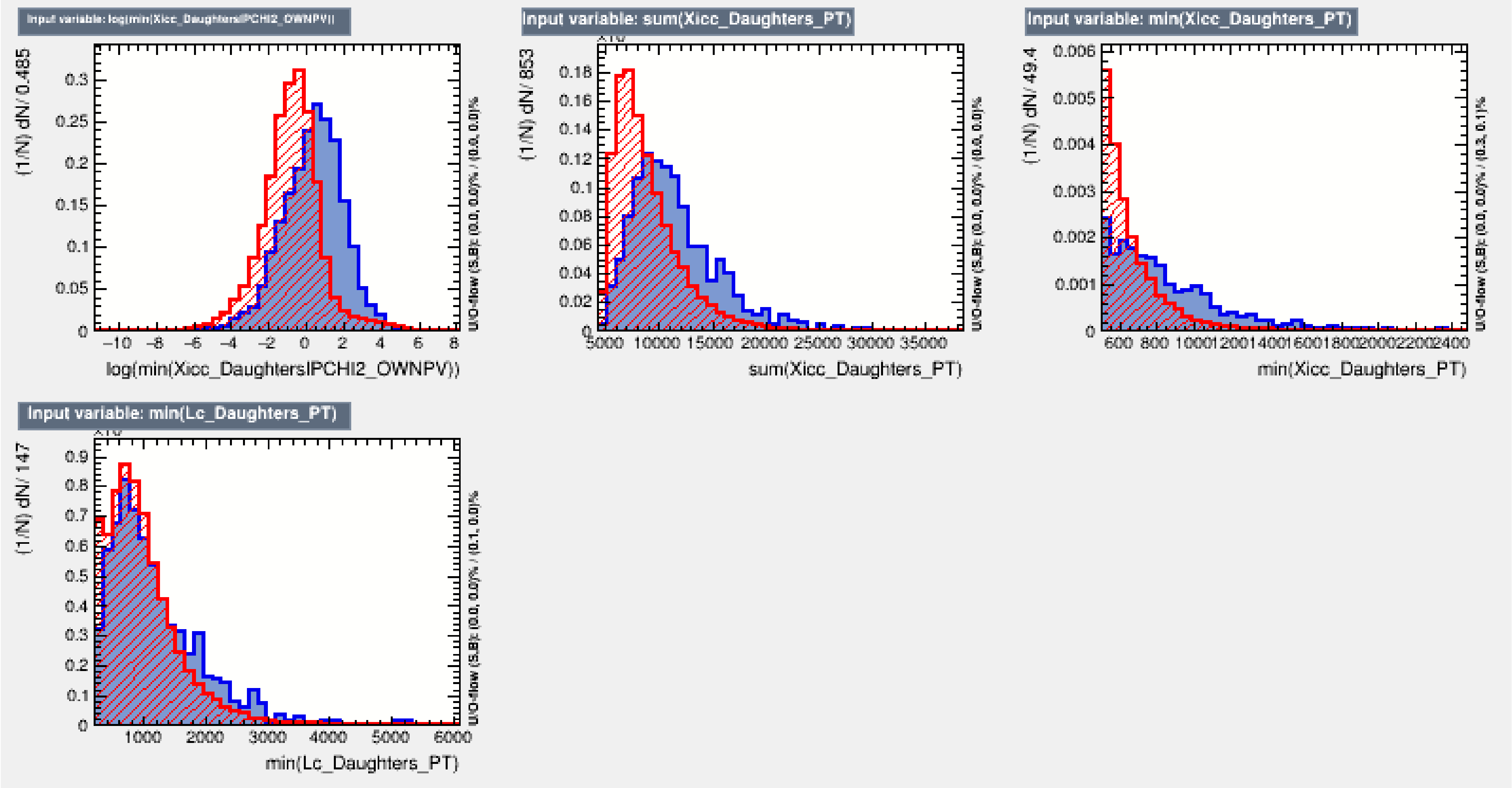
STEP1: Selection

Particules	Variable	Cuts
Daughters of Λ_c^+	Track quality	$\chi^2/ndf < 3$
	Momentum	$p > 1\,\mathrm{GeV}/c$
	Transverse momentum	$p_T > 0.2\,\mathrm{GeV}/c$
	Arithmetic sum of daughter	$> 3\,\mathrm{GeV}/c$
	Impact parameter signifiance	$\chi^2_{IP} > 6$
	p momentum	$p > 10\,\mathrm{GeV}/c$
	p particule ID	$\mathrm{DLL_{p\pi}} > 5$, $\mathrm{DLL_{pK}} > 5$
	K particule ID	$\mathrm{DLL_{K\pi}} > 5$
	π particule ID	$\mathrm{DLL_{K\pi}} < 5$
	Maximum p_T	$> 1\,\mathrm{GeV}/c$
	Second maximum p_T	$> 0.4\,\mathrm{GeV}/c$
	Maximum χ^2_{IP}	> 16
	Second maximum χ^2_{IP}	> 9
Λ_c^+	Vertex quality	$\chi^2_{vtx}/ndf < 10$
	Cosine of decay angle (DIRA)	$> cos(0.01)$
	Decay time	$\tau > 0.15\,\mathrm{ps}$
	Mass	$M \pm 75\,\mathrm{MeV}/c^2$
Daughters of Ξ_{cc}^{++}	Track quality	$\chi^2/\mathrm{ndf} < 3$
	Momentum	$p > 1\,\mathrm{GeV}/c$
	Transverse momentum	$p_T > 0.5\,\mathrm{GeV}/c$
	K particule ID	$\mathrm{DLL_{K\pi}} > 10$
	π particule ID	$\mathrm{DLL_{K\pi}} < 0$
Ξ_{cc}^{++}	Vector sum of daughter	$> 2\,\mathrm{GeV}/c$
	Vertex quality	$\chi^2_{\mathrm{vtx}}/\mathrm{ndf} < 60$
	Λ_c^+ vertex displacement w.r.t. Ξ_{cc}^{++}	$z_{\Lambda_c^+} - z_{\Xi cc^{++}} > 0.01mm$
	Distance of closest approach	$< 10mm$

STEP1: Input variables (1/2)



STEP1: Input variables (2/2)

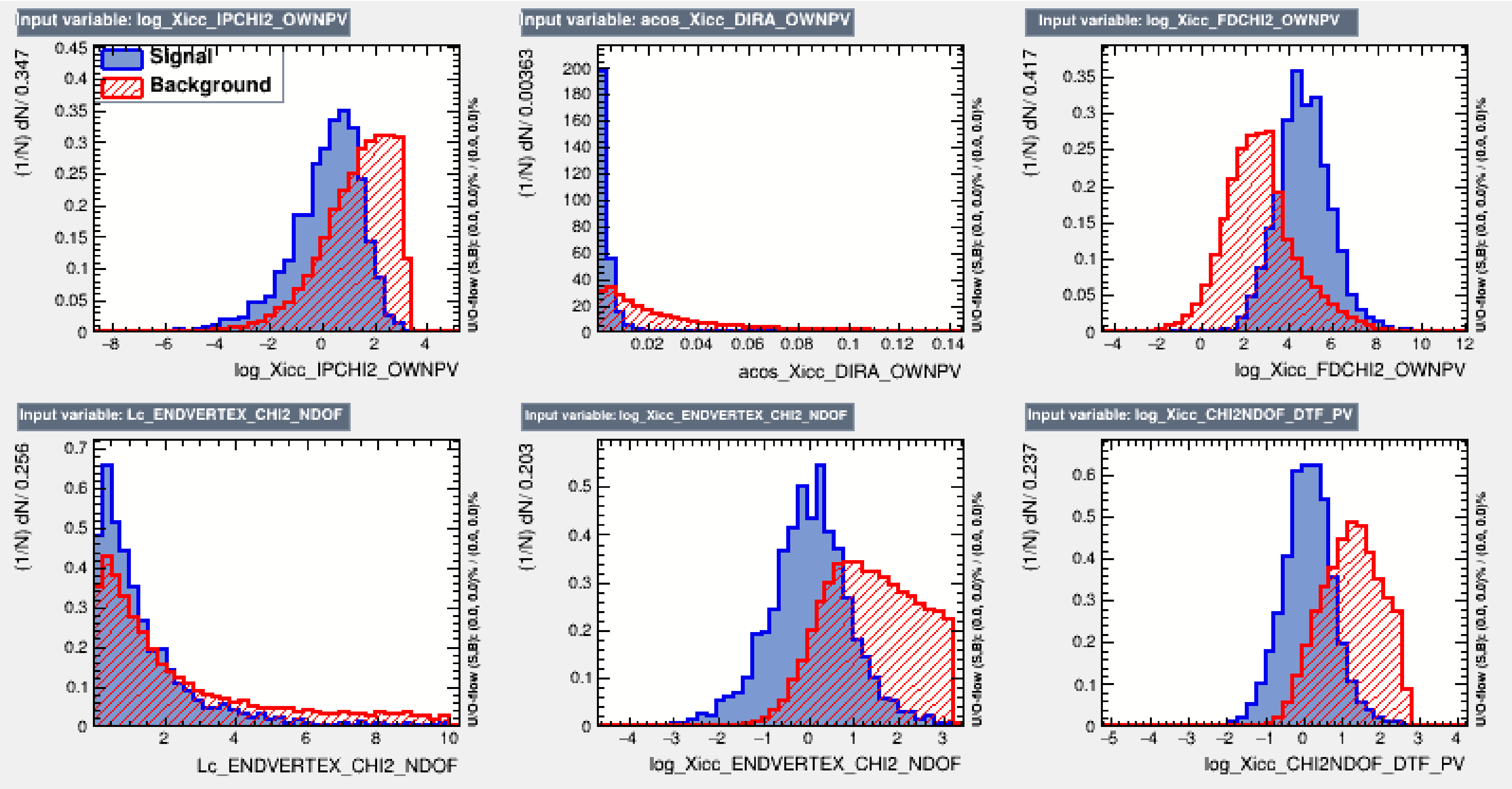


STEP2: Selection

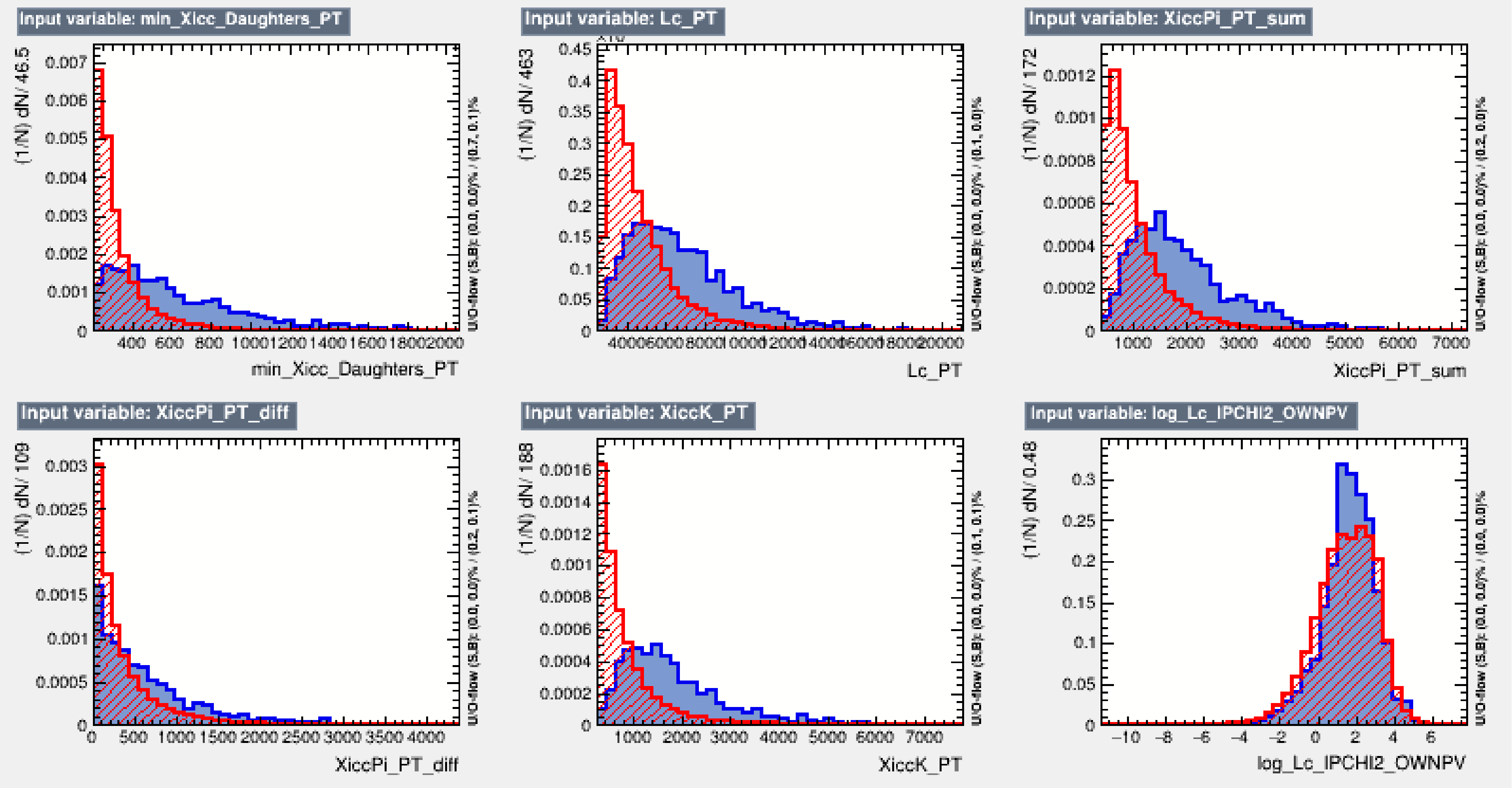
Particules	Variable	Cuts
Daughters of Λ_c^+	Track quality	$\chi^2/ndf < 3$
	Momentum	$p >$ GeV/c
	Transverse momentum	$p_T > 0.2\,\mathrm{GeV}/c$
	Arithmetic sum of daughter	$> 3\,\mathrm{GeV}/c$
	Impact parameter signifiance	$\chi^2_{IP} > 6$
	p momentum	$p > 10\,\mathrm{GeV}/c$
	p particule ID	$\mathrm{DLL}_{p\pi} > 5$, $\mathrm{DLL}_{pK} > 5$
	K particule ID	$\mathrm{DLL}_{K\pi} > 5$
	π particule ID	$\mathrm{DLL}_{K\pi} < 5$
	Maximum p_T	$> 1\,\mathrm{GeV}/c$
	Second maximum p_T	$> 0.4\,\mathrm{GeV}/c$
	Maximum χ^2_{IP}	> 16
	Second maximum χ^2_{IP}	> 9
Λ_c^+	Vertex quality	$\chi^2_{vtx}/ndf < 10$
	Cosine of decay angle (DIRA)	$> cos(0.01)$
	Decay time	$\tau > 0.15\,\mathrm{ps}$
	Mass	$M \pm 75\,\mathrm{MeV}/c^2$

Particules	Variable	Cuts
Daughters of Ξ_{cc}^{++}	Track quality	$\chi^2/ndf < 3$
	Ghost Probality	< 0.4
	Impact parameter	$\chi^2_{IP} > 1$
	Transverse momentum	$p_T(\pi) > 0.2\,\mathrm{GeV}/c$
	Transverse momentum	$p_T(K^+) > 0.25\,\mathrm{GeV}/c$
	K particule ID	$ProbNNk > 0.1$
	π particule ID	$ProbNNpi > 0.2$
Ξ_{cc}^{++}	Vector sum of daughter	$> 2\,\mathrm{GeV}/c$
	Vertex quality	$\chi^2_{vtx}/ndf < 25$
	Impact parameter χ^2	$\chi^2_{IP} < 25$
	Pointing angle	DIRA> 0.99

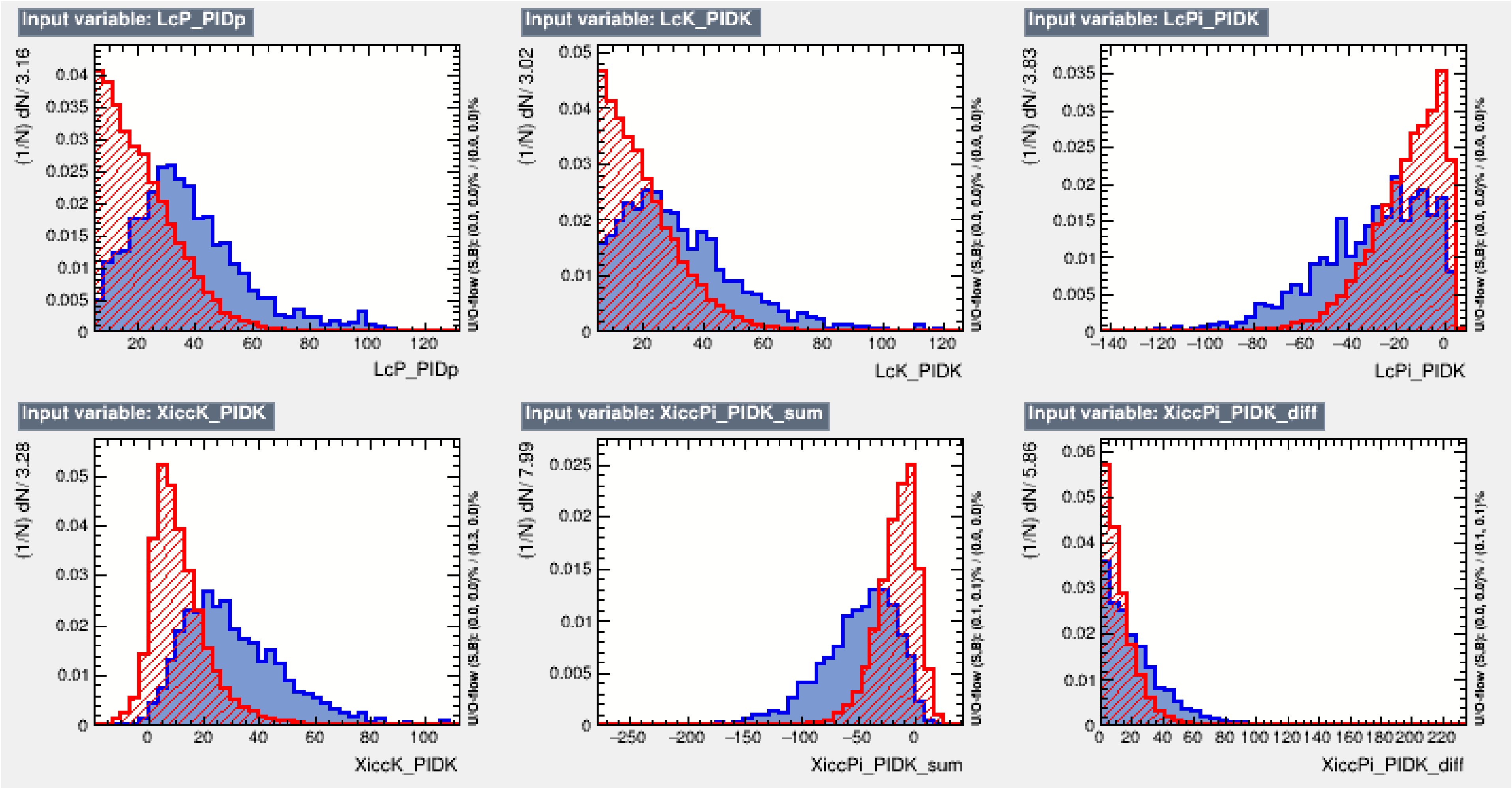
STEP2: Input variables (1/4)



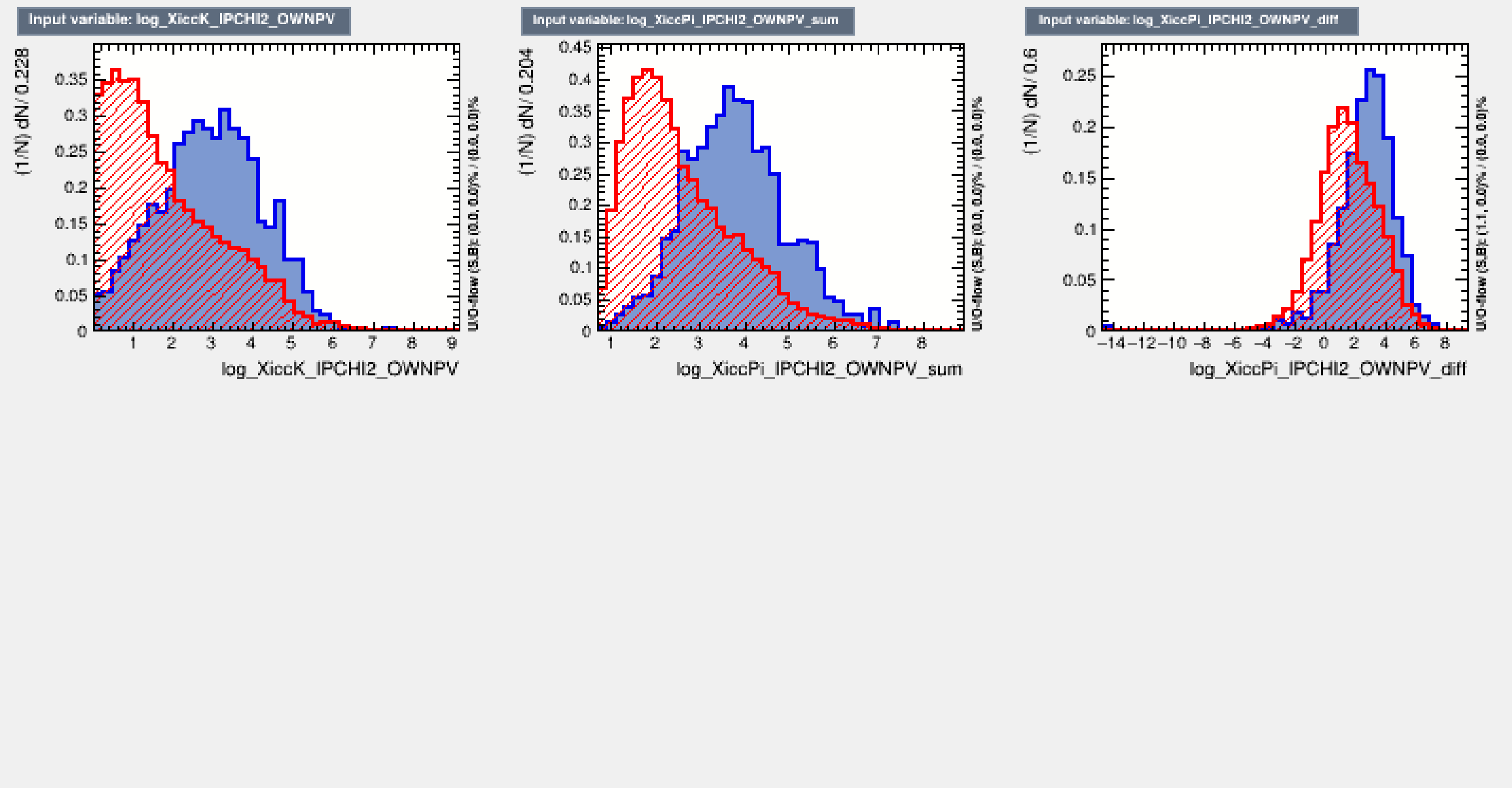
STEP2: Input variables (2/4)



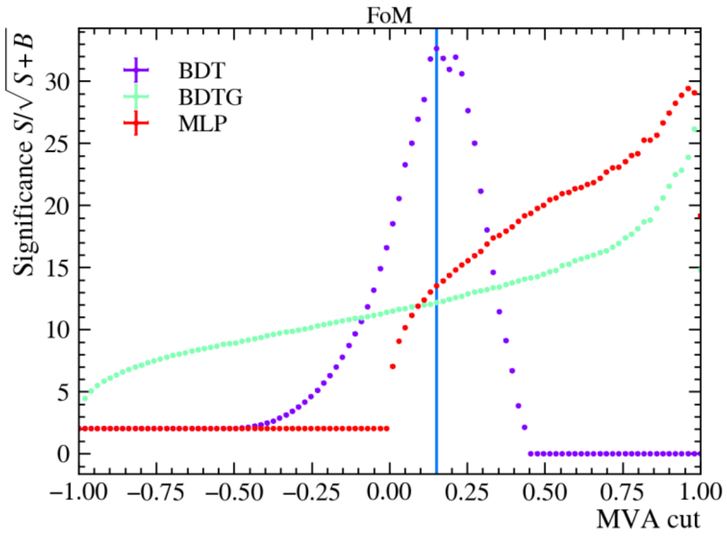
STEP2: Input variables (3/4)

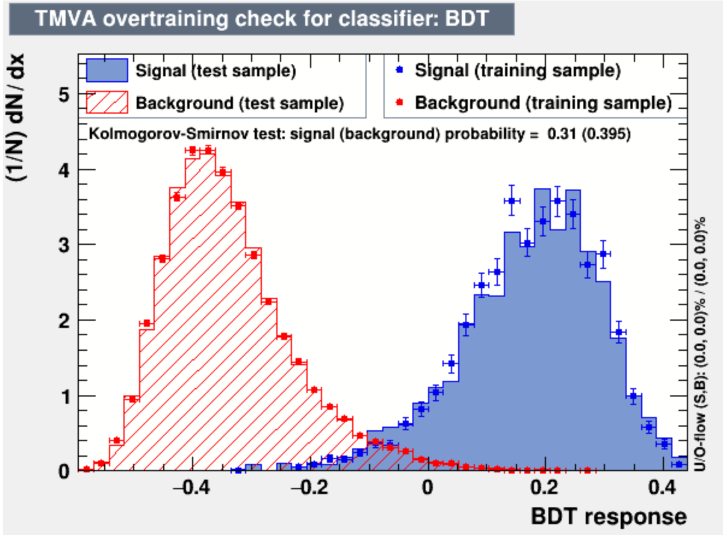


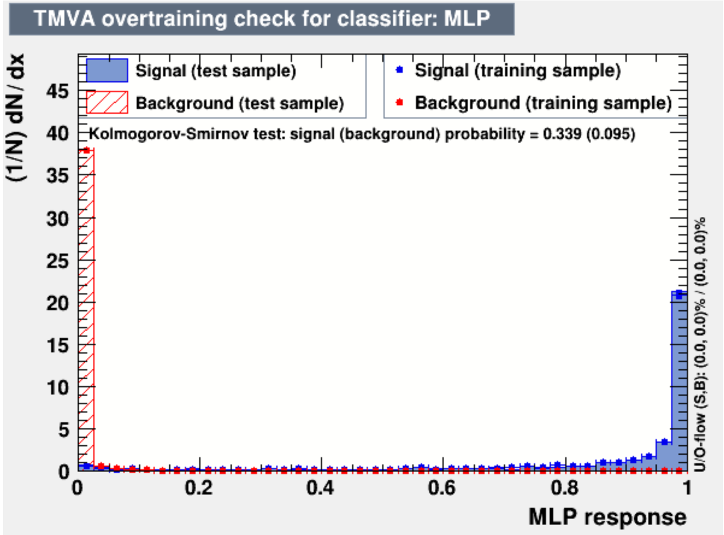
STEP2: Input variables (4/4)

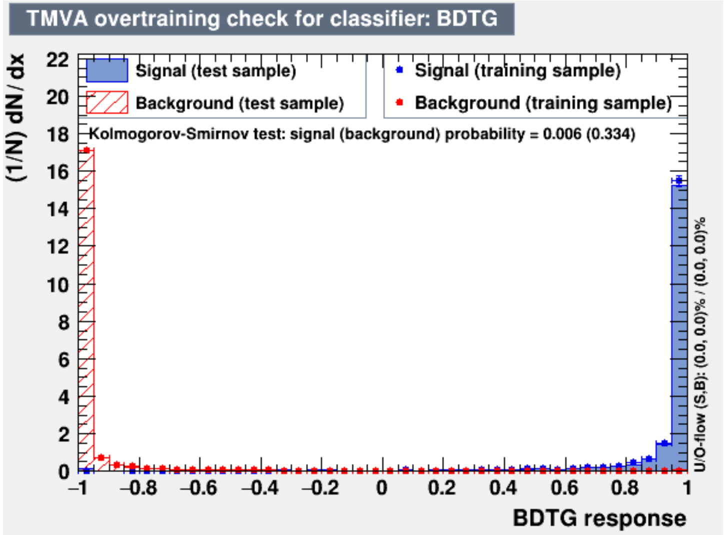


STEP2: MVA Training

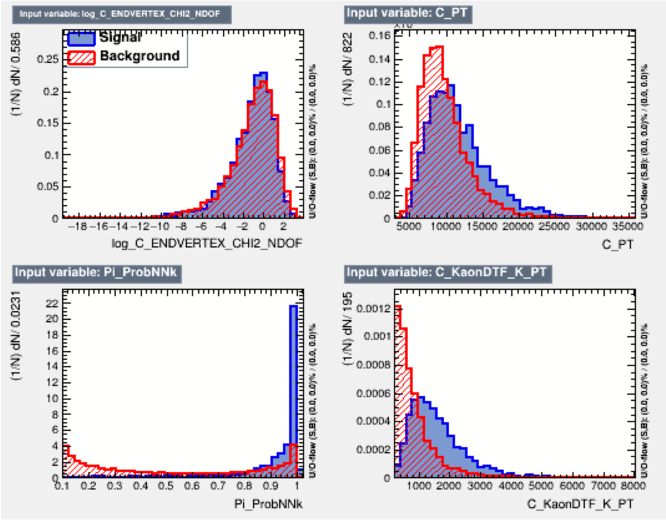




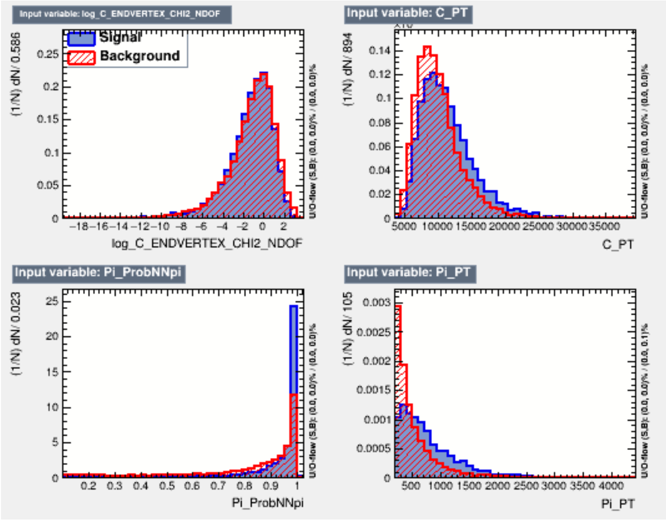




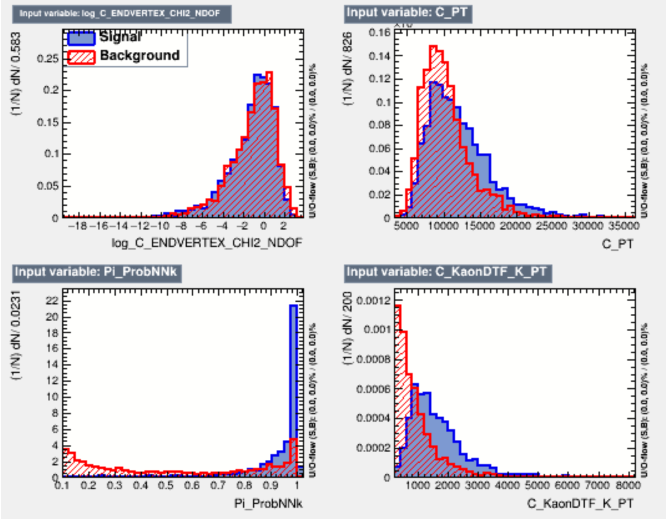
STEP3: Input variables



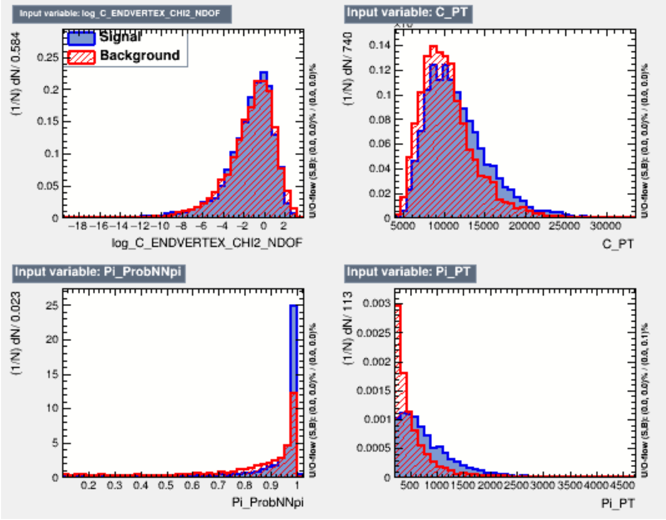
Ω_{cc}^{**+} Loose



Ξ_{cc}^{**+} Loose



Ω_{cc}^{**+} Tight



Ξ_{cc}^{**+} Tight