Analysis of $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ at LHCb using Run 3 data

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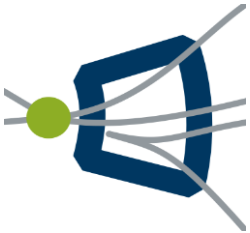
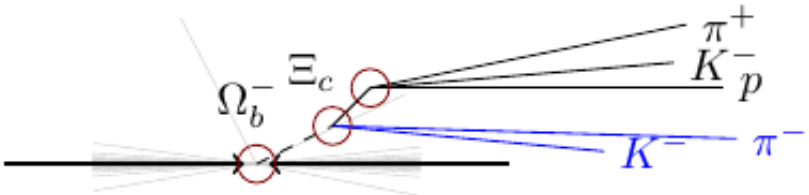
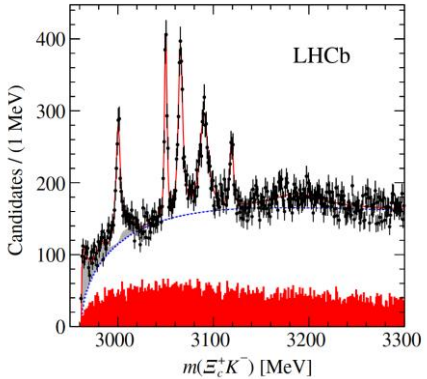


Physics motivation

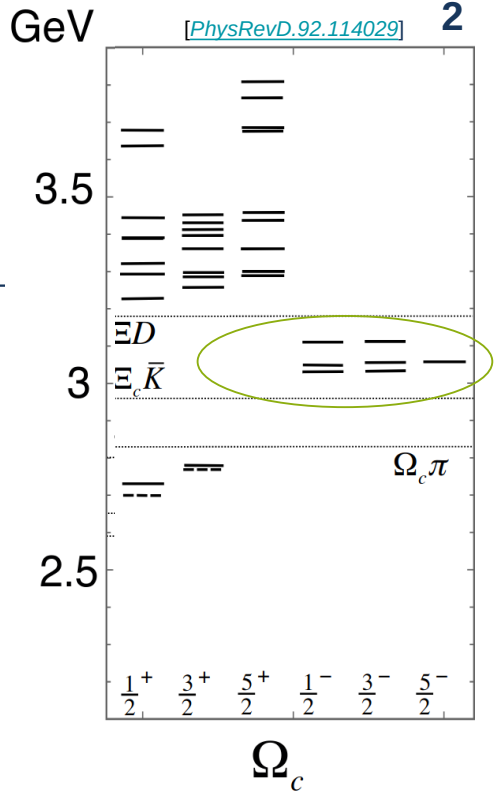
- Five new narrow Ω_c^0 states in prompt production observed by the LHCb collaboration [*Phys. Rev. Lett. 118 (2017) 182001*].
- Same states observed in decay $\Omega_b^- \to \Xi_c^+(\to p\, K^-\, \pi^+)\, K^-\, \pi^-$ [*PhysRevD.104.L091102*].
  - ➢ Best suited for analysis to study spin and parity.
- Aim for precise measurements of quantum numbers with Run 3 data.



[*Phys. Rev. Lett. 118 (2017) 182001*]

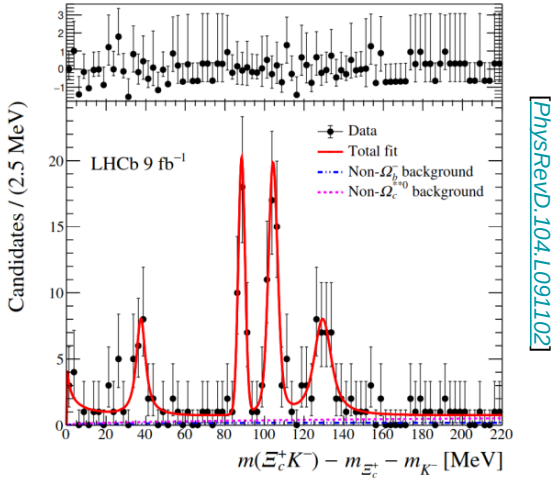


[*PhysRevD.92.114029*]



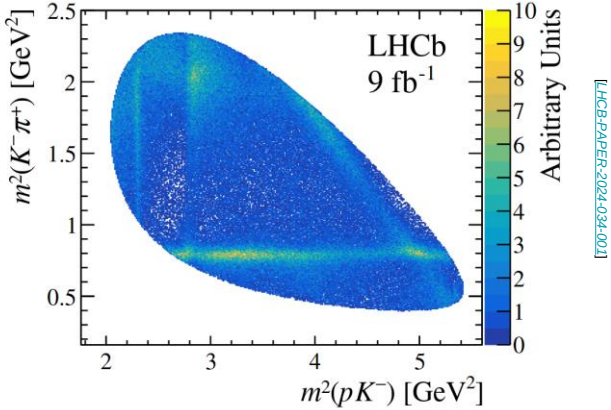
Analysis goals

- Spectroscopy of charm hadrons
  - Studying excited states of Ω_c^0.
  - Measure mass, widths and fit fractions.
- Spin properties
  - Studying sensitivity of helicity amplitudes on polarization of Ξ_c^+ decay products.
  - Include established amplitude models for $\Xi_c^+ \to p K^- \pi^+$.

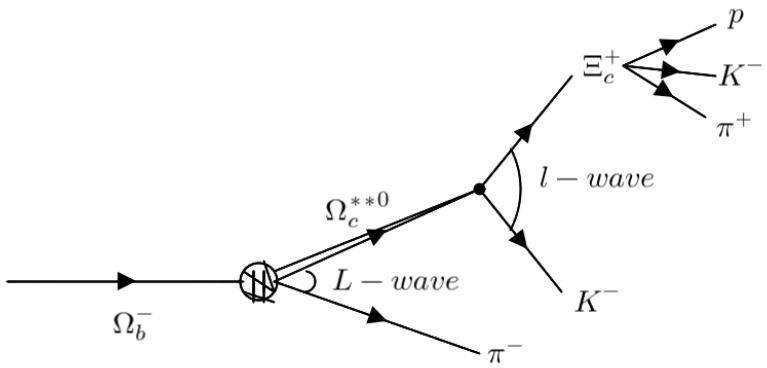


[PhysRevD.104.L091102]

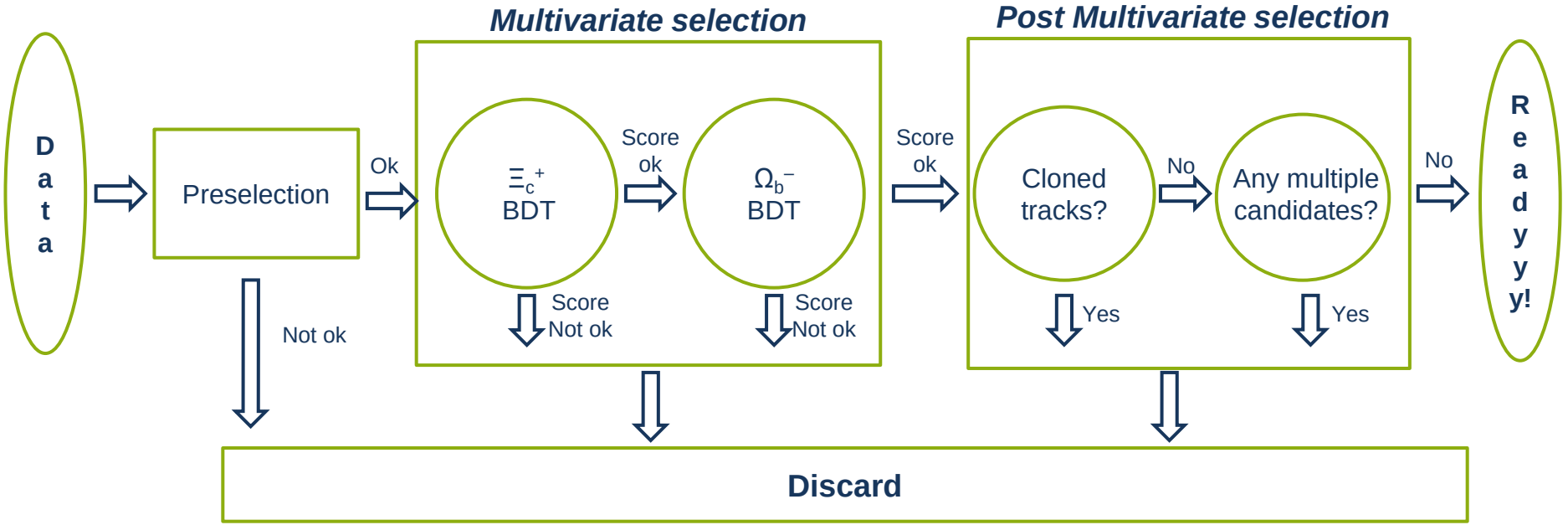
$\Xi_c^+ \to p K^- \pi^+$



[LHCB-PAPER-2024-034-001]



Full selection of events



Multivariate selection using GBDTs

- Decision trees (DTs) use simple decision rules from data features to make inferences.
- Gradient boosting is combining such ‘weaker’ trees for improved performance.
- For this analysis:
  - Ξ_c^+ BDT for $\Xi_c^+ \rightarrow pK^-\pi^+$ decays.
  - Ω_b^- BDT $\Omega_b^- \rightarrow \Xi_c^+K^-\pi^-$ decays.
- The features for training can be categorized into 3 parts:
  - Geometrical features (Radial distance, IPCHI2).
  - PID features (PROBNNs,PID).
  - Kinematic features (pT,mass).

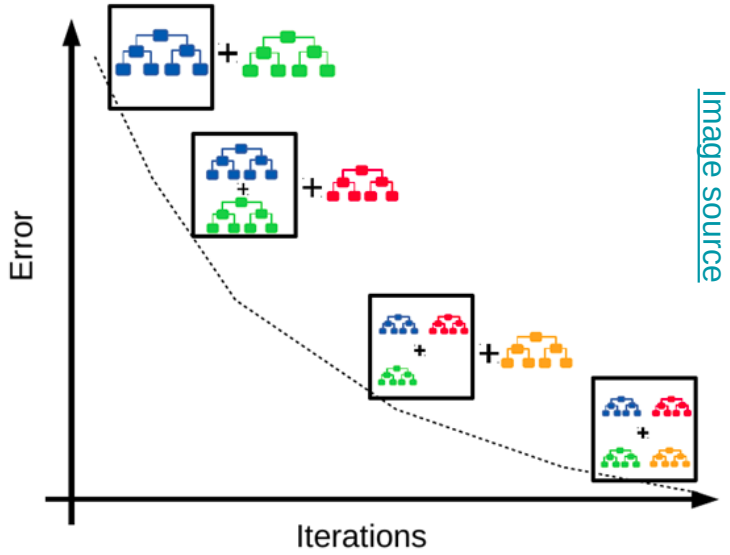
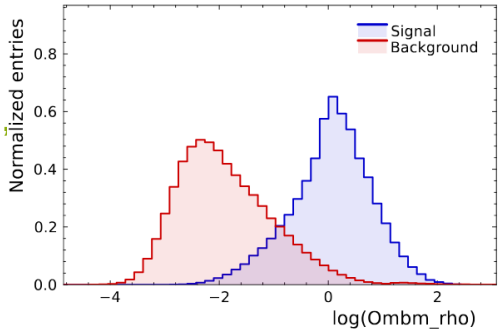
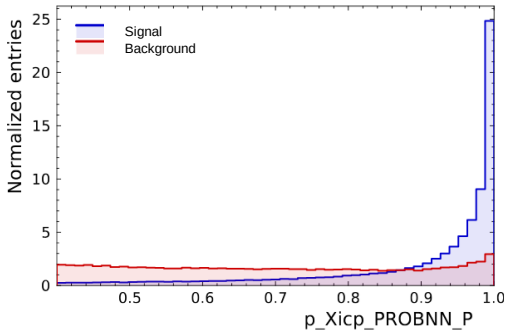


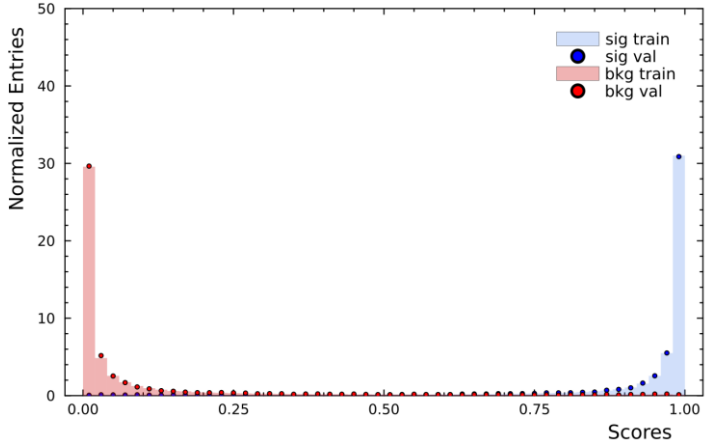
Image source

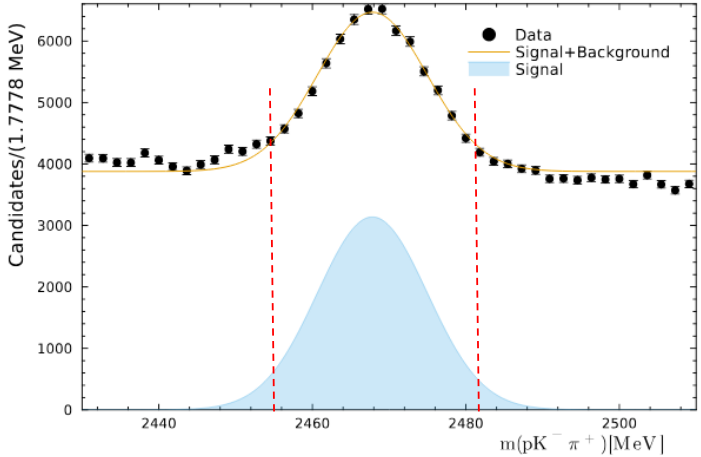


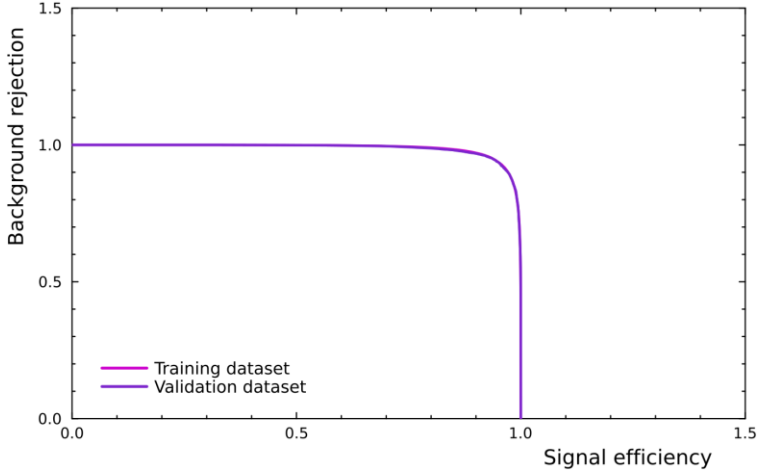


Ξ_c^+ BDT performance

- BDT performance is good
  - Nice separation of signal and background.
  - No visible traces of overfitting.
- Apply conditions for sufficient Ξ_c^+ candidates
  - Ξ_c^+ BDT score > 0.1 .
  - Select candidates in 2σ window around Ξ_c^+ mass peak.
  - Ξ_c^+ BDT score as input feature for Ω_b^- BDT.



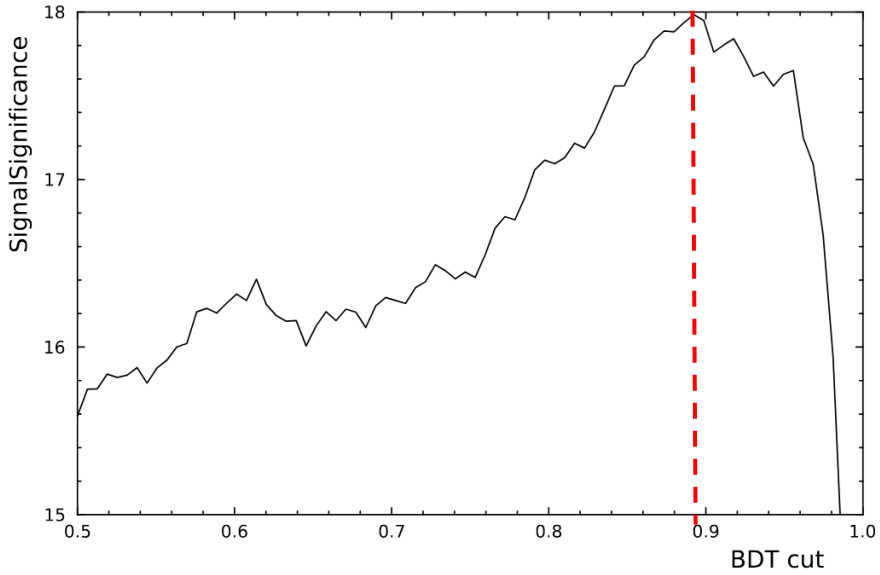




Optimization of Ω_b^- BDT

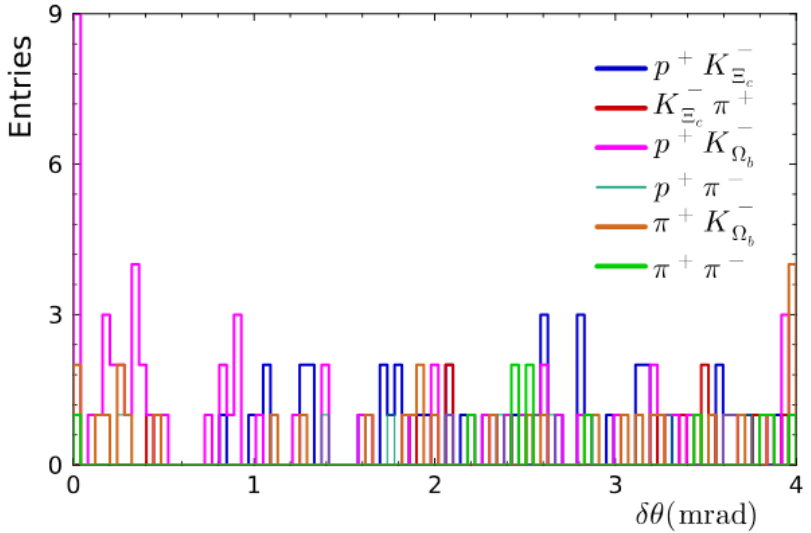
- Procedure :
  - Scan through a range of BDT scores.
  - Select events with scores larger than this set value (BDT cut).
  - Evaluate signal (S) and background (B) yields in a fixed 2σ interval around Ω_b^- mass.
- Ξ_c^+ BDT do not need to be optimized
  - For systematics :)

$$\text{SignalSignificance} = \frac{S}{\sqrt{S+B}}$$



Cloned tracks and multiple candidates

- Cloned tracks are removed if two-track combinations have opening angles (δθ) less than 1 mrad.
- Multiple candidates are removed by selecting candidate with highest BDT score.



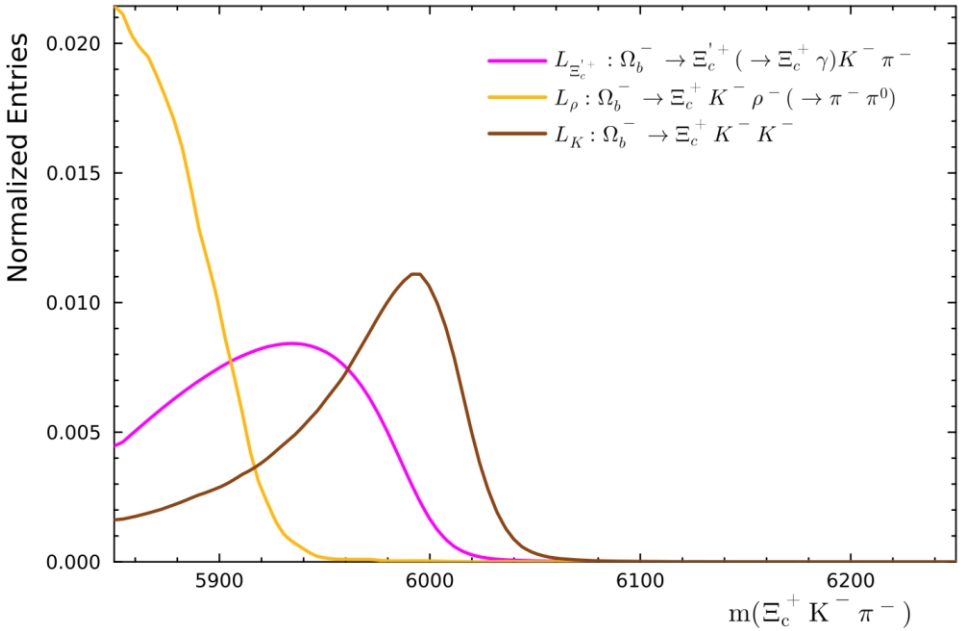
Year	Pre-BDT	Ξ_c^+ BDT	Optimized Ω_b^- BDT	Remove cloned tracks	Remove multiple candidates
2024	22,739,305	1,048,882	1976	1784	**1739**
2025	114,942,557	3,996,614	2906	2488	**2438**

Fit model for the $\Xi_c^+ K^- \pi^-$ mass spectrum

- The complete model can be written as:

$$\frac{dN}{dm(\Xi_c^+ K^- \pi^-)} = N_{sig}(f_{MC}\text{Normal}(m;\mu,\sigma\times\sigma_{ratio}) + (1-f_{MC})\text{Normal}(m;\mu,\sigma))$$
$$+ N_{bkg}\text{Exponential}(m;\lambda) + N_{\Xi_c'^+}L_{\Xi_c'^+}(m) + N_\rho L_\rho(m) + N_K L_K(m)$$

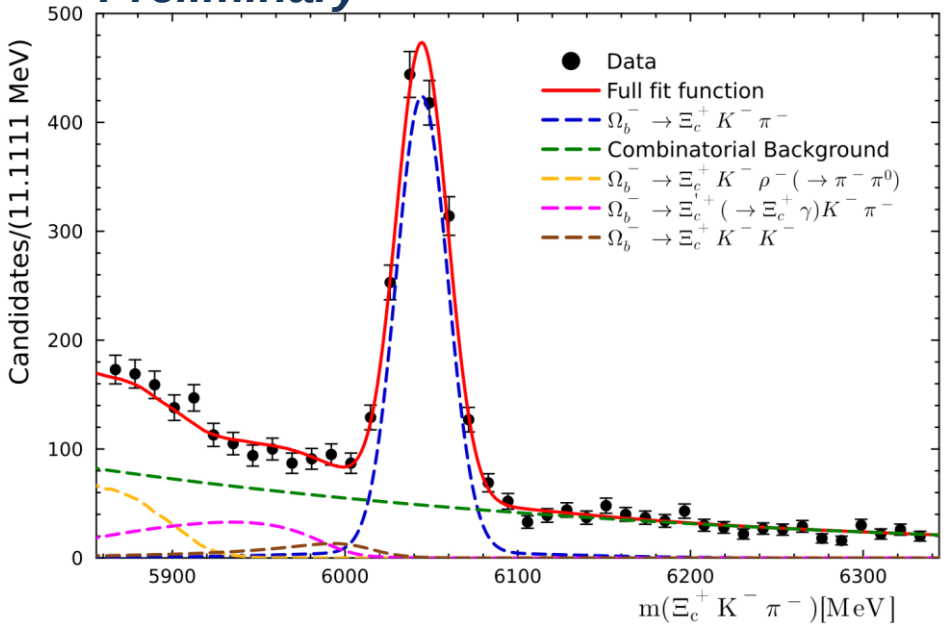
- Parameters f_{MC} and σ_{ratio} fixed from MC, rest all parameters are floated.
- 'L' are different lineshapes for feed-down backgrounds.
  - Modeled using simulated data from RapidSim.
- All components normalized to fit range.



$\Xi_c^+ K^- \pi^-$ mass spectrum

- An extended negative log likelihood (extended-nll) fit is performed in the fit range of (5850,6350) MeV.
  - Signal yield per luminosity is roughly **2.5x** more compared to Run 2.

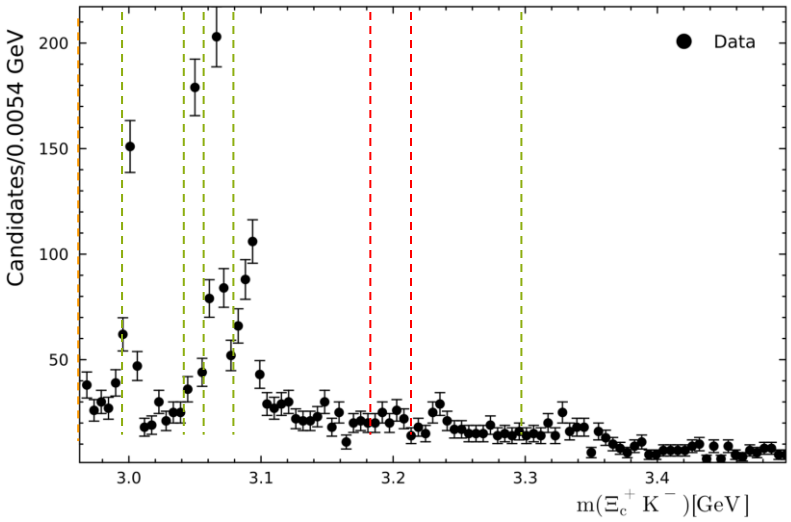
Preliminary

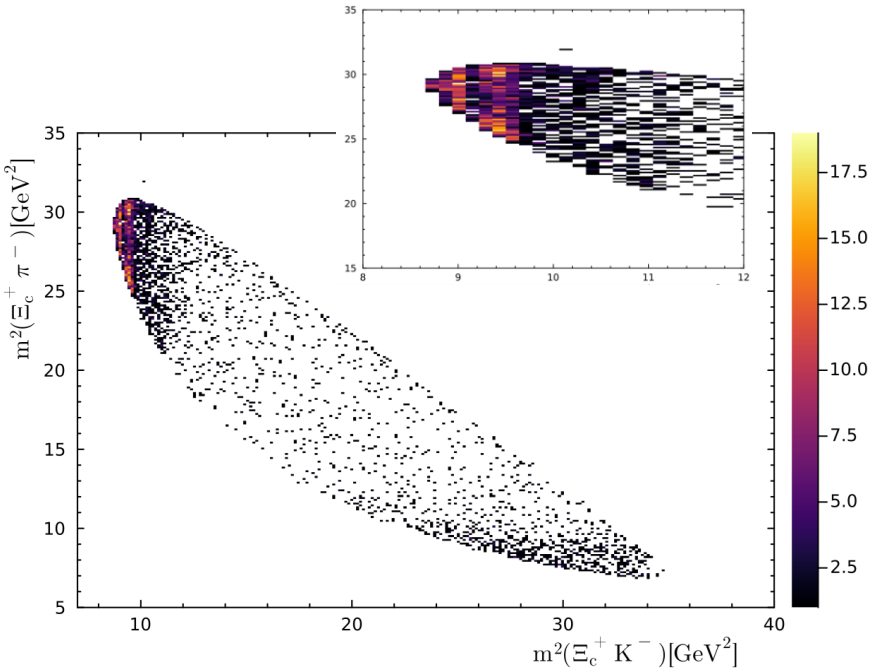


μ	6044.52 ± 0.75 MeV
σ	74.48 ± 3.45 MeV
λ	0.0027 ± 0.0003 MeV^{-1}
N_{sig}	**1464.22 ± 65.78**
N_{bkg}	1982.5 ± 79.03
$N_{\Xi'}$	343.45 ± 104.8
N_{ρ}	281.73 ± 58.63
N_K	105.06 ± 79.75

LHCb sample	Signal Yield	Signal Yield per fb^{-1}
Run 1 (3 fb^{-1})	44 ± 5	15 ± 2
Run 2 (6 fb^{-1})	199 ± 13	33 ± 2
Run 1 + Run 2 (9 fb^{-1})	240 ± 17	27 ± 1
Run 3 (~ 17.8 fb^{-1})	**1464 ± 66**	**82 ± 4**

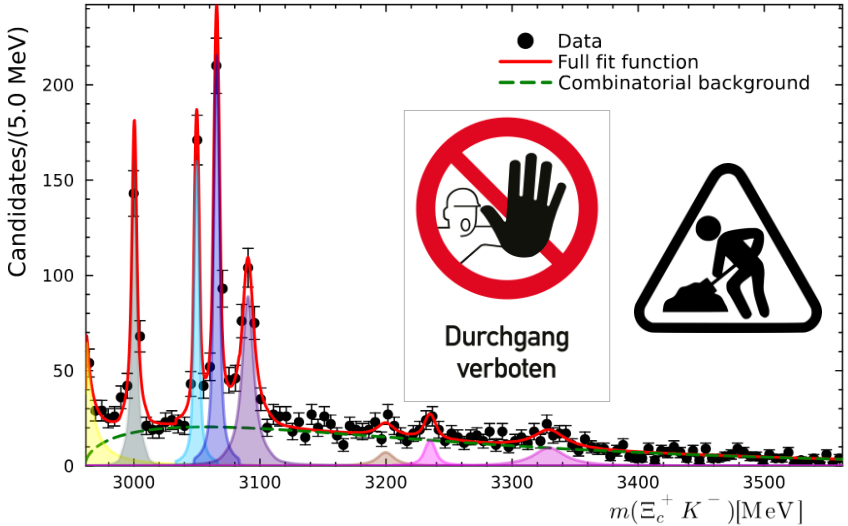
$\Xi_c^+ K^-$ spectrum



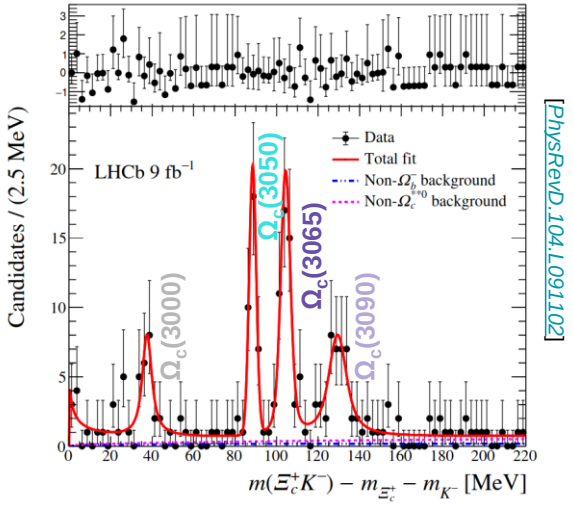


- All excited Ω_c^0 resonances appear in a small region of the spectrum:
  - Observed resonances incomplete set of quantum numbers.
  - Unexplained peaking structures that 'maybe' are resonances.
  - The $\Xi_c^+ K^-$ threshold enhancement considered for study.

Fitting $\Xi_c^+ K^-$ spectrum … not so pretty!



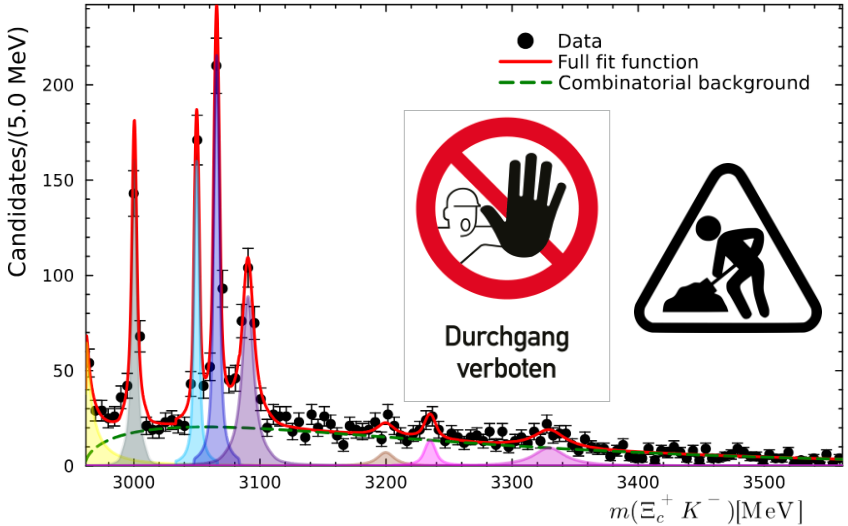
Run1 + Run2



[PhysRevD.104.L091102]

- To fit spectrum :
  - Resonance peaks : Relativistic Breit Wigner (RBW) ⊗ Resolution.
  - Combinatorial background : Exponential x Phase space function.
- Extremely narrow peaks dominated by resolution.
- Resolution model is to be investigated.

Fitting $\Xi_c^+K^-$ spectrum … not so pretty!



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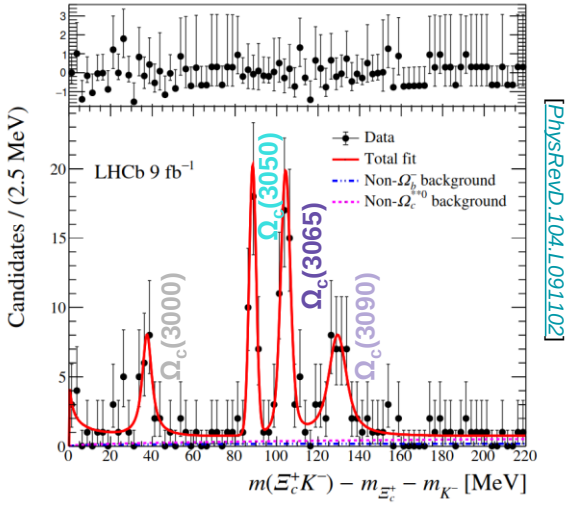

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To be continued …

Summary and next steps

- Run 3 data looks promising for studying $\Omega_b^- \rightarrow \Xi_c^+ K^- \pi^-$ process to study excited states of Ω_c^0 .
- Data is now clean enough with background substantially reduced after careful multivariate selection and removal of unwanted events.
- $\Xi_c^+ K^- \pi^-$ spectrum is understood well.
- Resonances in the $\Xi_c^+ K^-$ spectra are under study, promising to measure J^P of these states with high fidelity.

BACKUP

Discriminating variables for BDTs

Variable	Definition	Applied to	BDT
$1-\sqrt{1-\text{ProbNN}}$	The probability that the daughters are correctly identified	p, K^-, π^-, K^-, π^-	Ξ_c^+, Ω_b^-
$\log(p_T)$	The natural logarithm of the transverse momentum	p, K^-, π^-, Ξ_c^+, K^-, π^-, Ω_b^-	Ξ_c^+, Ω_b^-
$\log(PID)$	The natural logarithm of the PID of particle	p	Ξ_c^+
$\log(\chi^2_{IP})$	The natural logarithm of the impact parameter χ^2 of the particles w.r.t primary vertex (PV)	p, K^-, π^-, Ξ_c^+, K^-, π^-, Ω_b^-	Ξ_c^+, Ω_b^-
$\log(\chi^2_{FD})$	The natural logarithm of the flight distance χ^2 of the composite particles	Ξ_c^+, Ω_b^-	Ξ_c^+, Ω_b^-
$\log(\rho)$	The natural logarithm of the radial distance of composite particle from the beam axis	Ξ_c^+, Ω_b^-	Ξ_c^+, Ω_b^-
$\log(\max(p_T))$	The natural logarithm of the maximum of the daughter transverse momenta	p, K^-, π^-, K^-, π^-	Ξ_c^+, Ω_b^-
$\log(\min(p_T)$	The natural logarithm of the minimum of the daughter transverse momenta	p, K^-, π^-, K^-, π^-	Ξ_c^+, Ω_b^-
$\log(\max(\chi^2_{IP})$	The natural logarithm of the maximum of the impact parameter χ^2 of the daughters	p, K^-, π^-, K^-, π^-	Ξ_c^+, Ω_b^-
$\log(\min(\chi^2_{IP})$	The natural logarithm of the minimum of the impact parameter χ^2 of the daughters	p, K^-, π^-	Ξ_c^+
BDT score	Score of the Ξ_c^+ BDT		Ω_b^-

Data

- Data from 2024 and 2025 (partial) of Run 3 as tabulated below.
- Pre-selection for data done at trigger level and ntuple generation level are tabulated below.
- Following cuts were applied to the generated ntuples:
  - log(Xicp_rho) > -2
  - p_Xicp_PROBNN_P > 0.4
  - log(Minimum_IPCHI2_XicDau) > 2.0

Data block	Luminosity (fb^{-1})
Sprucing24c2a	3.192
Sprucing24c3a	2.087
Sprucing24c4a	1.146
Sprucing25c1	2.018
Sprucing25c2	~4.282
Sprucing25c3	~2.676
Sprucing25c4	2.407

Selection criteria while making ntuples

$\pi^{\pm}$	ProbNN > 0.1 PID_K < 20
p	ProbNN > 0.1 PID_P > -10
K^-	ProbNN > 0.1 PID_K > -10 $p_T > 250$ MeV $\chi^2_{IP} > 4$

Selection criteria at trigger level

Ω_b^-	5850 MeV $< M <$ 6350 MeV $p_T > 5000$ MeV Vertex $\chi^2_{DOF} < 10$ $\chi^2_{IP} < 25$ $\tau > 0.2$ ps DIRA > 0.999
Ξ_c^+	2418 MeV $< M <$ 2518 MeV Vertex $\chi^2_{DOF} < 10$ $\chi^2_{FD} < 36$ DIRA > 0 $\chi^2_{IP} > 0$ DOCA < 0.2 mm
π^-	PID_K < 5 $P > 3000$ MeV $p_T > 300$ MeV
K^-	PID_K > -5 $P > 5000$ MeV $p_T > 500$ MeV
p	PID_K > -5 $P > 8000$ MeV $p_T > 500$ MeV

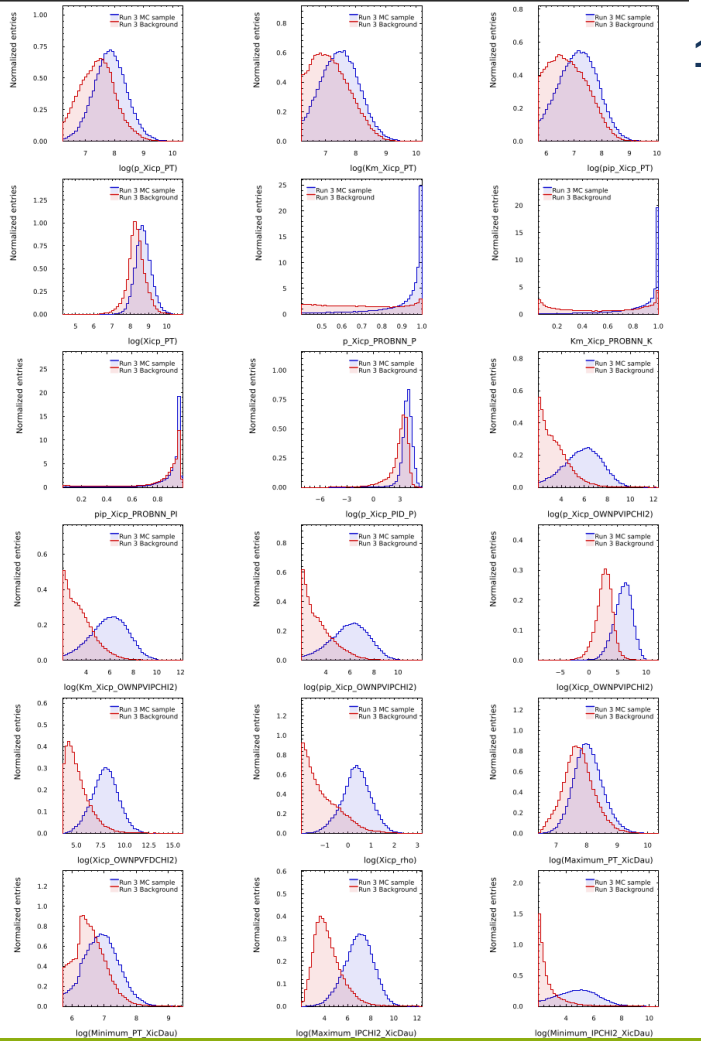
Multivariate selection statistics

- For training the models
  - 2024 MC is used for signal events
  - Sidebands from 2024 data are used for background
    - (2508,2518) MeV for Xicp_BDT
    - (6250,6350) MeV for Ombm_BDT

	Training Set	Validation Set
Xicp_BDT	Signal : 105240 Background : 87349	Signal : 11694 Background : 9707
Ombm_BDT	Signal : 13337 Background : 13337	Signal : 1483 Background : 1482

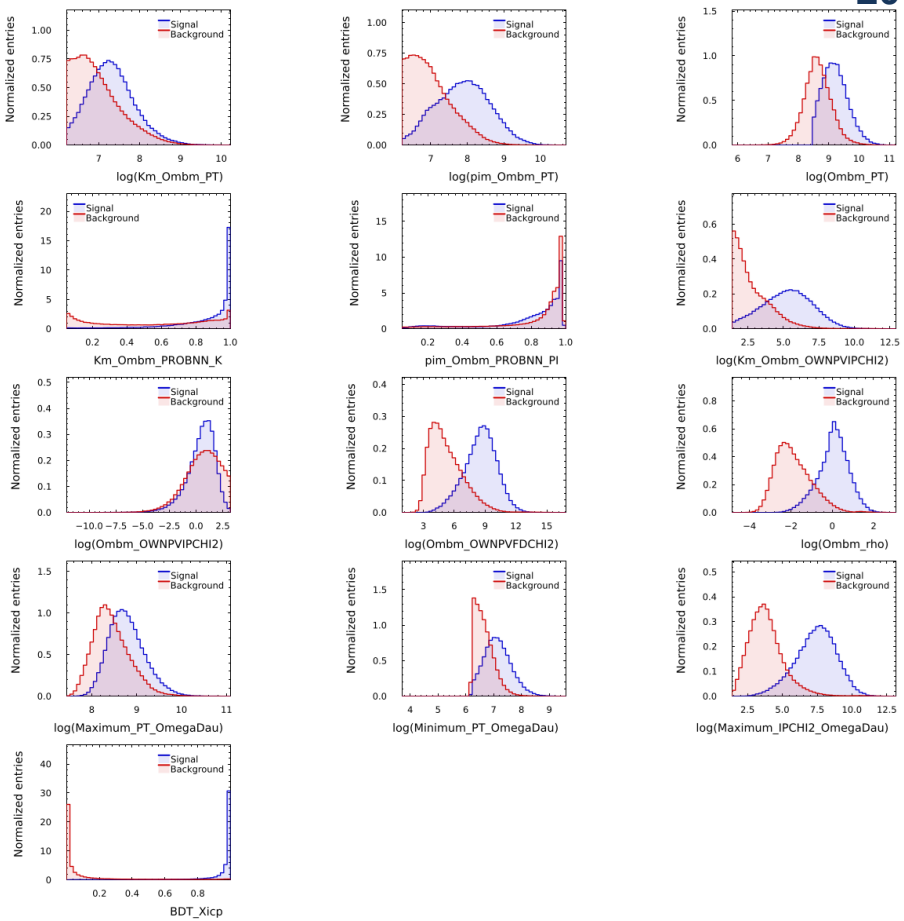
Xicp_BDT features

- Feature importance:
  - log(Maximum_IPCHI2_XicDau)
  - log(Xicp_OWNPVIPCHI2)
  - log(Minimum_IPCHI2_XicDau)
  - log(Xicp_rho)
  - p_Xicp_PROBNN_P
  - Km_Xicp_PROBNN_K
  - log(p_Xicp_PID_P)
  - log(Xicp_OWNPVFDCHI2)
  - log(p_Xicp_PT)
  - log(Minimum_PT_XicDau)
  - log(pip_Xicp_PT)
  - log(pip_Xicp_OWNPVIPCHI2)
  - log(Xicp_PT)
  - pip_Xicp_PROBNN_PI
  - log(Maximum_PT_XicDau)
  - log(Km_Xicp_PT)
  - log(Km_Xicp_OWNPVIPCHI2)
  - log(p_Xicp_OWNPVIPCHI2)



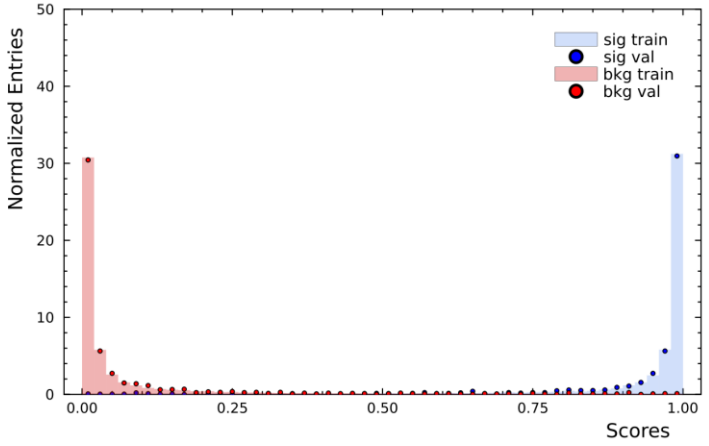
Ombm_BDT features

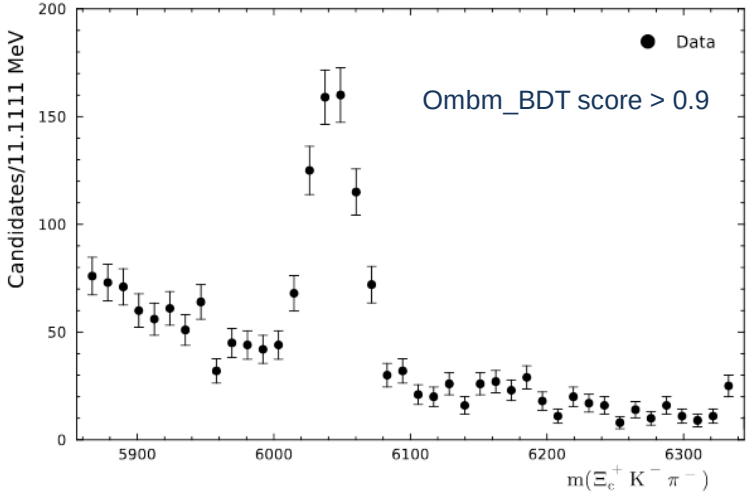
- Feature importance
  - **BDT_Xicp (Xicp_BDT score)**
  - log(Maximum_IPCHI2_OmegaDau)
  - log(Minimum_PT_OmegaDau)
  - log(Ombm_rho)
  - Km_Ombm_PROBNN_K
  - log(Ombm_PT)
  - log(Ombm_OWNPVIPCHI2)
  - log(pim_Ombm_PT)
  - log(Km_Ombm_OWNPVIPCHI2)
  - log(Ombm_OWNPVFDCHI2)
  - log(Km_Ombm_PT)
  - log(Maximum_PT_OmegaDau)
  - pim_Ombm_PROBNN_PI

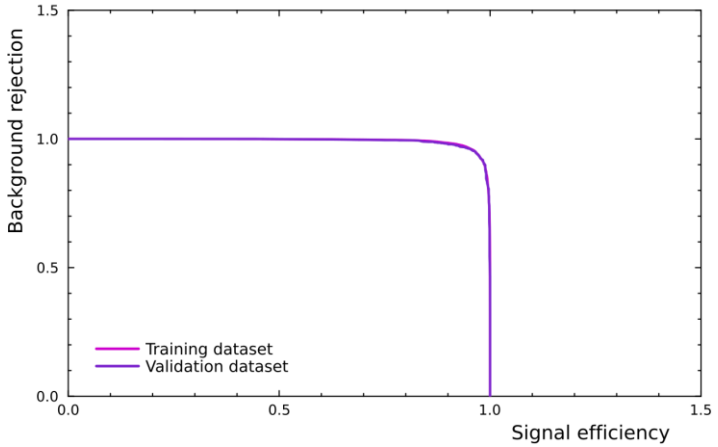


Ω_b^- BDT performance

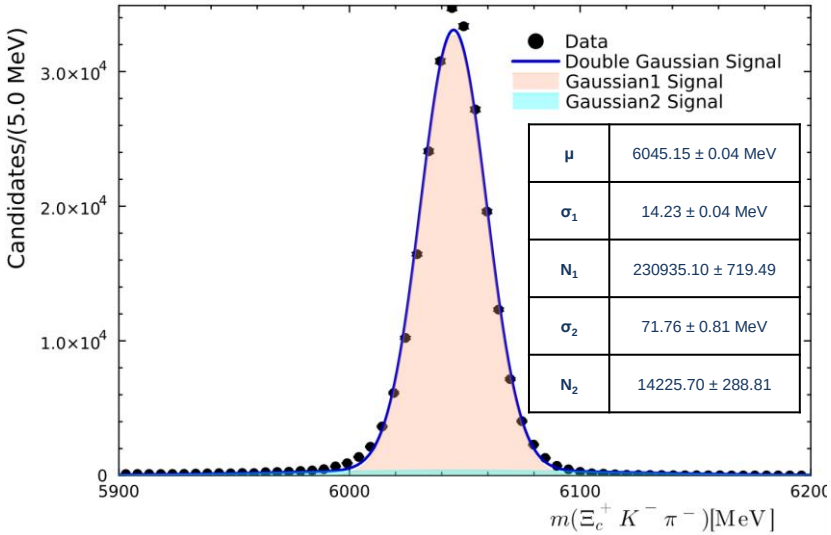
- BDT performance is good just like in Ξ_c^+ BDT
- Quite reduced background for high scores
  - Ω_b^- signal distinctly visible at expected PDG value







Fit model for the $\Xi_c^+K^-\pi^-$ mass spectrum



μ	6045.15 ± 0.04 MeV
σ_1	14.23 ± 0.04 MeV
N_1	230935.10 ± 719.49
σ_2	71.76 ± 0.81 MeV
N_2	14225.70 ± 288.81

$$f_{MC} = \frac{N_1}{N_1 + N_2}$$

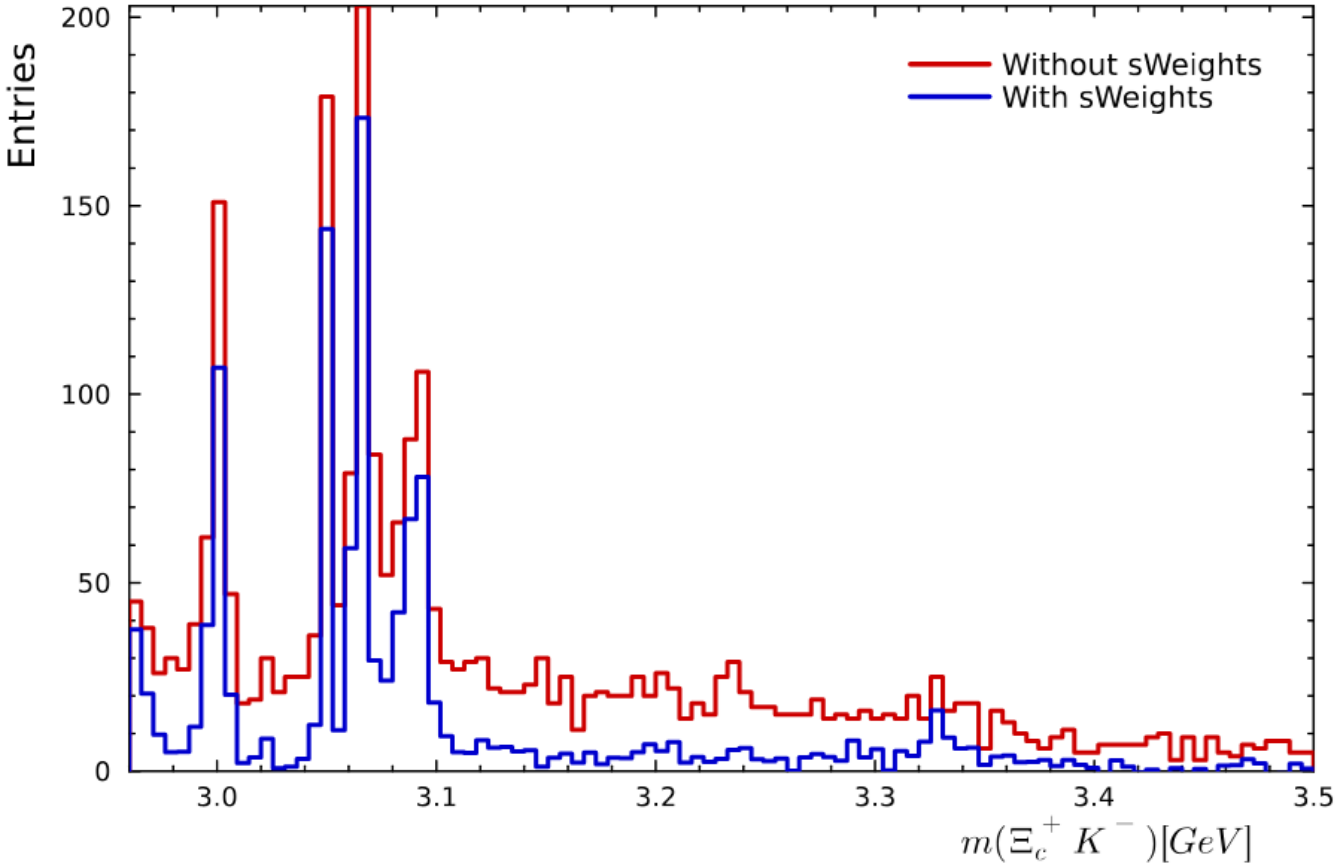
$$\sigma_{MC} = \sqrt{f\sigma_1^2 + (1-f)\sigma_2^2}$$

- The fit model to describe the $\Xi_c^+K^-\pi^-$ spectra comprises of three components:
  - Double Gaussian signal model with ratio of widths and fit fraction fixed from MC.
  - Exponential function for the combinatorial background
  - Lineshapes for feed-down backgrounds.
- The double gaussian fit for $\Xi_c^+K^-\pi^-$ spectra is shown for MC. From fit data, we get
  - Fit fraction (f_{MC}) = 0.94
  - Effective width (σ_{MC}) = 22.11 MeV
  - $\sigma_{ratio} = \sigma_1/\sigma_2 = 0.19$

Cloned tracks and multiple candidates

- After multivariate selection, further cleaning of data is done.
- Cloned tracks are looked for using δθ distributions.
  - δθ is the angle measured between two tracks using their momenta.
  - Tracks with very small δθ are more prone to be ‘cloned’.
  - Remove these events if δθ < 1 mrad
- For multiple candidates,
  - Define UniqueID = EventNumber + 10^9xRunNumber
  - Events with same UniqueID are counted as multiple
  - candidates.
  - From this set, select events with highest Ombm BDT score.

$\Xi_c^+ K^-$ spectrum



Analysis goals

[LHCB-PAPER-2024-034-001]