



MODEL AGNOSTIC  
MEASUREMENT OF  
 $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$  ANGULAR  
COEFFICIENTS

IoP HEPP & APP Annual Conference - 04/04/22

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on behalf of the LHCb Collaboration

UNIVERSITY OF OXFORD

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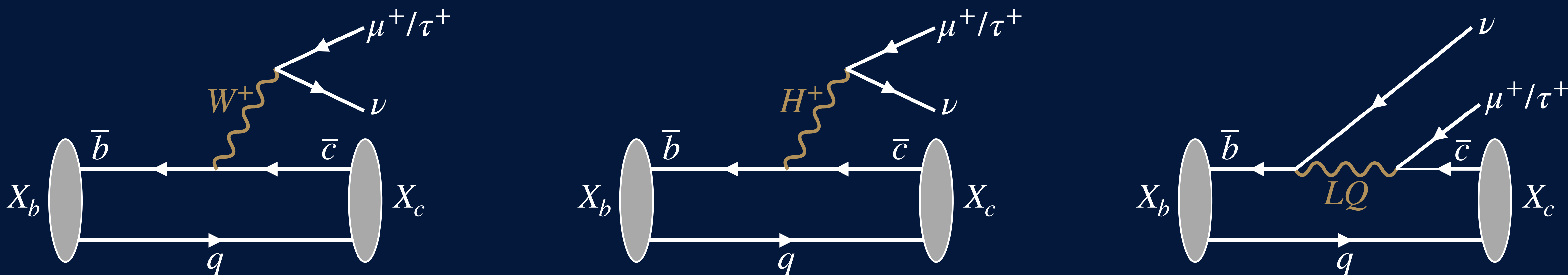
 INTRODUCTION - LEPTON FLAVOUR UNIVERSALITY
 

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- ▶ Standard Model assumes electroweak coupling to each of the three charged leptons is identical
  - ▶ Lepton Flavour Universality (LFU)
- ▶ Measurements of ratios of branching fractions with final states differing by lepton flavour:

$$\mathcal{R}(X_c) \equiv \frac{\mathcal{B}(X_b \rightarrow X_c \tau^+ \nu_\tau)}{\mathcal{B}(X_b \rightarrow X_c \mu^+ \nu_\mu)} \quad X_b : b\text{-hadron}, X_c : c\text{-hadron}$$

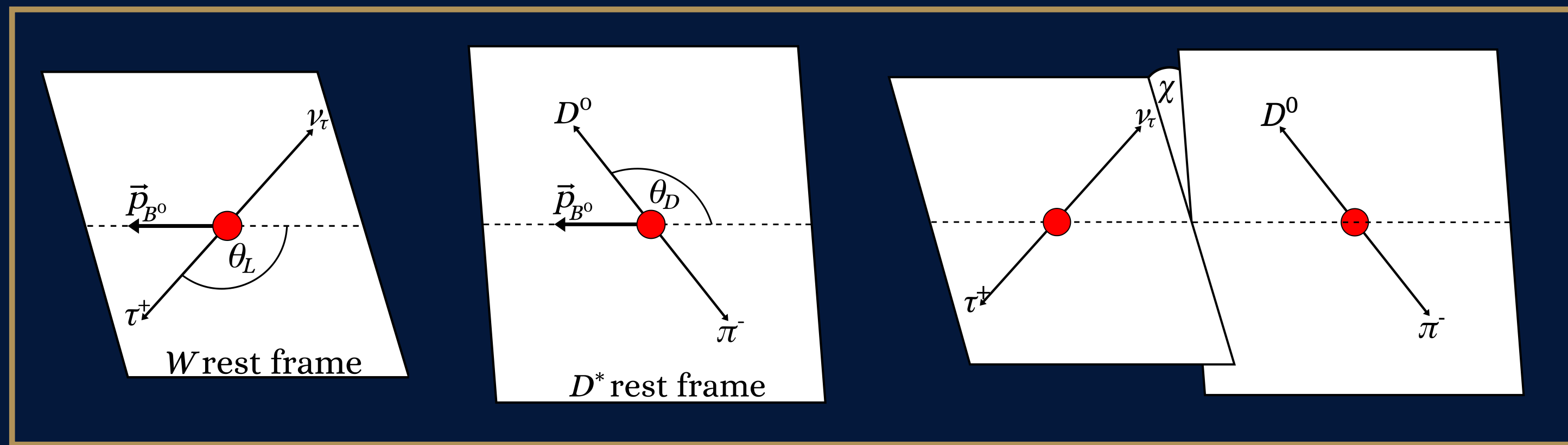
- ▶ Current measurements from B-factories and LHCb show discrepancy with SM, but not  $> 5\sigma$
- ▶ LFUV would be a clear sign of New Physics (NP)

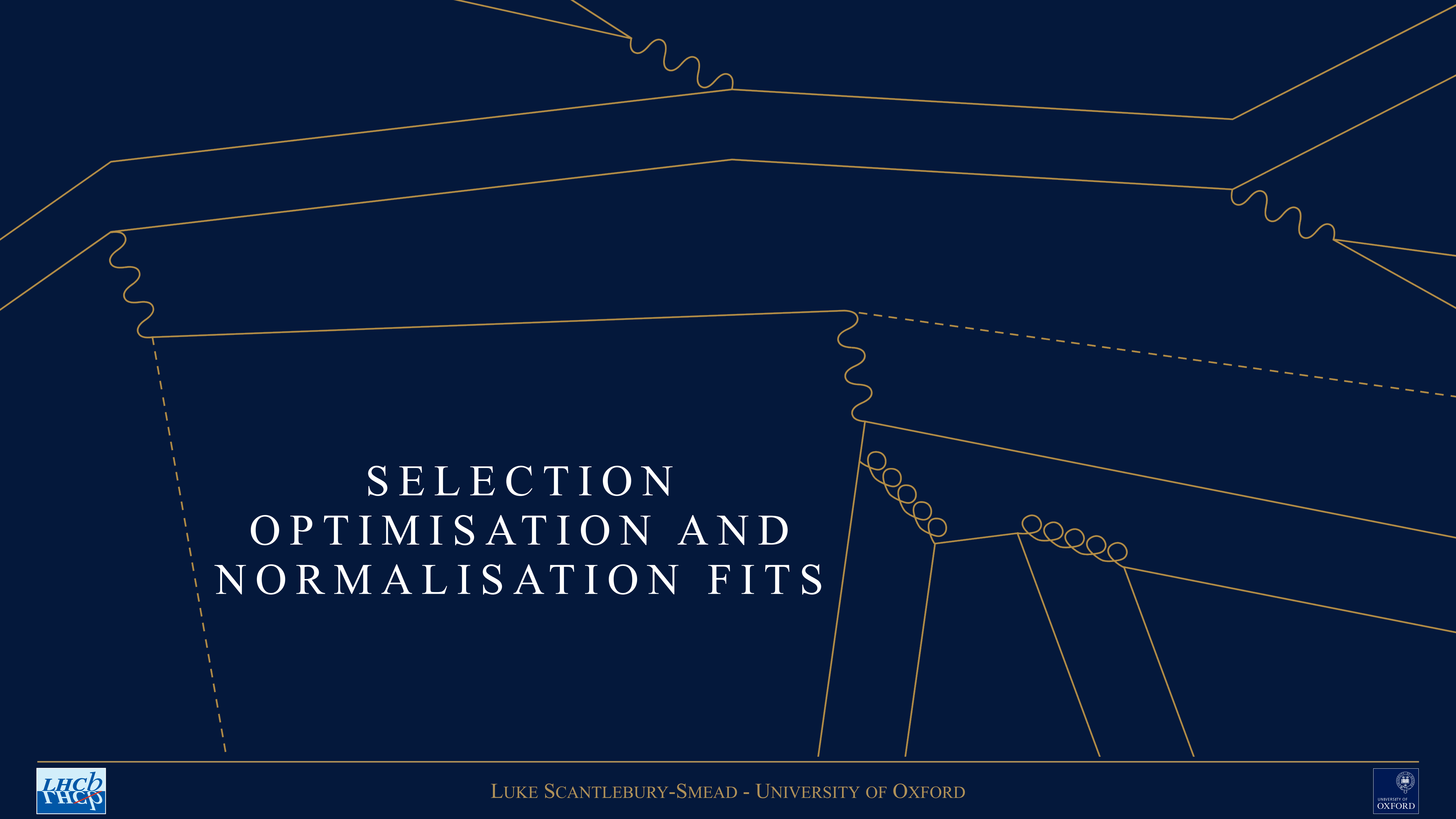


## INTRODUCTION - ANGULAR ANALYSIS

- ▶ Measure the 12  $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$  angular coefficients and  $\mathcal{R}(D^*)$ 
  - ▶ Multidimensional fit strategy with **three decay angles** and other discriminating variables
    - ▶ Based on proof-of-concept paper using RapidSim samples - [JHEP 11, \(2019\) 133](#)
- ▶ NP can be detected in angular coefficients even if  $\mathcal{R}(D^*)$  is compatible with SM
- ▶ Full Run 1 + 2 LHCb data set and simulation samples:  $9\text{fb}^{-1}$

$$\frac{d^4\Gamma}{dq^2 d \cos \theta_D d \cos \theta_L d\chi} = \frac{9}{32\pi} \left\{ I_{1c} \cos^2 \theta_D + I_{1s} \sin^2 \theta_D \right. \\
+ [I_{2c} \cos^2 \theta_D + I_{2s} \sin^2 \theta_D] \cos 2\theta_L \\
+ [I_{6c} \cos^2 \theta_D + I_{6s} \sin^2 \theta_D] \cos \theta_L \\
+ [I_3 \cos 2\chi + I_9 \sin 2\chi] \sin^2 \theta_L \sin^2 \theta_D \\
+ [I_4 \cos \chi + I_8 \sin \chi] \sin 2\theta_L \sin 2\theta_D \\
\left. + [I_5 \cos \chi + I_7 \sin \chi] \sin \theta_L \sin 2\theta_D \right\}$$



A particle physics diagram on a dark blue background with gold lines. It shows a central interaction region with various lines representing particles and wavy lines representing photons or gluons. Some lines end in small circles, possibly representing vertices or specific particle types. The diagram is partially enclosed by a dashed gold line on the left and bottom.

# SELECTION OPTIMISATION AND NORMALISATION FITS

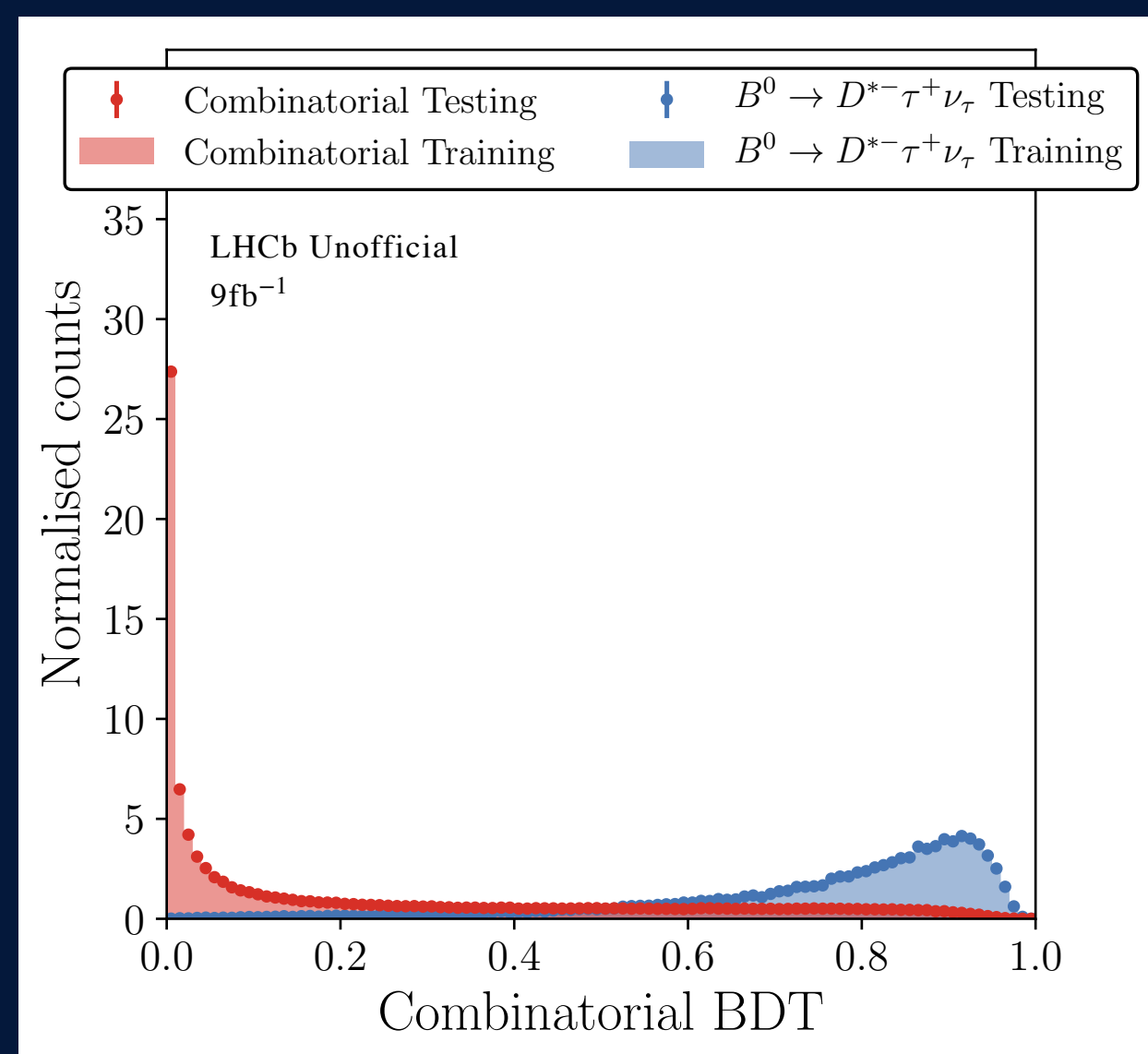


## USING MVA TO REDUCE BACKGROUND

### ▶ Combinatorial BDT

#### ▶ Signal MC vs WS data

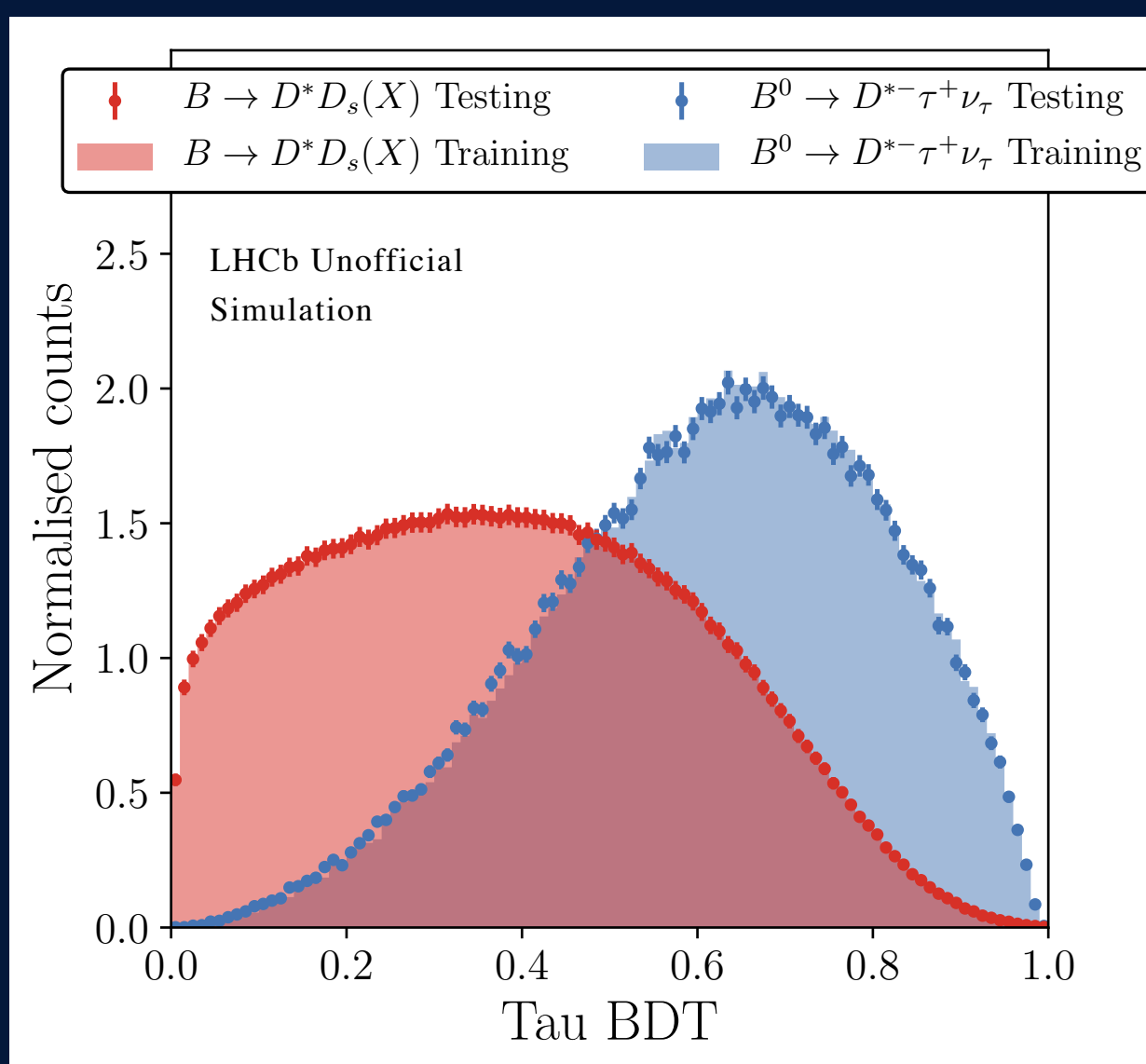
#### ▶ Variables: Track and vertex quality, particle PT, etc.



### ▶ Tau BDT

#### ▶ Signal MC vs $B \rightarrow D^*D_s(X)$ MC

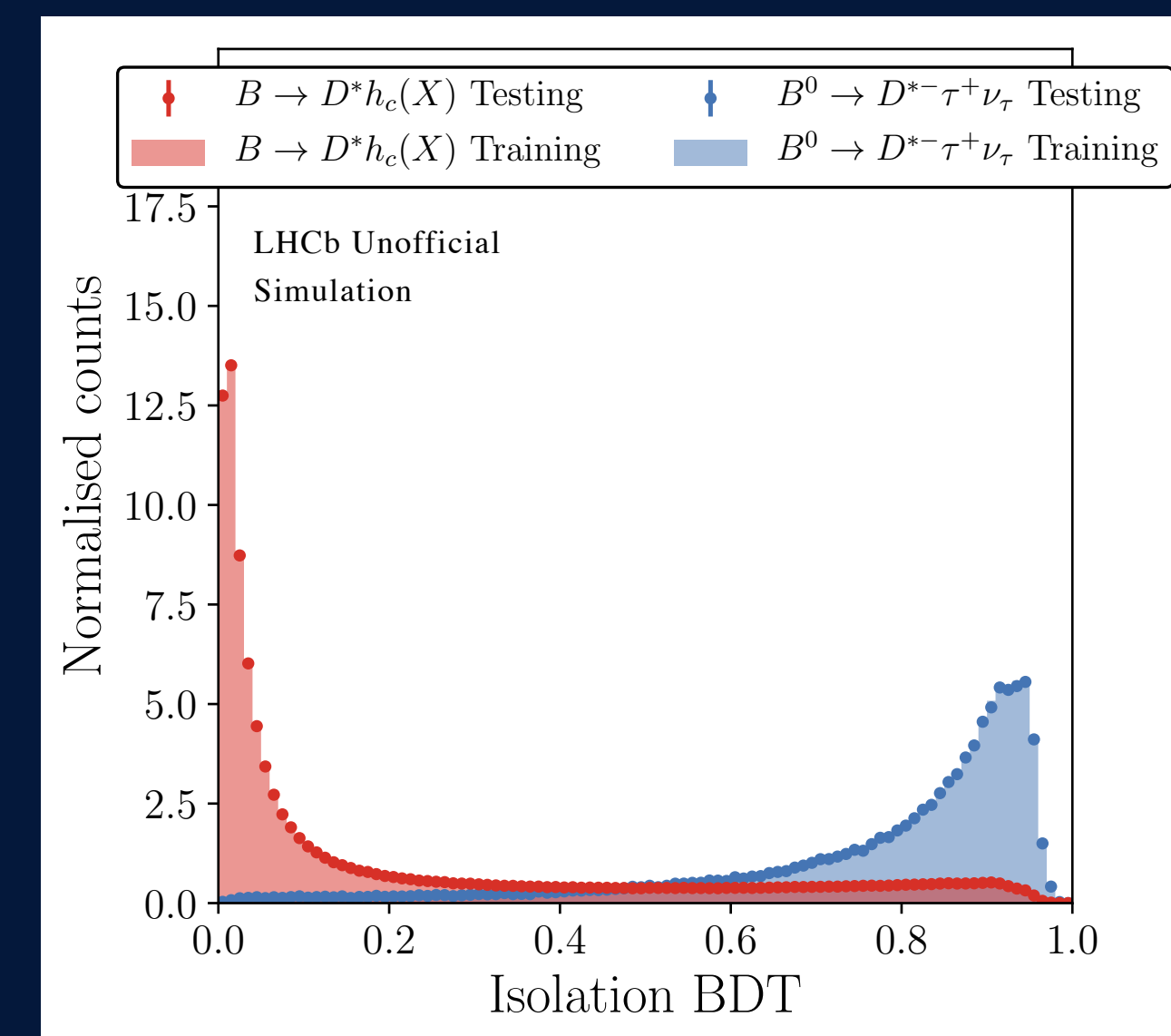
#### ▶ Variables: $\tau \rightarrow \pi^+\pi^-\pi^+$ information, $B^0$ information



### ▶ Isolation BDT

#### ▶ Signal MC vs $B \rightarrow D^*D_s(X)$ MC

#### ▶ Variables: charged and neutral isolation variables



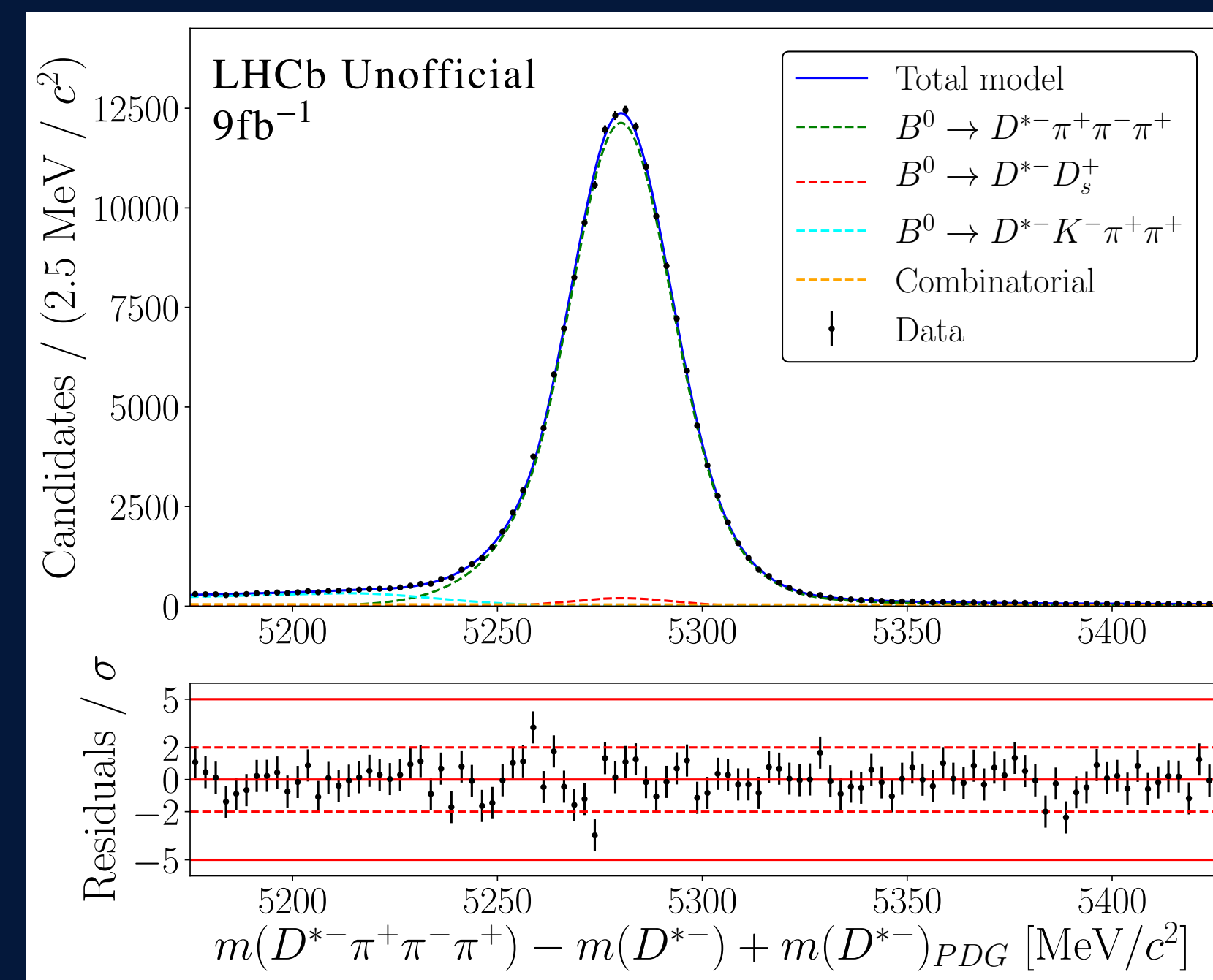
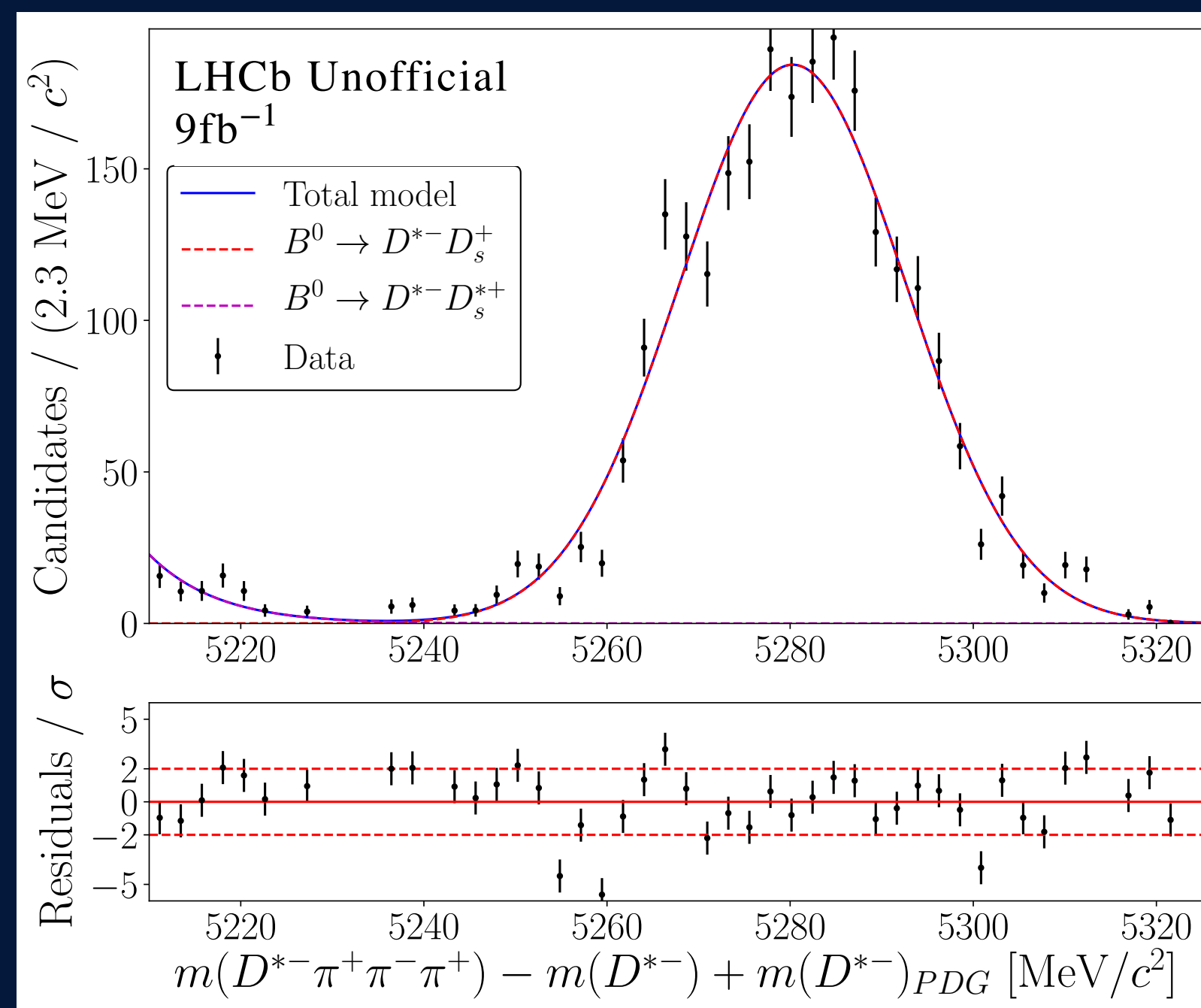
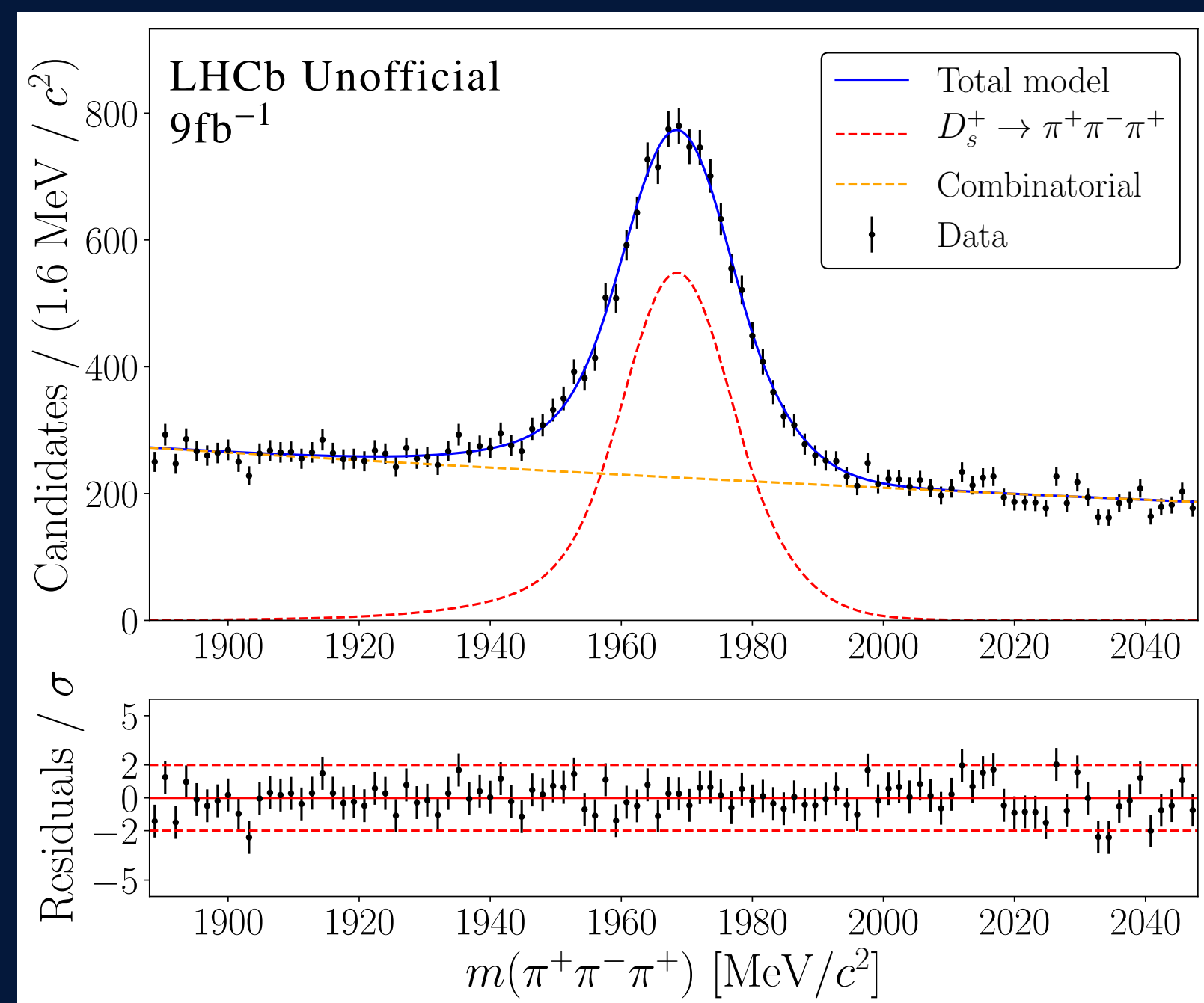
## MVA SELECTION OPTIMISATION

- ▶ In order to obtain control and signal samples, need to have a selection in place
- ▶ Selection involved several rectangular cuts, as well as 3 BDT cuts
- ▶ BDT cuts are optimised simultaneously using numerical method
- ▶ Cuts are optimised to maximise signal purity while maintaining a particular signal yield
- ▶ Signal yield is approximated using normalisation fits:  $B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+$

$$N_{sig} = N_{norm} * \frac{\epsilon_{sig}}{\epsilon_{norm}} * \frac{\mathcal{B}(B^0 \rightarrow D^{*-}\tau^+\nu_\tau) \cdot (\mathcal{B}(\tau^+ \rightarrow \pi^+\pi^-\pi^+\bar{\nu}_\tau) + \mathcal{B}(\tau^+ \rightarrow \pi^+\pi^-\pi^+\pi^0\bar{\nu}_\tau))}{\mathcal{B}(B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+)}$$

- ▶  $\mathcal{B}(B^0 \rightarrow D^{*-}\tau^+\nu_\tau)$  multiplied by a random number  $\in [0.75, 1.25]$  to blind optimisation to SM value

# NORMALISATION FITS



## ▶ Three normalisation fits

- ▶  $m(\pi^+\pi^-\pi^+)$  - measure  $D_s^+ \rightarrow \pi^+\pi^-\pi^+$  peak - calculate  $_s$ Weights
- ▶  $m(D^{*-}\pi^+\pi^-\pi^+)$  with  $_s$ Weights - measure  $B^0 \rightarrow D^{*-}D_s^+$  yield
- ▶  $m(D^{*-}\pi^+\pi^-\pi^+)$  - measure  $B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+$  yield
- ▶ Calculate estimate of optimised signal yield



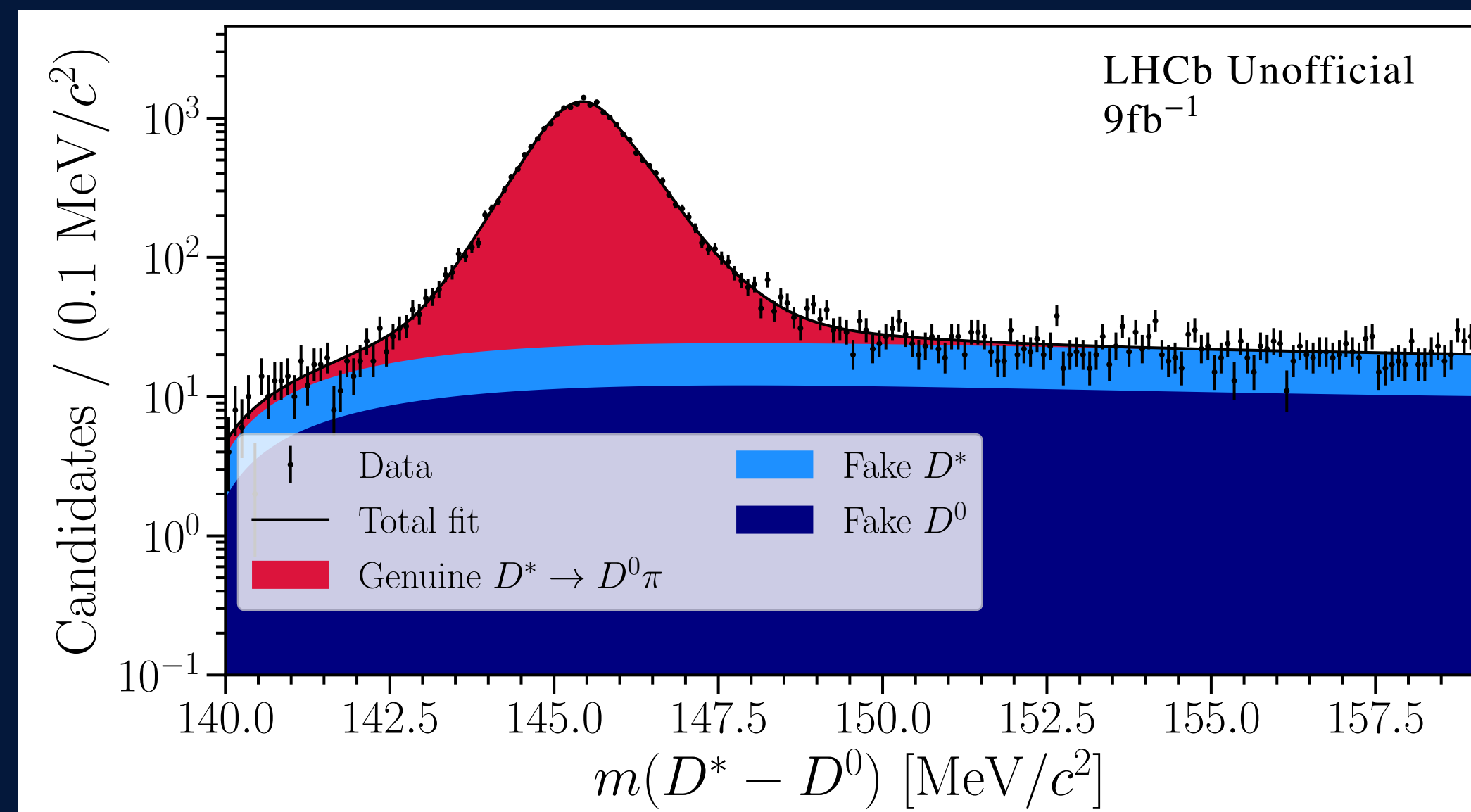
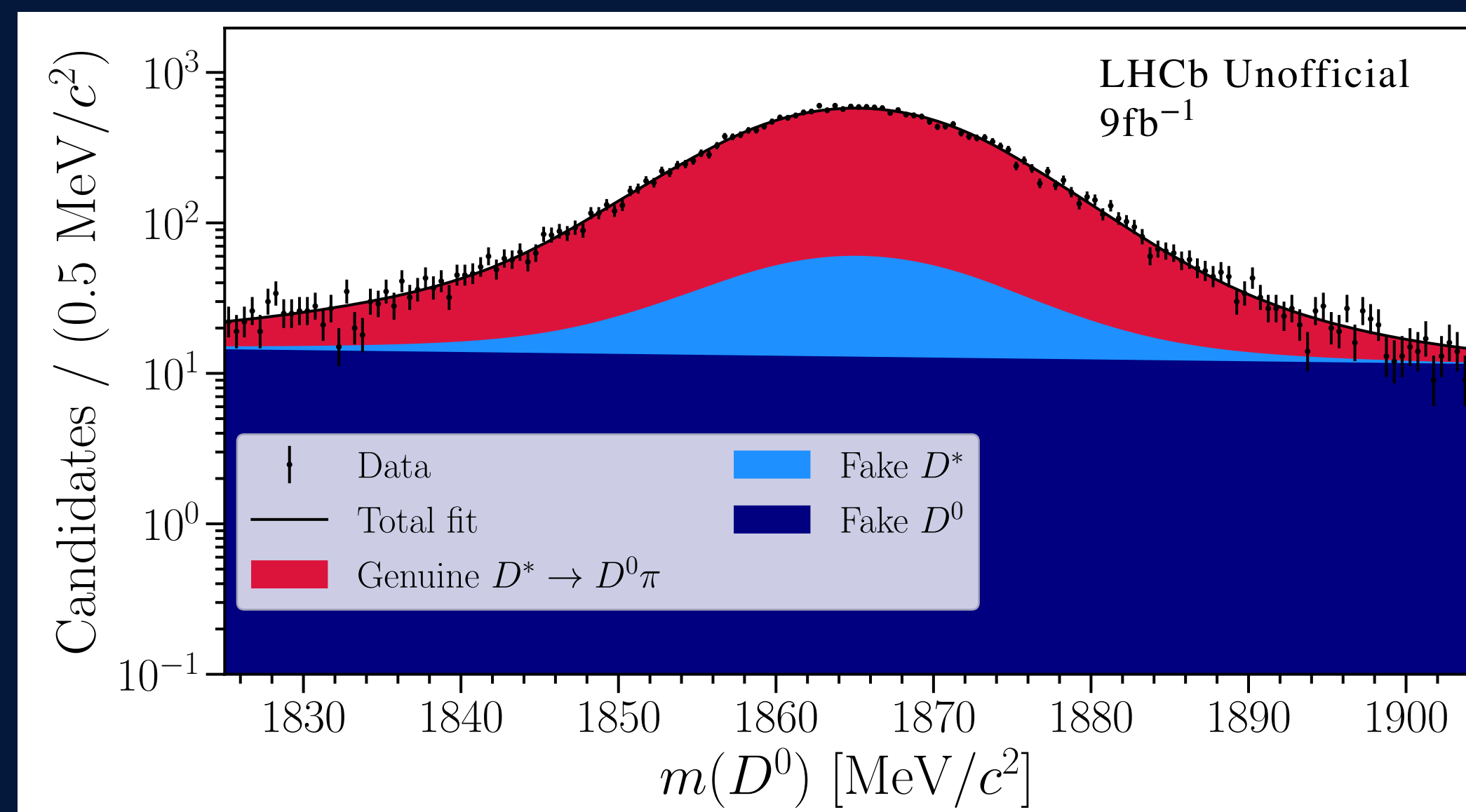
A Feynman diagram illustrating a B meson decay process. The diagram shows a B meson (represented by a solid line) decaying into a D\* meson (represented by a dashed line) and a D meson (represented by a solid line). The D\* meson further decays into a D meson and a photon (represented by a wavy line). The D meson then decays into a proton and a neutron (represented by two solid lines). The photon decays into an electron and a positron (represented by two solid lines). The diagram is set against a dark blue background with gold lines.

# REMOVING FAKE $D^*$



## MEASURING FAKE $D^*$ RATE - DATA FIT

- ▶ True  $D^*$  - peaks in both
- ▶ Fake  $D^*$  - peaks in  $m(D^0)$ , not in  $m(D^* - D^0)$
- ▶ Fake  $D^0$  - does not peak in either
- ▶ Use floating yields for each of these components
- ▶ Can remove combinatorial background that rectangular  $m(D^0)$ , and  $m(D^* - D^0)$  cuts wouldn't
- ▶ Increase in purity from this step
- ▶ Still other sources of combinatorial background
  - ▶ True  $D^*$  + fake  $3\pi$  combinatorial - modelled with inclusive MC
  - ▶ B1B2 background - modelled with WS data after sWeight fit is performed on WS data

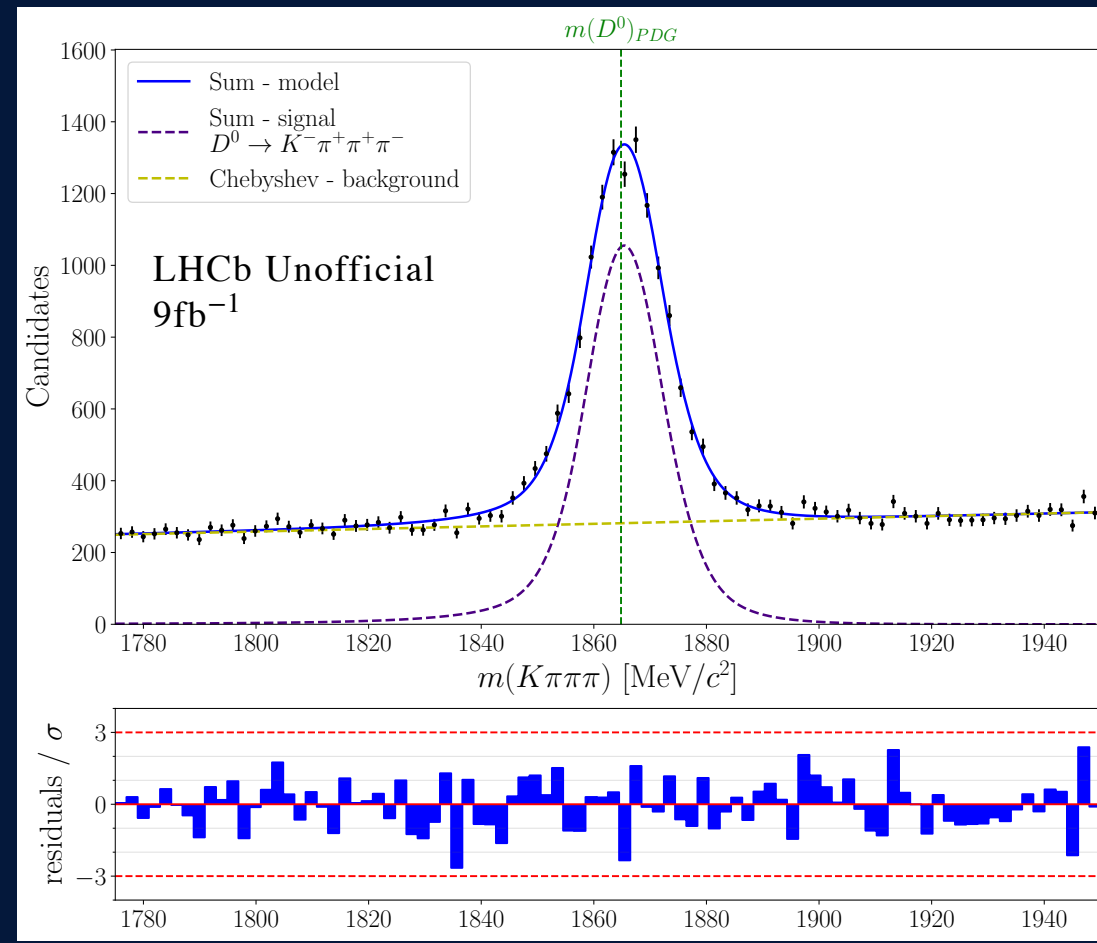




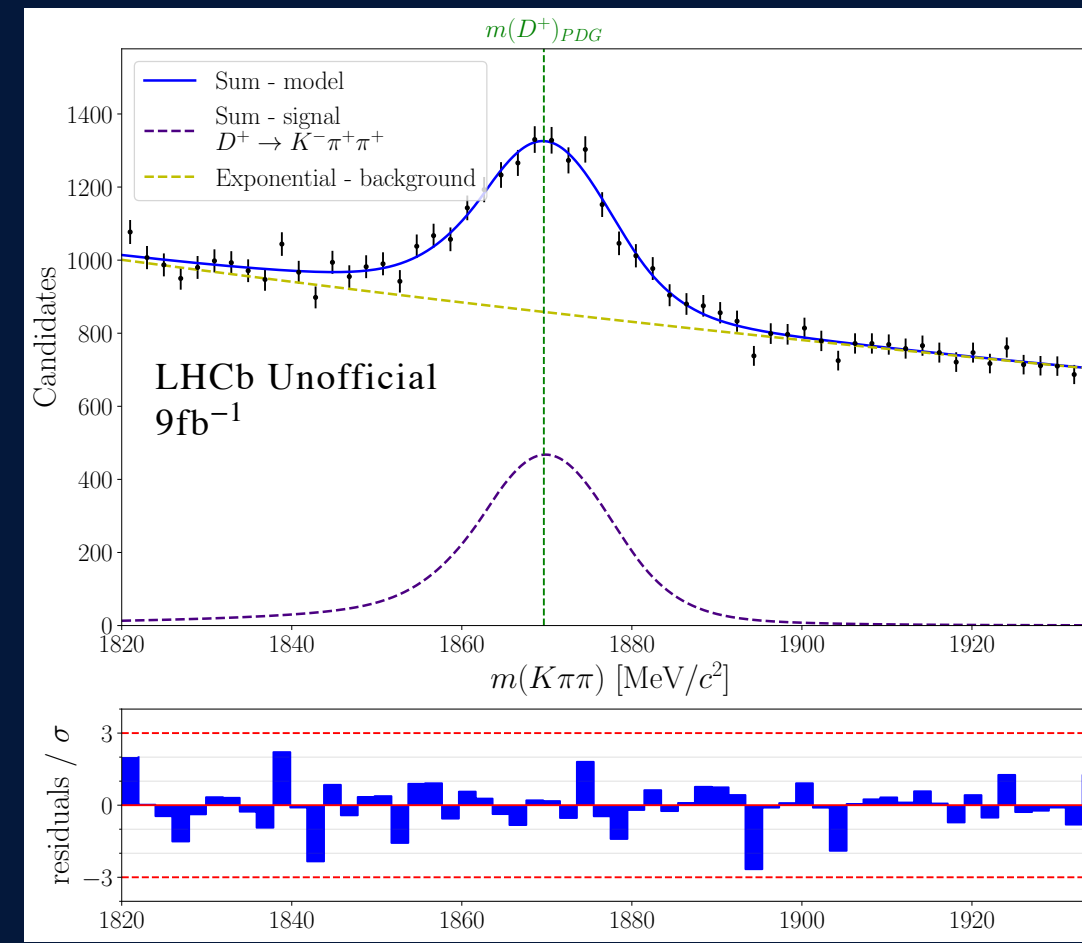
# CONTROL STUDIES

## CONTROL STUDIES

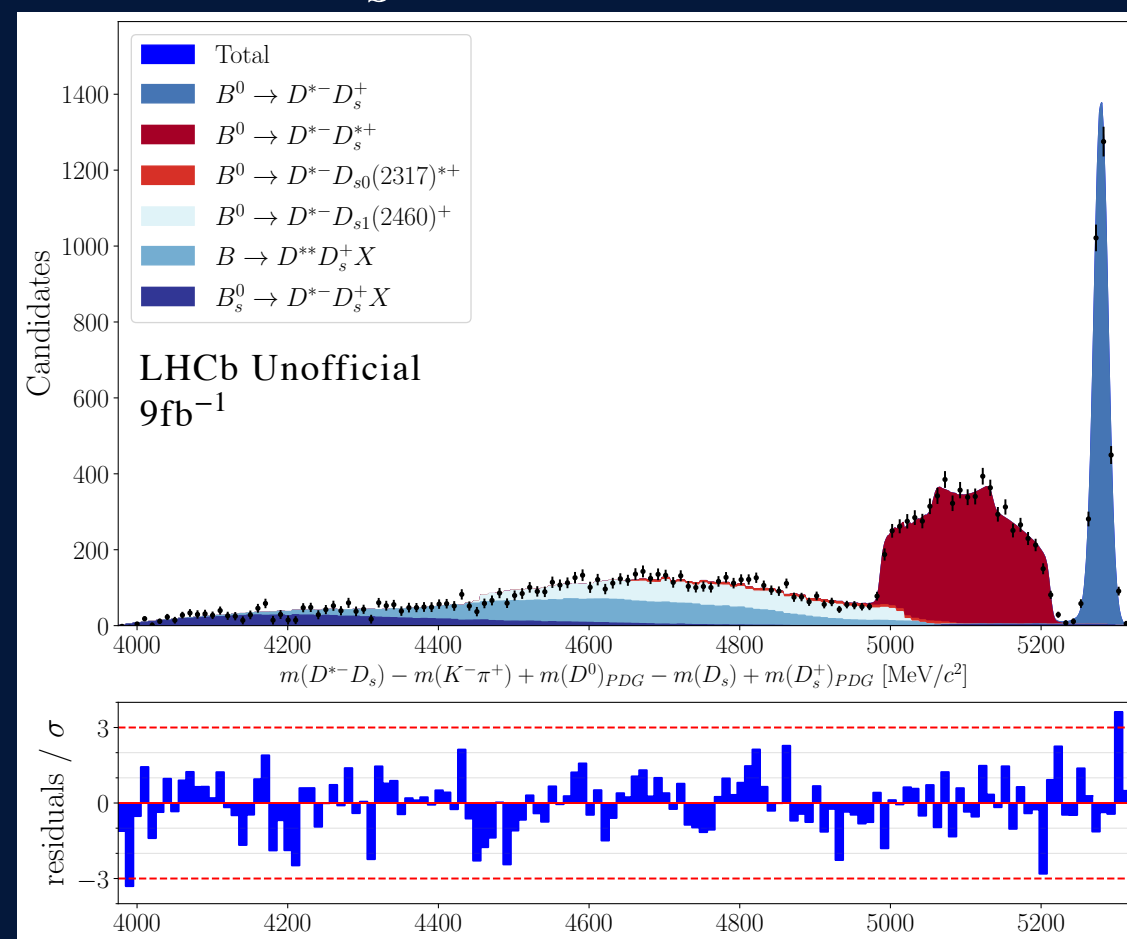
$$B \rightarrow D^{*-} D^0(X)$$



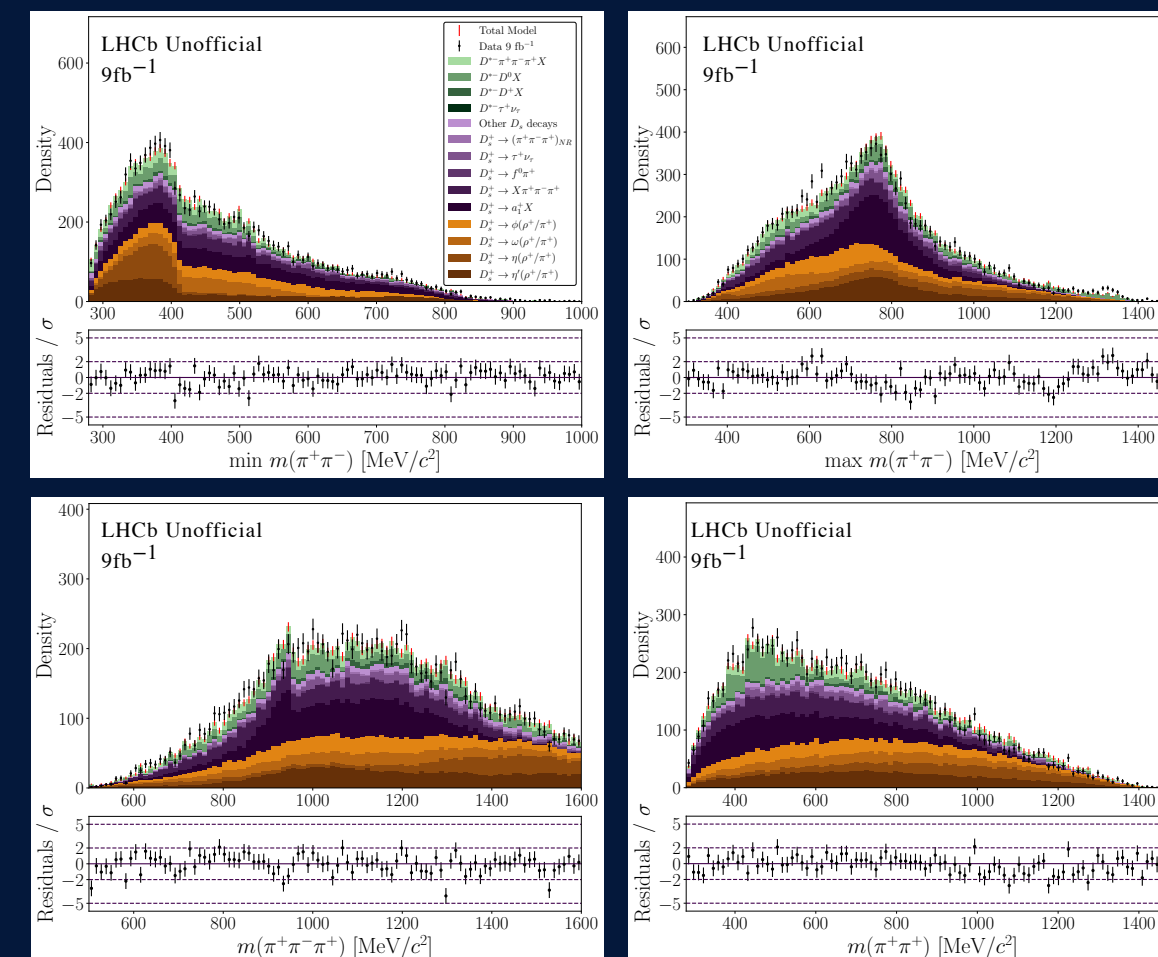
$$B \rightarrow D^{*-} D^+(X)$$



$$B \rightarrow D^{*-} D_s(X)$$



$$D_s \rightarrow \pi^+ \pi^- \pi^+(X)$$



▶ Control studies used to measure data/simulation agreement

▶ Obtain sets of weights to correct simulation

▶ Improve data/simulation agreement

▶ Correct decay fractions in simulation

▶ Methodology aligned with the Run 1

$\mathcal{R}(D^*)$  measurement

[PRL 120 \(2018\) 171802,](#)

[PRD 97 \(2018\) 072013](#)

A Feynman diagram illustrating a signal fit. It shows a particle interaction with several external lines and internal propagators. The diagram features a central vertex from which several lines extend. Some lines are solid, while others are dashed. There are also wavy lines and a series of small circles connected by lines, representing a specific interaction or fit. The text "SIGNAL FIT" is centered in the diagram.

# SIGNAL FIT



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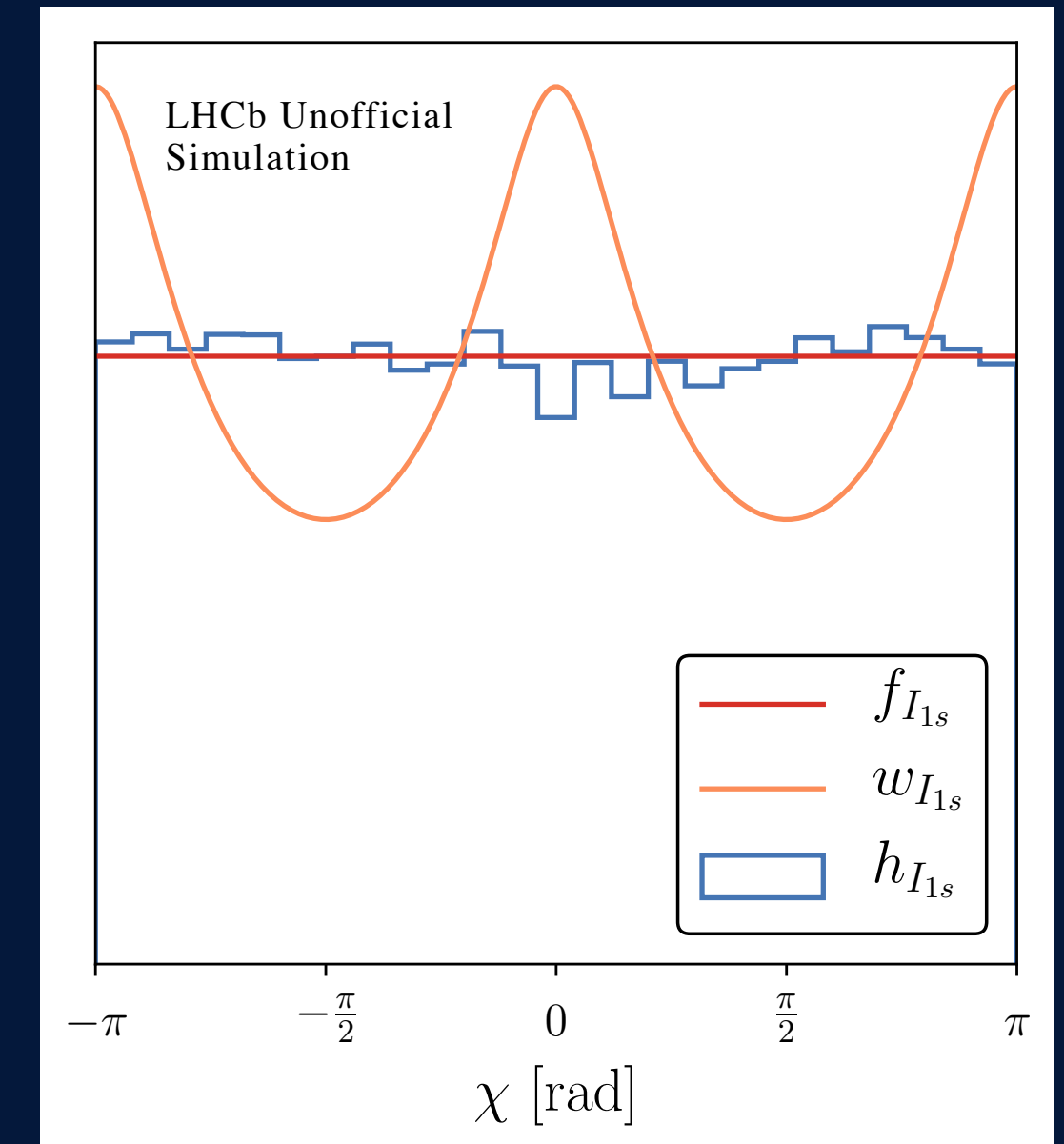
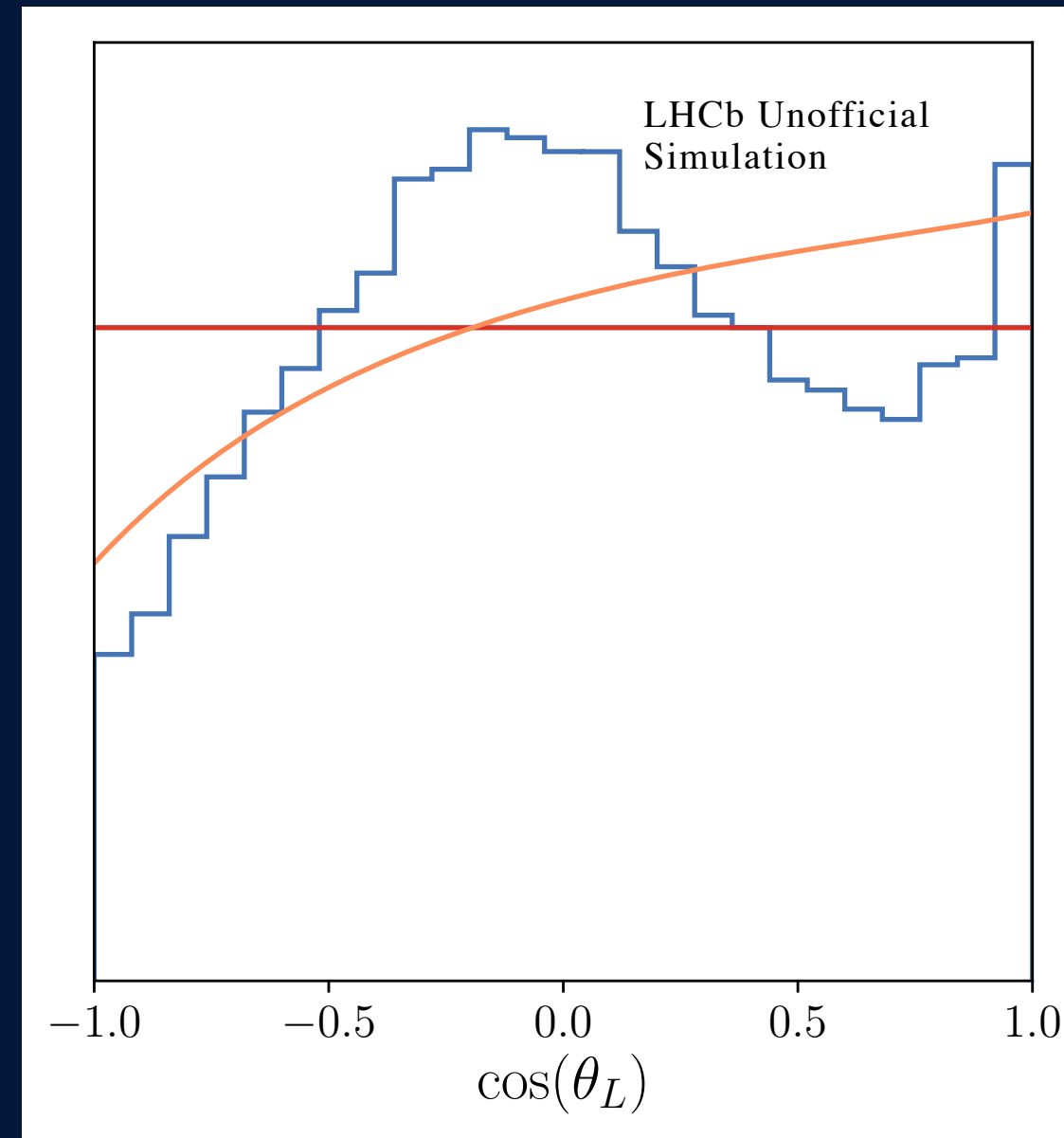
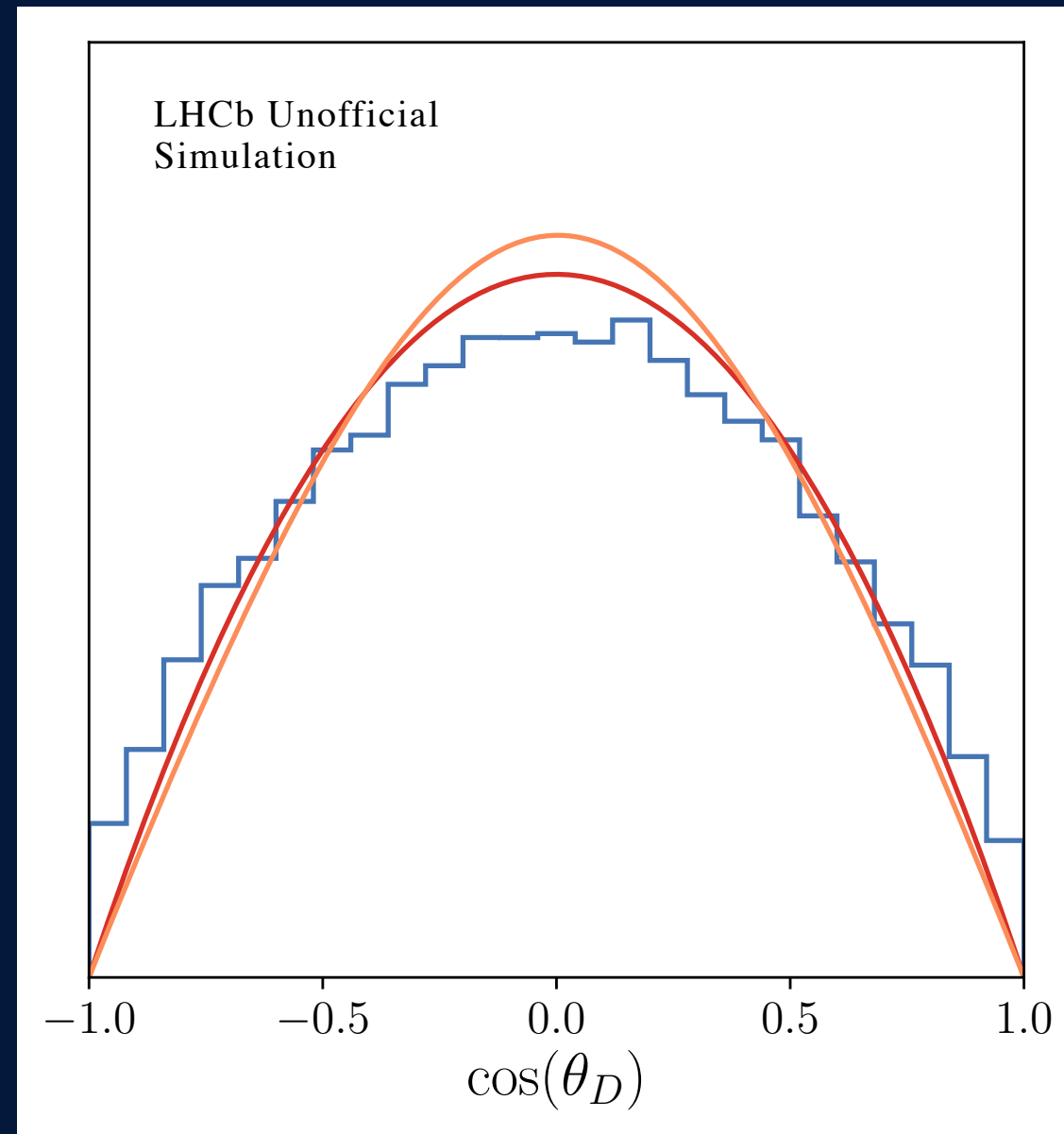
## SIGNAL FIT - SIGNAL PDF

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- ▶ Simultaneous multidimensional template fit
  - ▶ 3D fit in the decay angles
  - ▶ 3D fit in BDT,  $q^2$ ,  $\tau$   $z$  flight distance significance
  
- ▶ In traditional  $\mathcal{R}(D^*)$  analyses, the signal and background PDFs use SM simulation as the templates
  - ▶ Assumes SM and a form factor model
  
- ▶ In this analysis, background templates are still SM shapes taken from simulation
- ▶ The signal simulation is divided into 12 model independent angular templates,  $h_{I_x}$ 
  - ▶ Signal template is the sum of these angular templates
    - ▶ Each  $h_{I_x}$  is normalised by their  $I_x$  coefficient which floats in the fit:

$$P_{D^*\tau\nu} = \left( \frac{1}{3} (4 - 6I_{1s} + I_{2c} + 2I_{2s}) \right) h_{I_{1c}} + \sum_x I_x h_{I_x}$$

# SIGNAL PDF CREATION



- ▶ Take angular function for a particular  $I_x$ ,

$$f_{I_x}: I_{1s} \sin^2 \theta_D$$

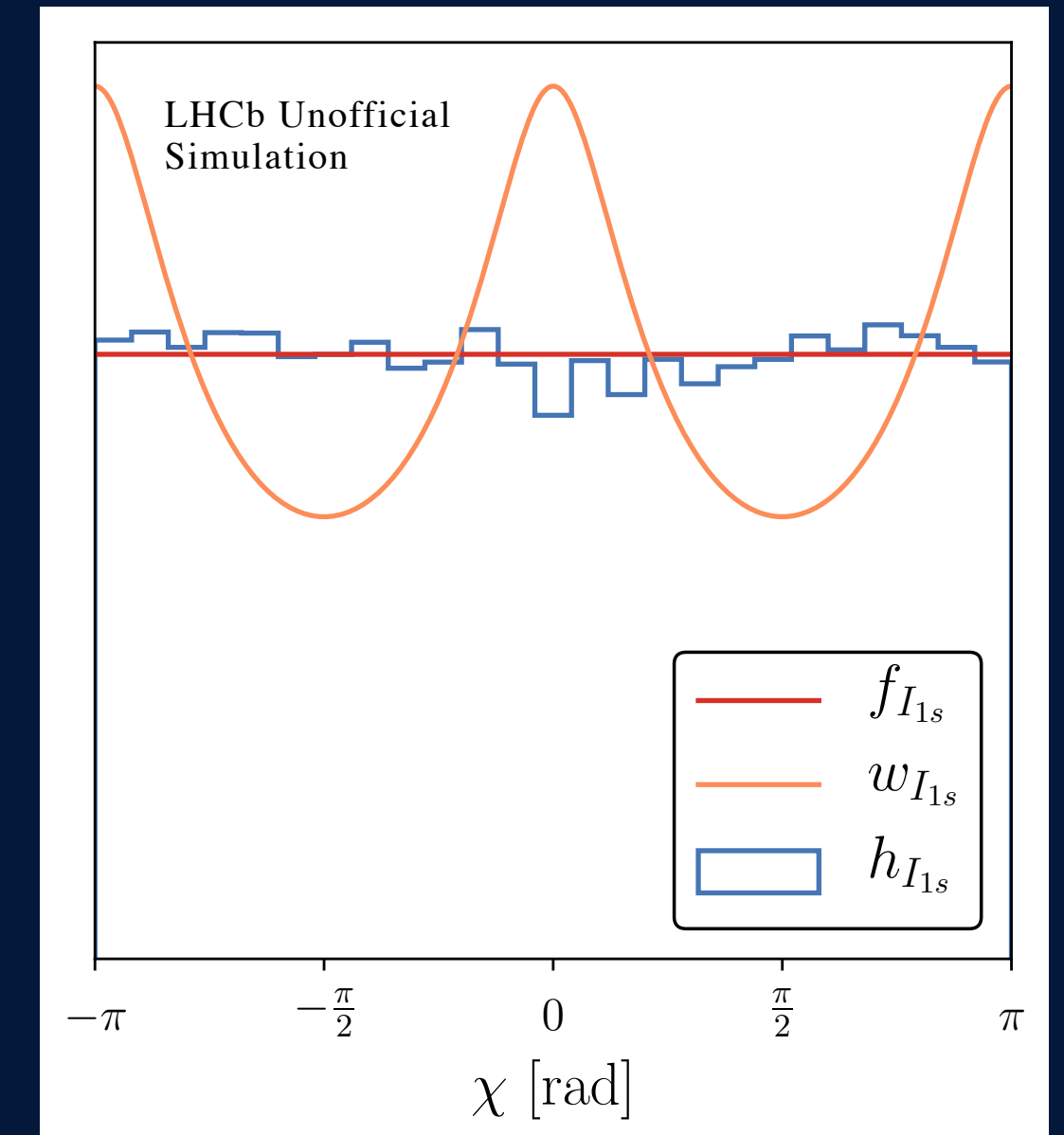
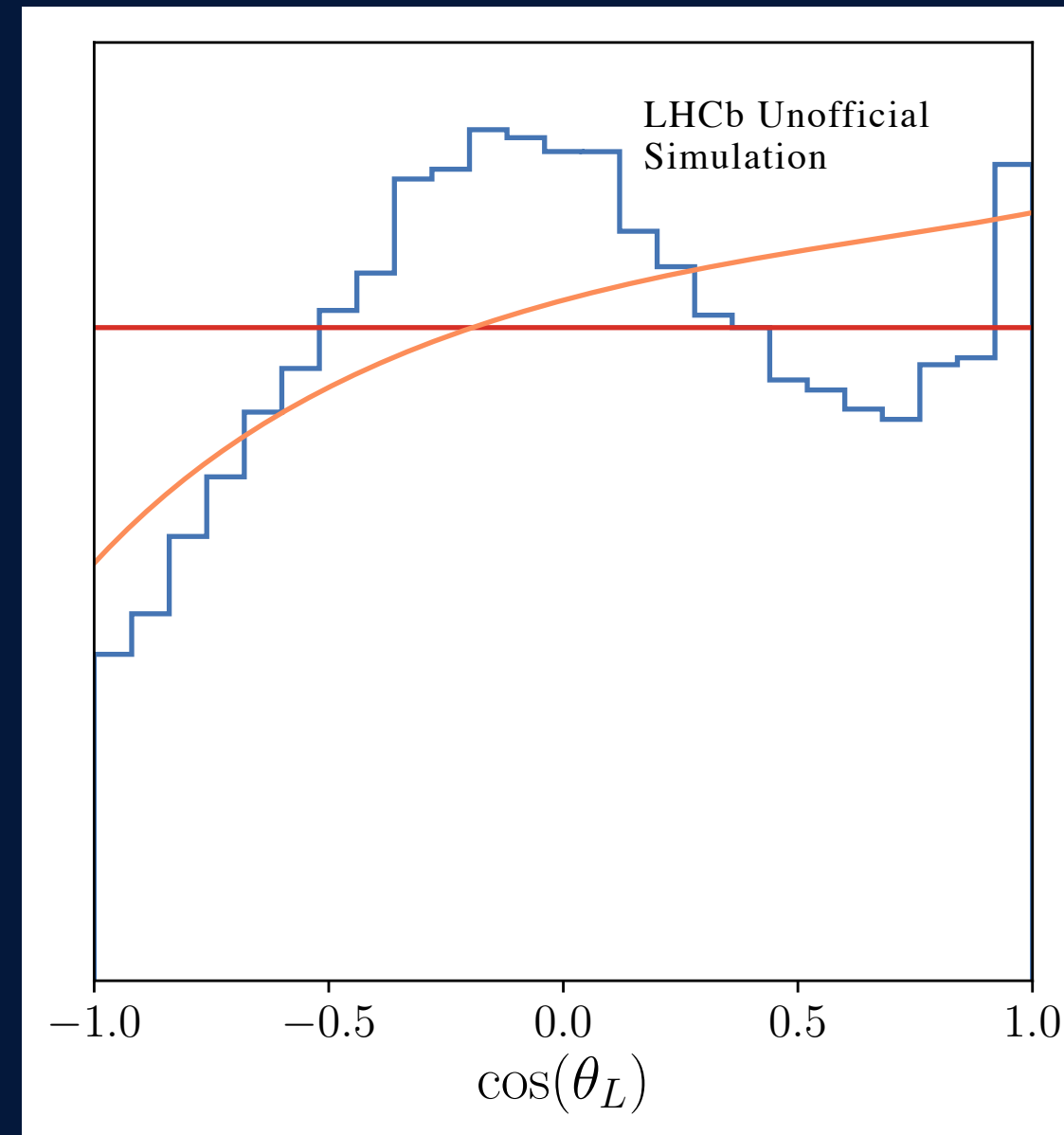
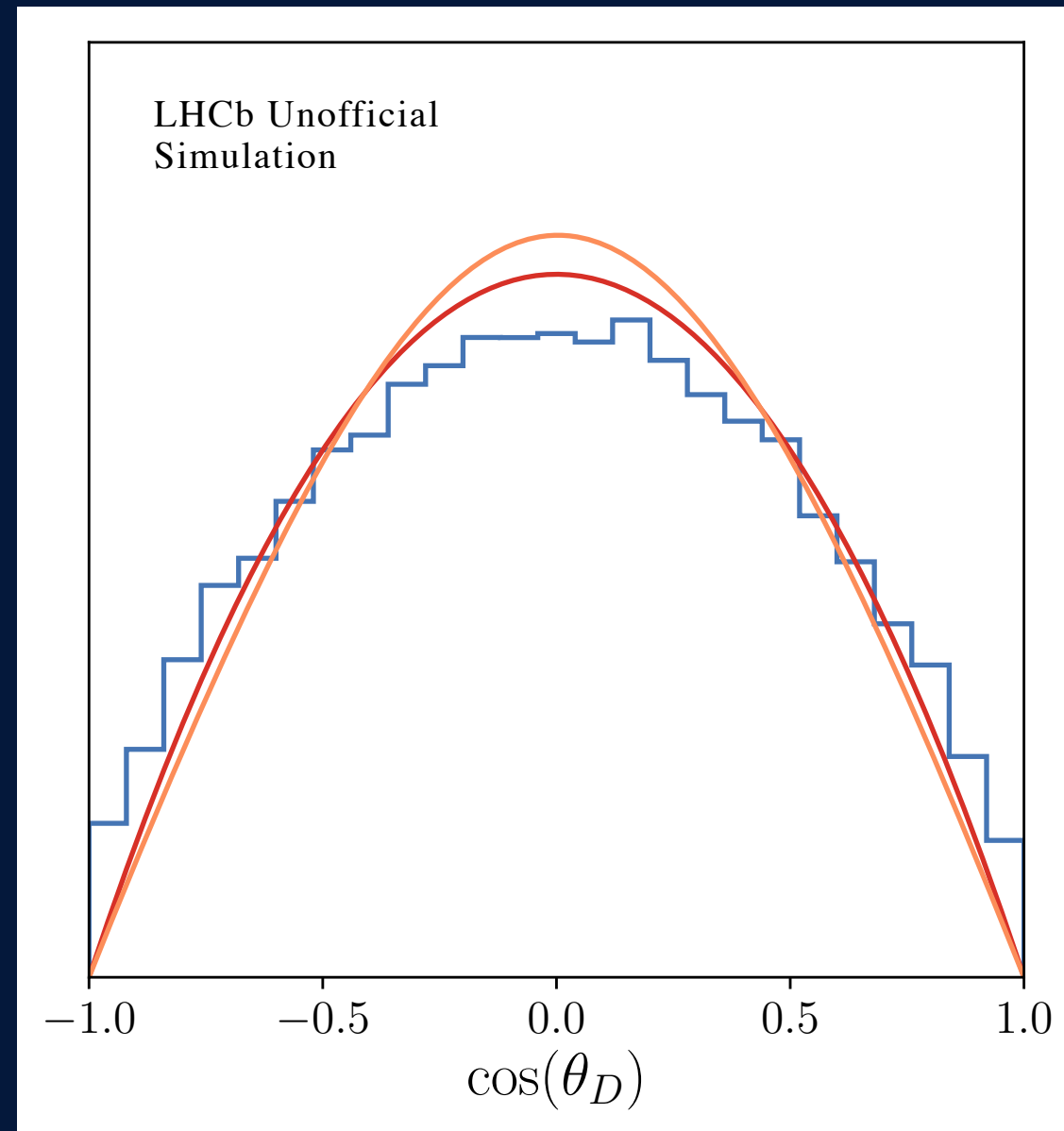
- ▶ Divide by the total model  $M$  to obtain weight

$$\text{function, } w_{I_x} \quad M = \frac{d^4\Gamma}{dq^2 d \cos \theta_D d \cos \theta_L d \chi}$$

- ▶ Calculate the value of the weight function for signal simulation (using truth variables)

$$\begin{aligned} \frac{d^4\Gamma}{dq^2 d \cos \theta_D d \cos \theta_L d \chi} &= \frac{9}{32\pi} \left\{ I_{1c} \cos^2 \theta_D + I_{1s} \sin^2 \theta_D \right. \\ &+ [I_{2c} \cos^2 \theta_D + I_{2s} \sin^2 \theta_D] \cos 2\theta_L \\ &+ [I_{6c} \cos^2 \theta_D + I_{6s} \sin^2 \theta_D] \cos \theta_L \\ &+ [I_3 \cos 2\chi + I_9 \sin 2\chi] \sin^2 \theta_L \sin^2 \theta_D \\ &+ [I_4 \cos \chi + I_8 \sin \chi] \sin 2\theta_L \sin 2\theta_D \\ &\left. + [I_5 \cos \chi + I_7 \sin \chi] \sin \theta_L \sin 2\theta_D \right\} \end{aligned}$$

# SIGNAL PDF CREATION



- ▶ Take angular function for a particular  $I_x$ ,

$$f_{I_x}: I_{1s} \sin^2 \theta_D$$

- ▶ Divide by the total model  $M$  to obtain weight

$$\text{function, } w_{I_x} \quad M = \frac{d^4\Gamma}{dq^2 d \cos \theta_D d \cos \theta_L d \chi}$$

- ▶ Calculate the value of the weight function for signal simulation (using truth variables)

- ▶ Apply weights to signal simulation to create  $I_x$  template,  $h_{I_x}$  (in reconstructed space)

- ▶  $h_{I_x}$  and  $f_{I_x}$  deviate due

- ▶ Selection effects
- ▶ Missing  $\nu$
- ▶ Angular resolution

# ANGULAR FIT - TOY

▶ Toy fit based on expected statistics in data

▶ Signal toy generated with  $I_x$  according to <https://arxiv.org/abs/1912.09335>

▶ Expected precision of 7-8% on  $\mathcal{R}(D^*)$   
(no systematics included)

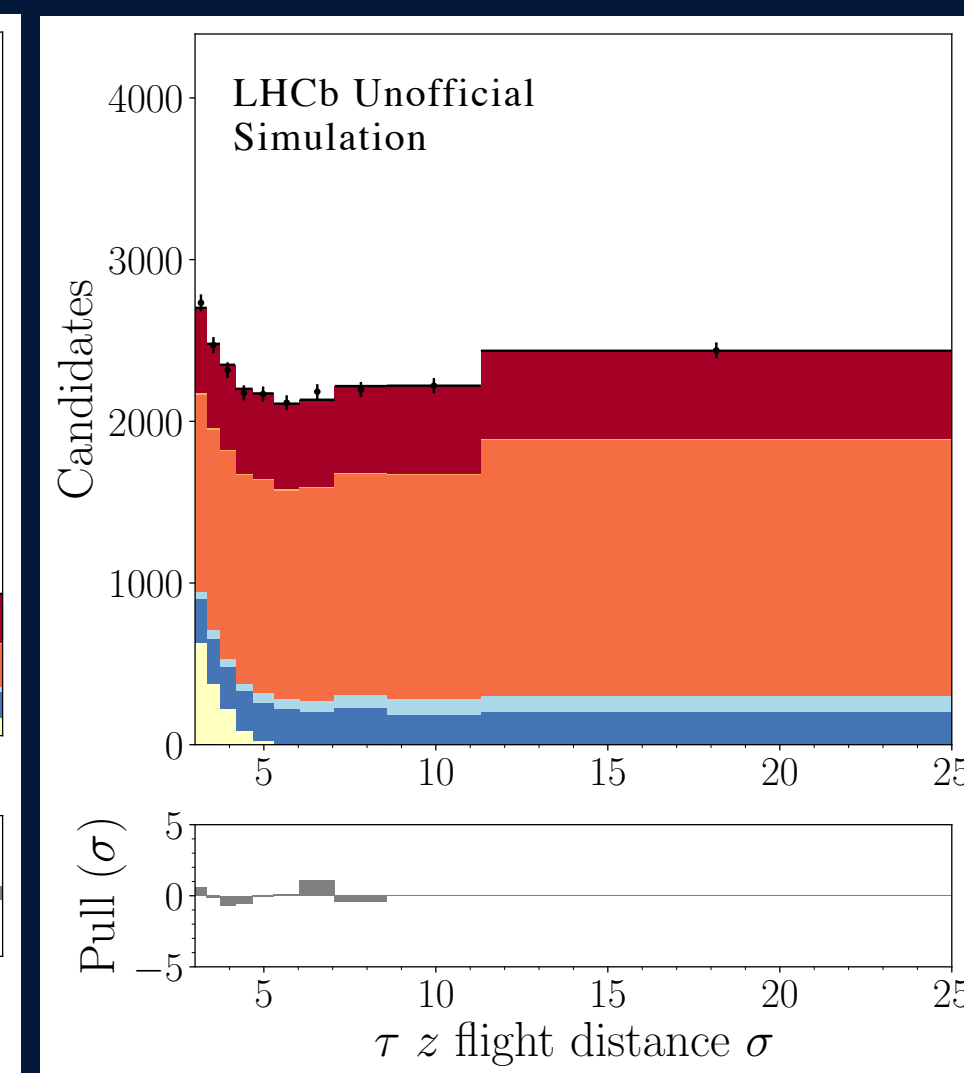
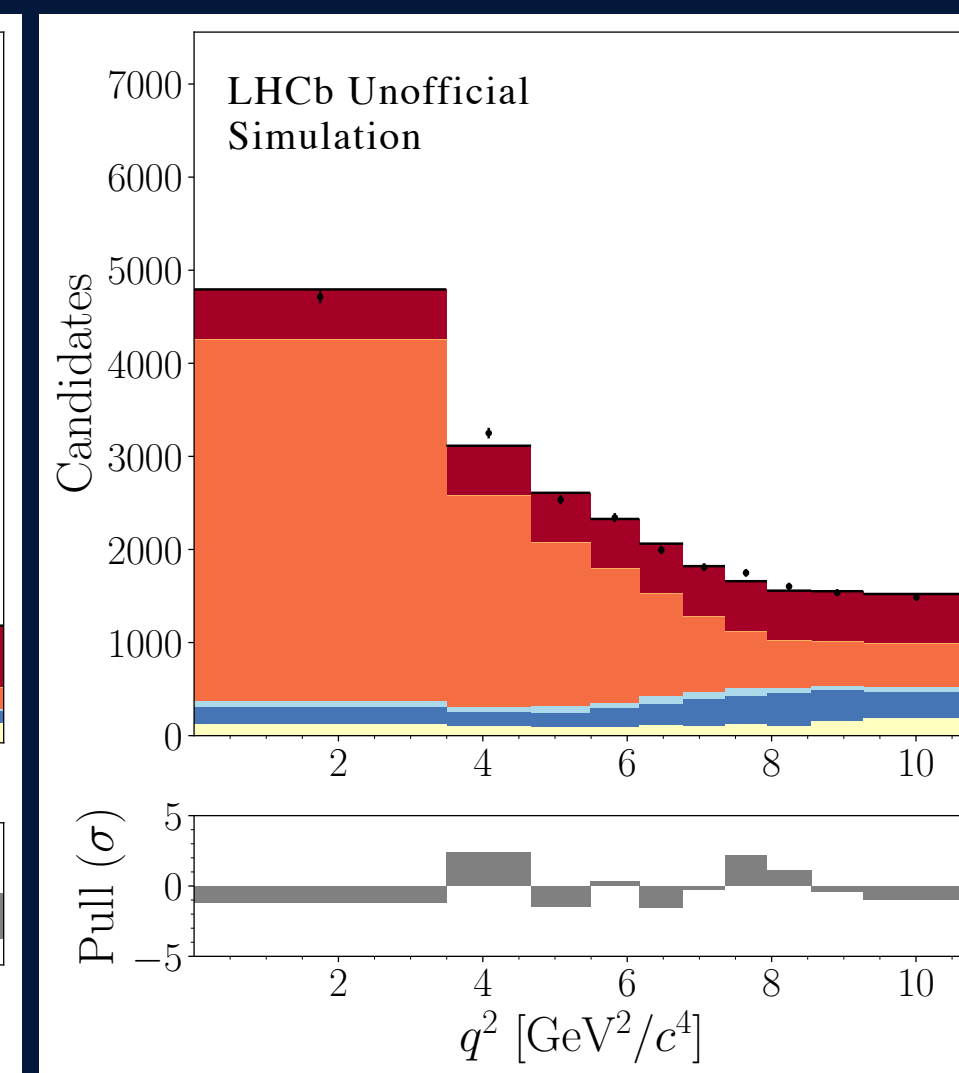
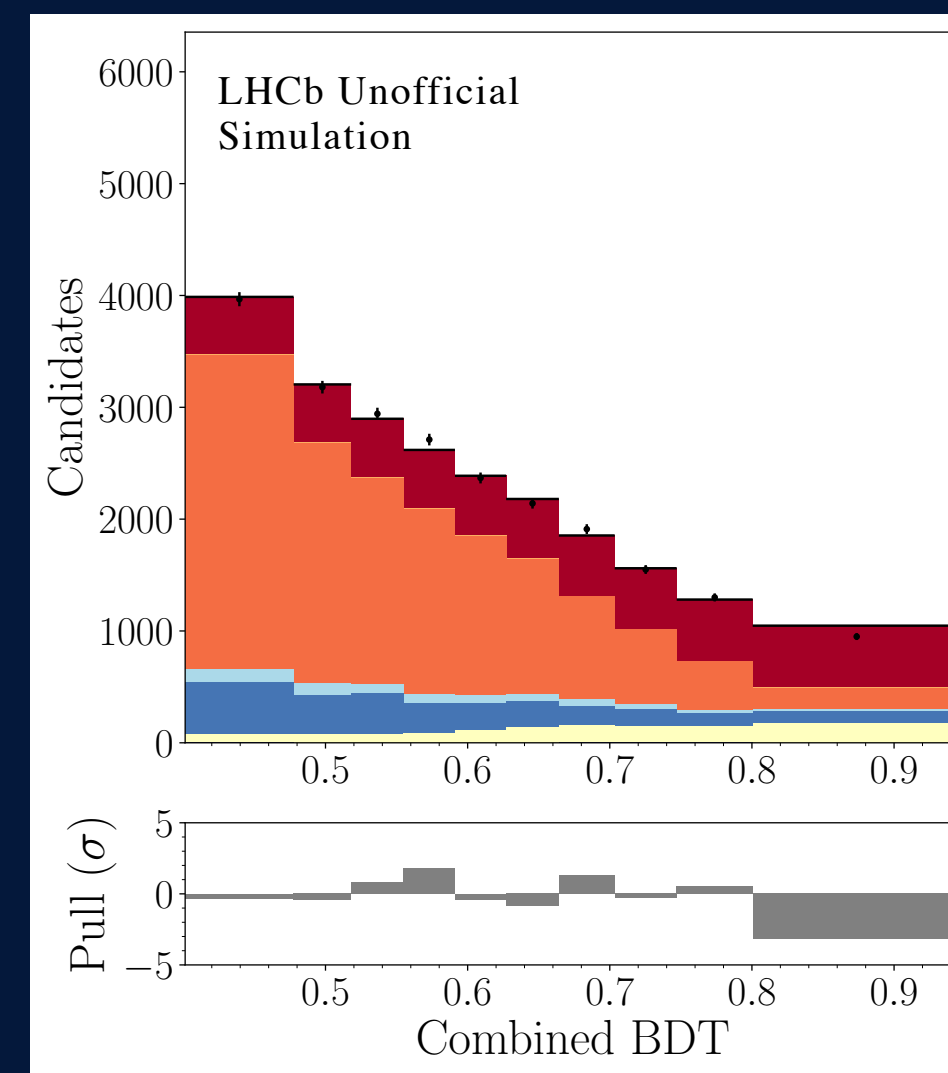
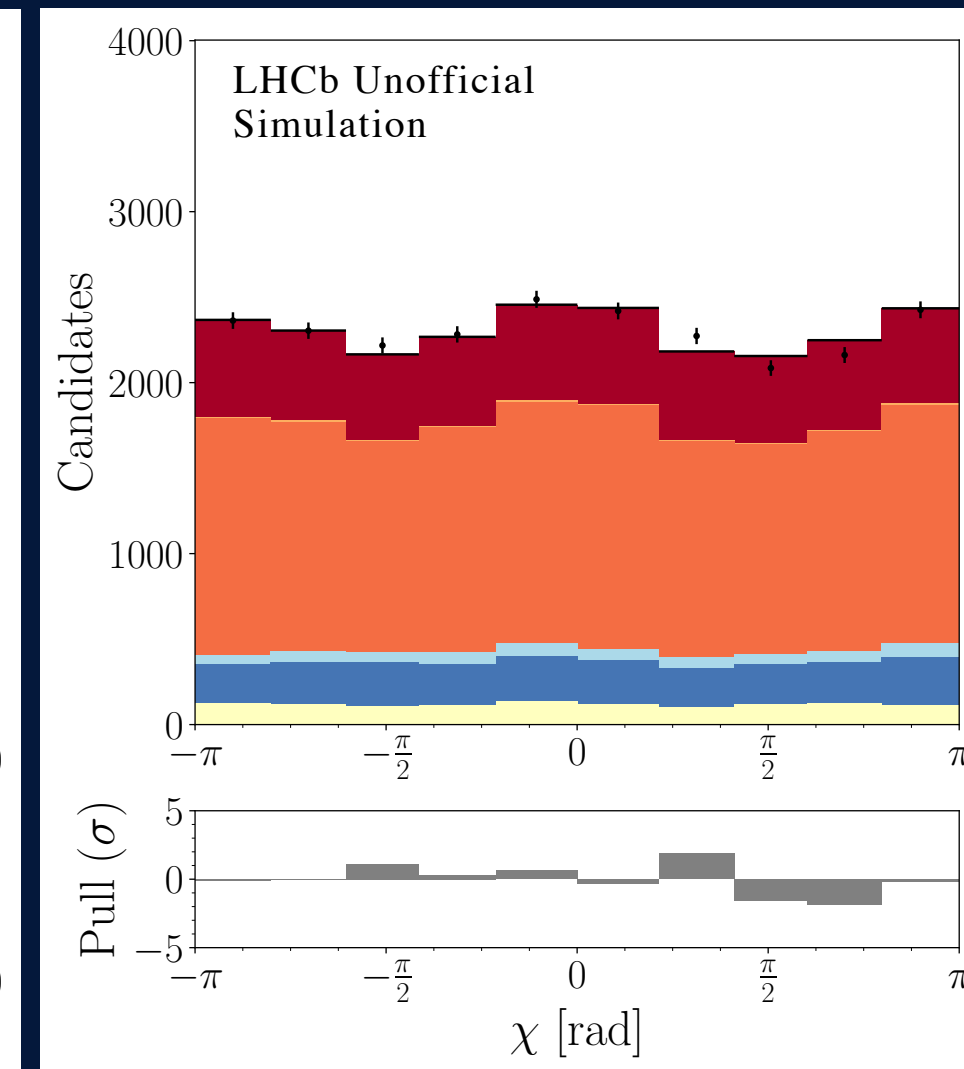
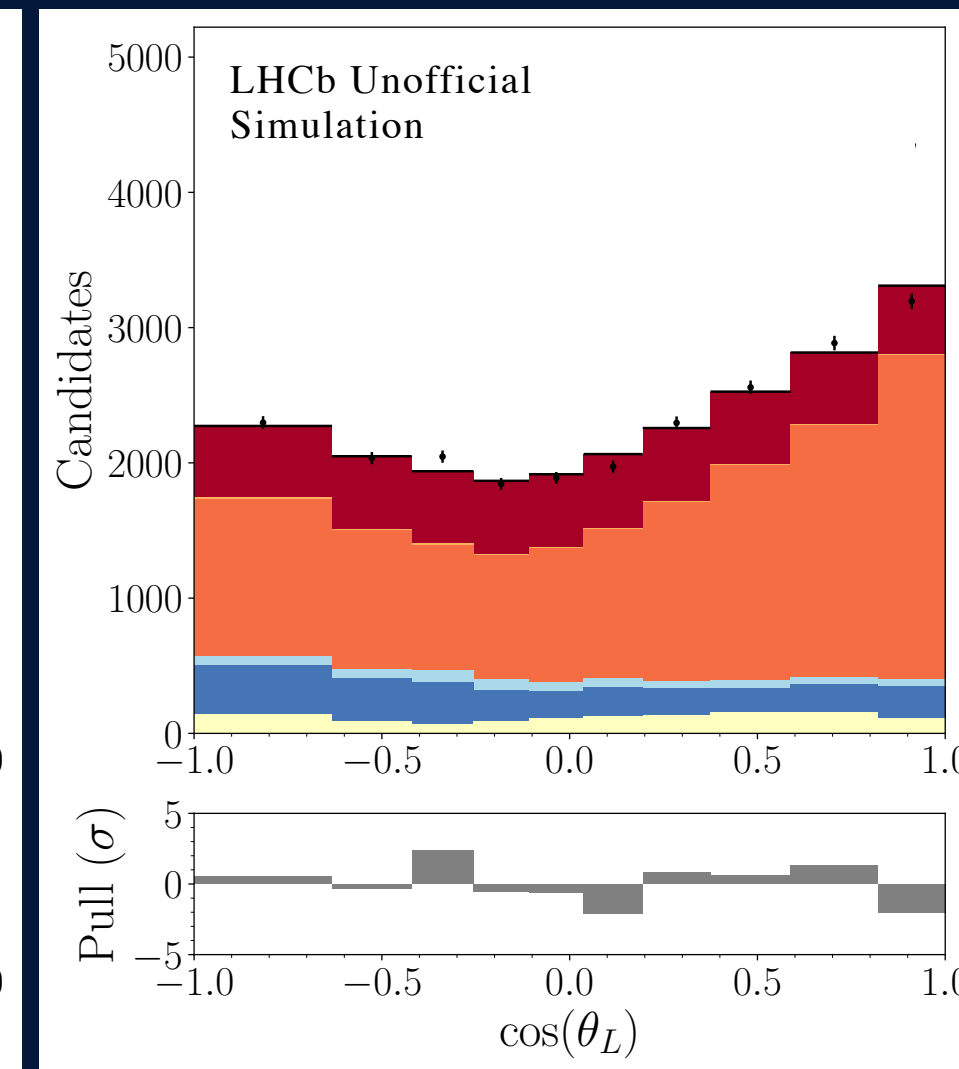
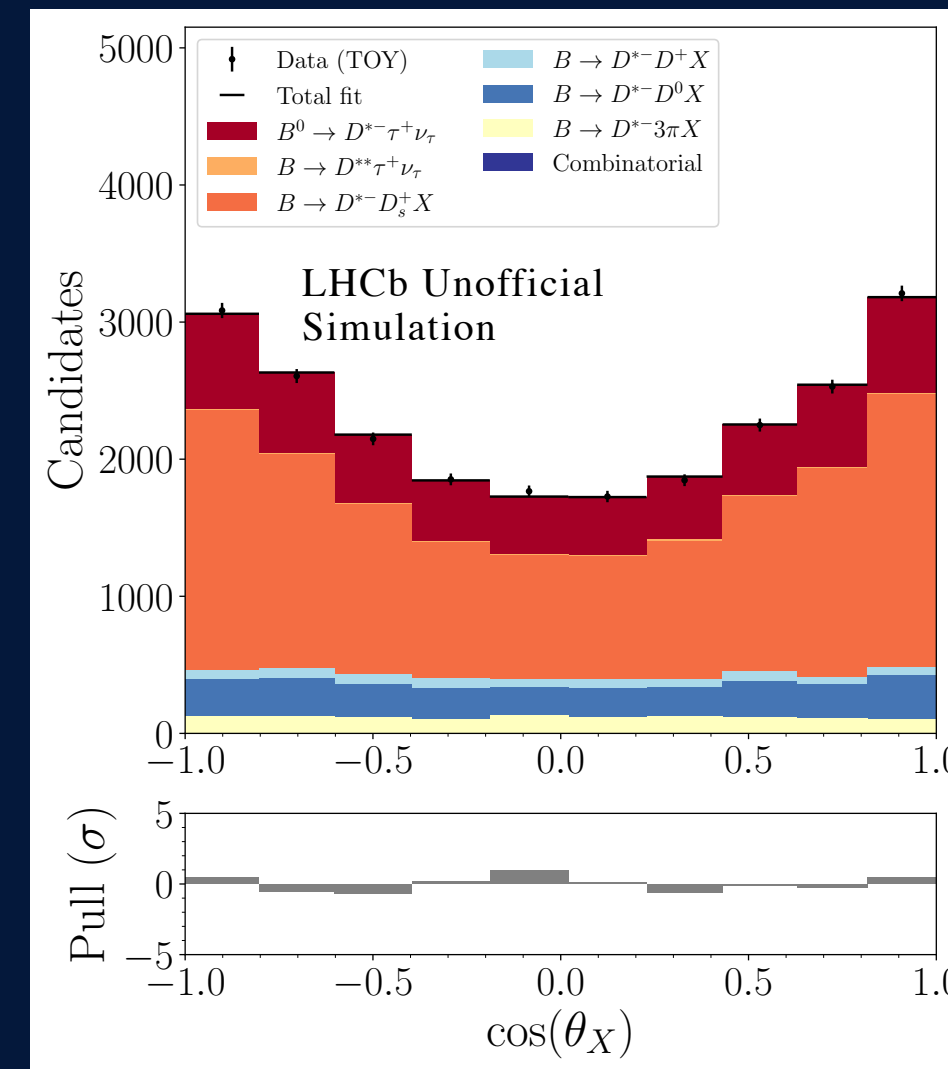
▶ Similar precision to Run 1 result

[PRL 120 \(2018\) 171802](#), [PRD 97 \(2018\) 072013](#)

▶ BDT has less separation due to model independent restrictions on input variables

▶ Additional freedom in signal PDF due to 12 angular templates

▶  $I_x$  measured in fit with signal template





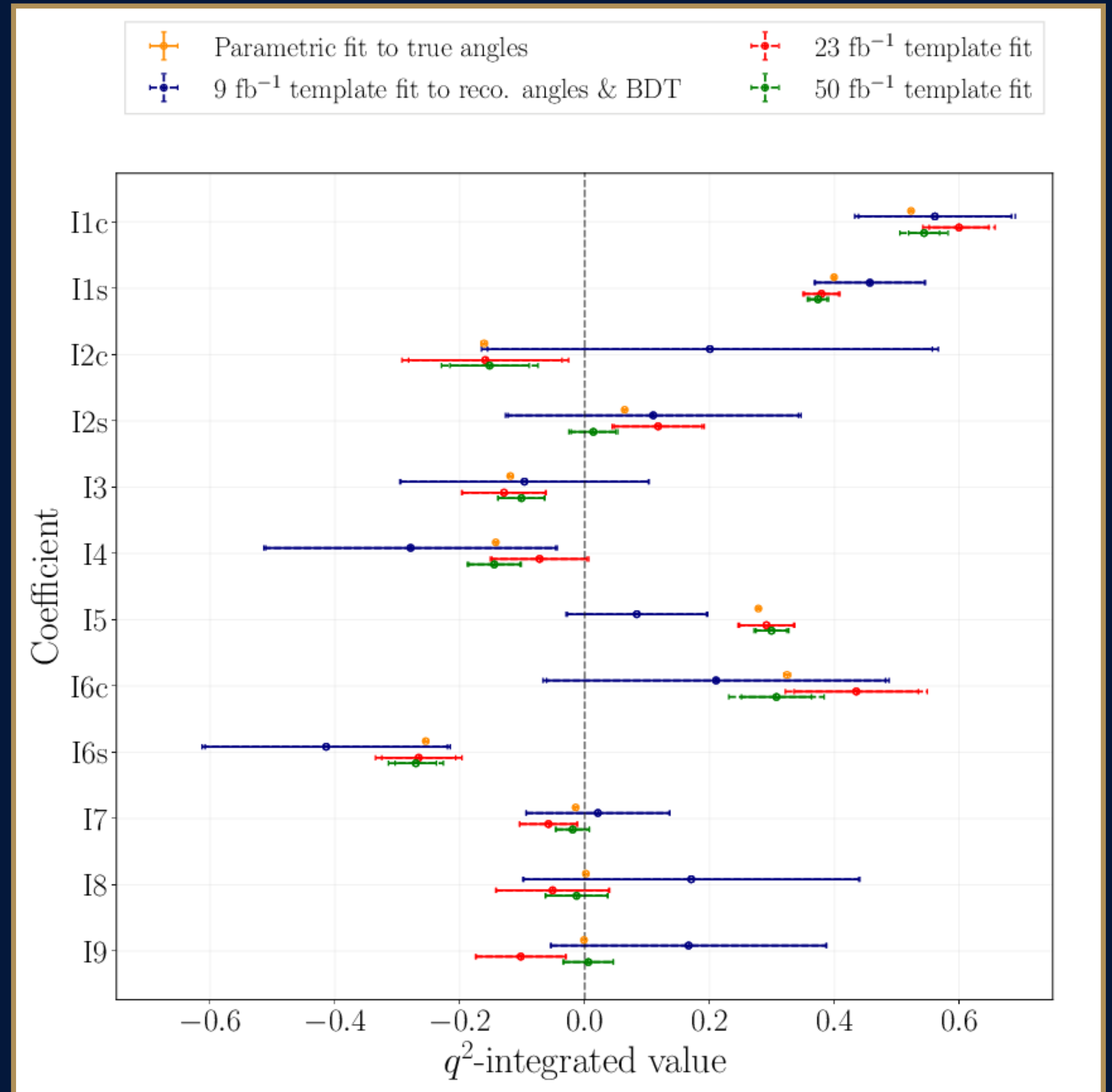
# ANGULAR ANALYSIS: ANGULAR COEFFICIENTS

▶ Expected performance of angular coefficient measurements for different dataset sizes:

▶  $9\text{fb}^{-1}$ : Run 1 + 2 (blue)

▶  $23\text{fb}^{-1}$ : Run 1 + 2 + 3 (red)

▶  $50\text{fb}^{-1}$ : Run 1 + 2 + 3 + 4 (green)



JHEP 11, (2019) 133

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## SUMMARY

- ▶ Measuring the 12  $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$  angular coefficients and  $\mathcal{R}(D^*)$ 
  - ▶ Expected precision of 7-8% on  $\mathcal{R}(D^*)$  (no systematics included)
  - ▶ First measurement of angular coefficients for  $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$
  
- ▶ Selection involves three BDTs
  - ▶ BDT cuts optimised simultaneously using normalisation fits to estimate signal yield
  
- ▶ Control studies to correct simulation for the largest backgrounds in the signal fit
  - ▶  $B \rightarrow D^{*-}D^0(X)$
  - ▶  $B \rightarrow D^{*-}D^+(X)$
  - ▶  $B \rightarrow D^{*-}D_s^+(X)$
  - ▶  $D_s^+ \rightarrow \pi^+\pi^-\pi^+(X)$
  
- ▶ Signal fit requires 12 angular templates for signal PDF
  - ▶ 3D + 3D fit in decay angles + discriminating variables



BACK UP SLIDES



# BDT TRAINING



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## USING BDTs TO REDUCE BACKGROUND

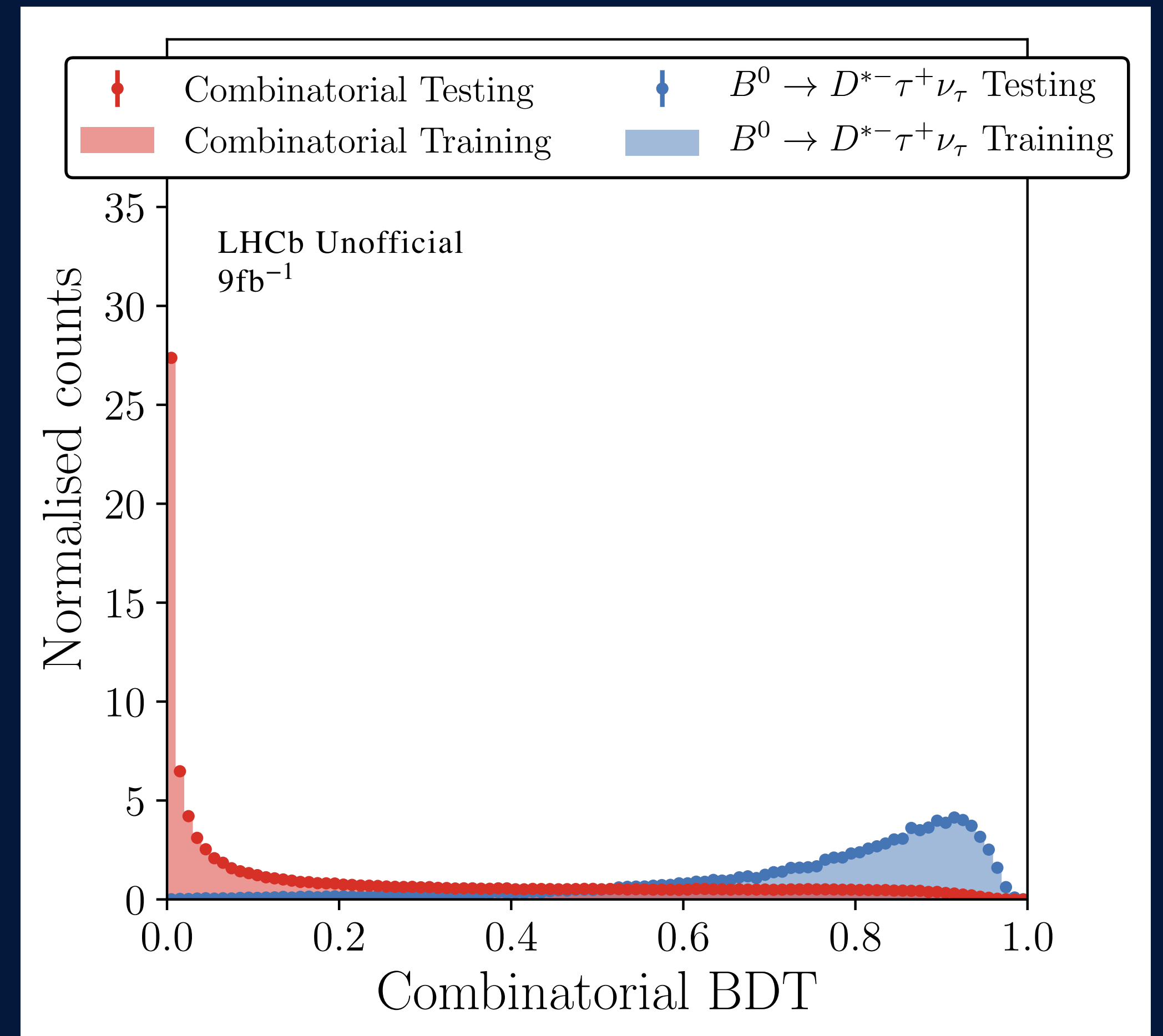
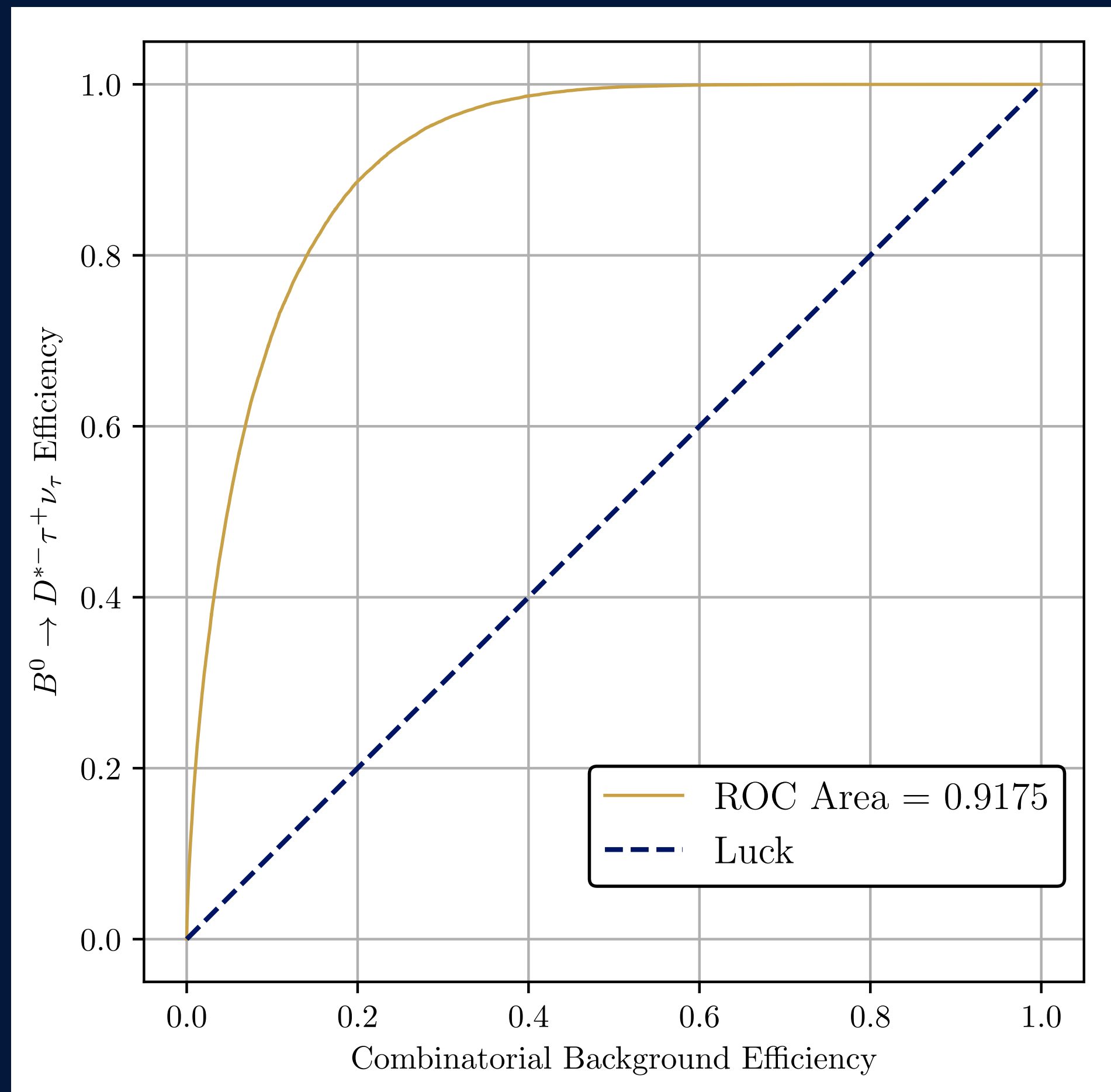
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- ▶ Use three BDTs to suppress different backgrounds or focus on different properties
- ▶ Train a BDT using these three BDTs as input variables for potential use in signal fit
- ▶ Trained with xGBoost in scikit learn package
  
- ▶ Combinatorial BDT
  - ▶ Signal MC - truth matched + preselection
  - ▶ WS data - preselection
  - ▶ Variables: Track and vertex quality, particle PT, etc.
  
- ▶ Tau BDT
  - ▶ Signal MC - truth matched + preselection
  - ▶  $B \rightarrow D^*D_s(X)$  MC - truth matched + preselection
  - ▶ Variables:  $\tau \rightarrow \pi^+\pi^-\pi^+$  information,  $B^0$  information
  
- ▶ Isolation BDT
  - ▶ Signal MC - truth matched + preselection
  - ▶  $B \rightarrow D^*D_s(X)$  MC - truth matched + preselection
  - ▶ Variables: charged and neutral isolation variables

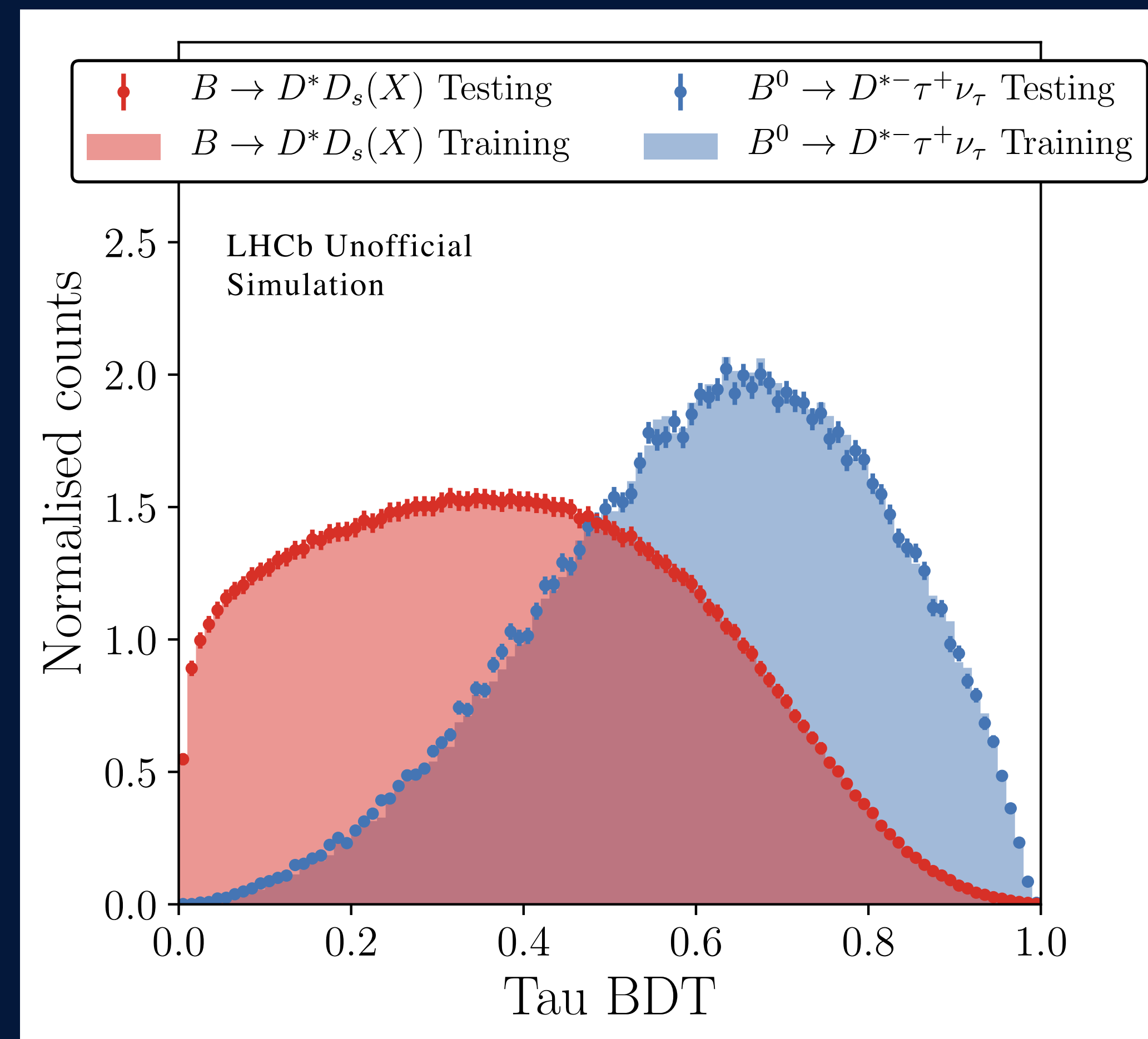
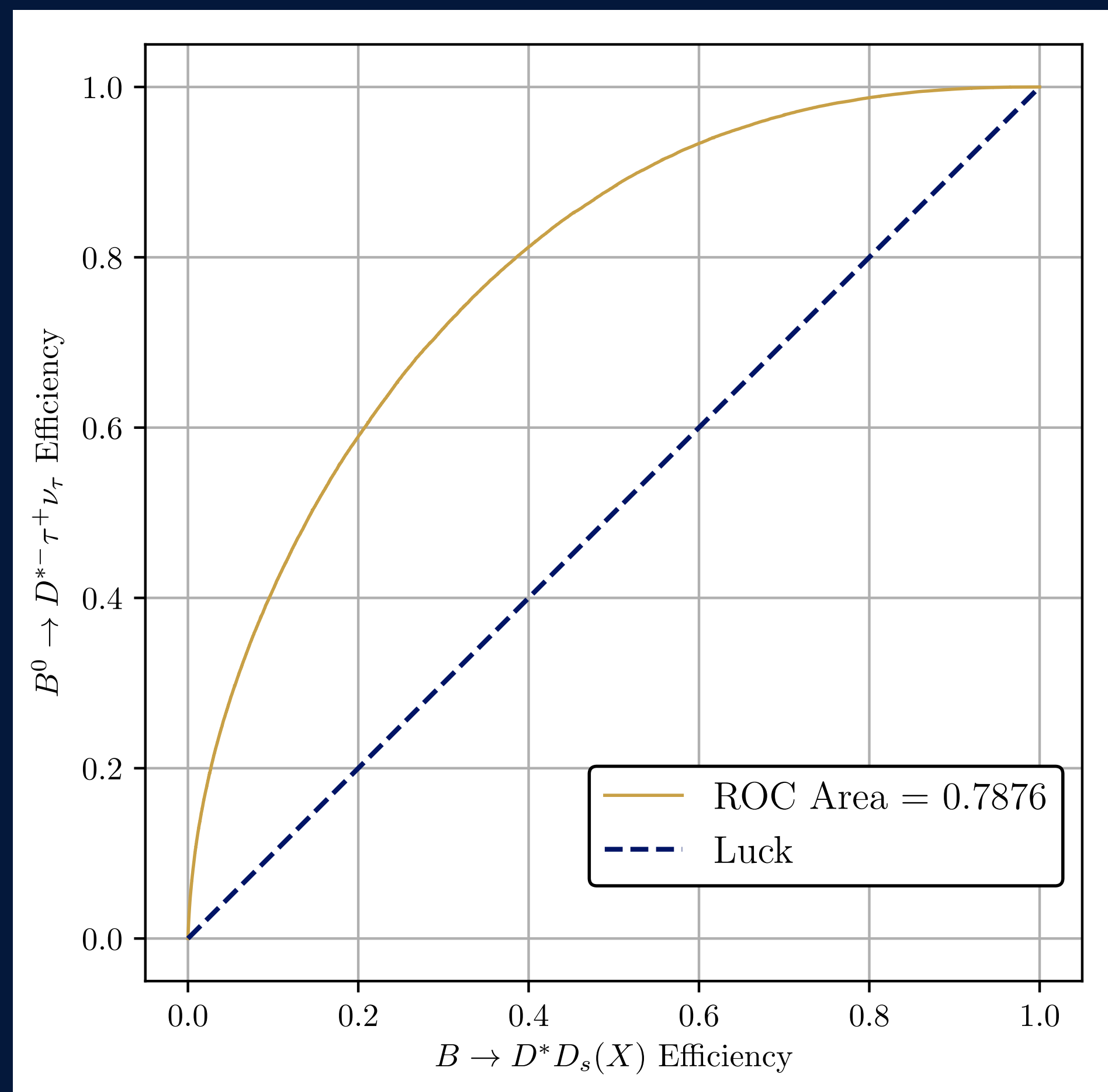
## SIGNAL SELECTION

Variable	Condition
Trigger	(B0_L0HadronDecision_TOS or B0_L0Global_TIS) and (B0_Hlt1TrackMVADecision_TOS or B0_Hlt1TwoTrackMVADecision_TOS) and (B0_Hlt2Topo2BodyDecision_TOS or B0_Hlt2Topo3BodyDecision_TOS or B0_Hlt2Topo4BodyDecision_TOS)
PV( $\tau^+$ )	= PV( $D^0$ )
$V_z(\tau^+) - V_z(\text{PV})/\text{error}$	> 10.0
$m(\pi^+\pi^-\pi^+)$	< 1600 MeV/c <sup>2</sup>
$m(D^{*-}\pi^+\pi^-\pi^+)$	< 4700.0 MeV/c <sup>2</sup>
$m(D^* - D^0)$	∈ [140.0, 160.0] MeV/c <sup>2</sup>
$m(D^0)$	∈ $m(D^0)_{\text{PDG}} \pm 40.0$ MeV/c <sup>2</sup>
$\tau$ flight distance significance	∈ [3.0, 25.0]

## COMBINATORIAL BDT - TRAINING

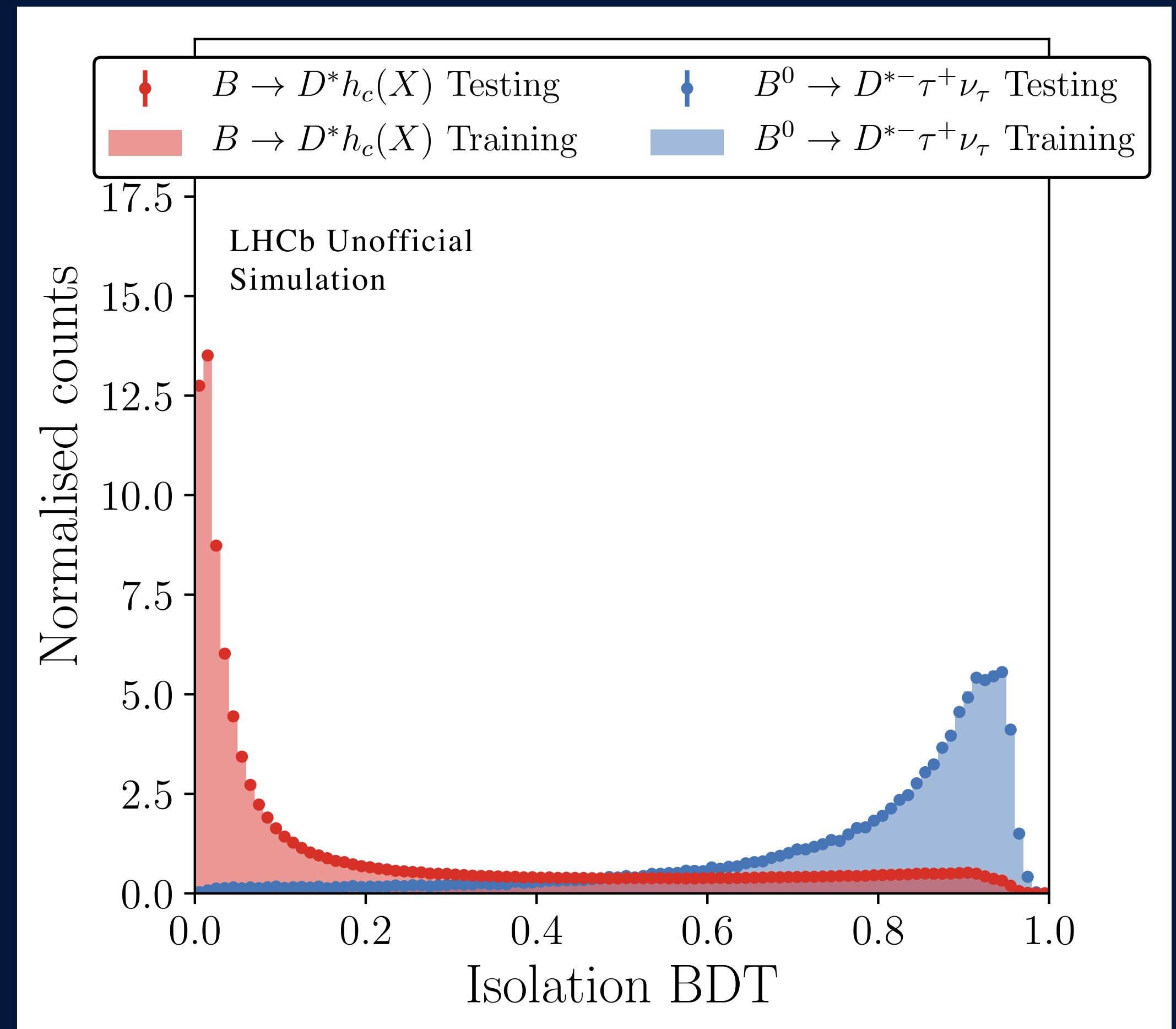
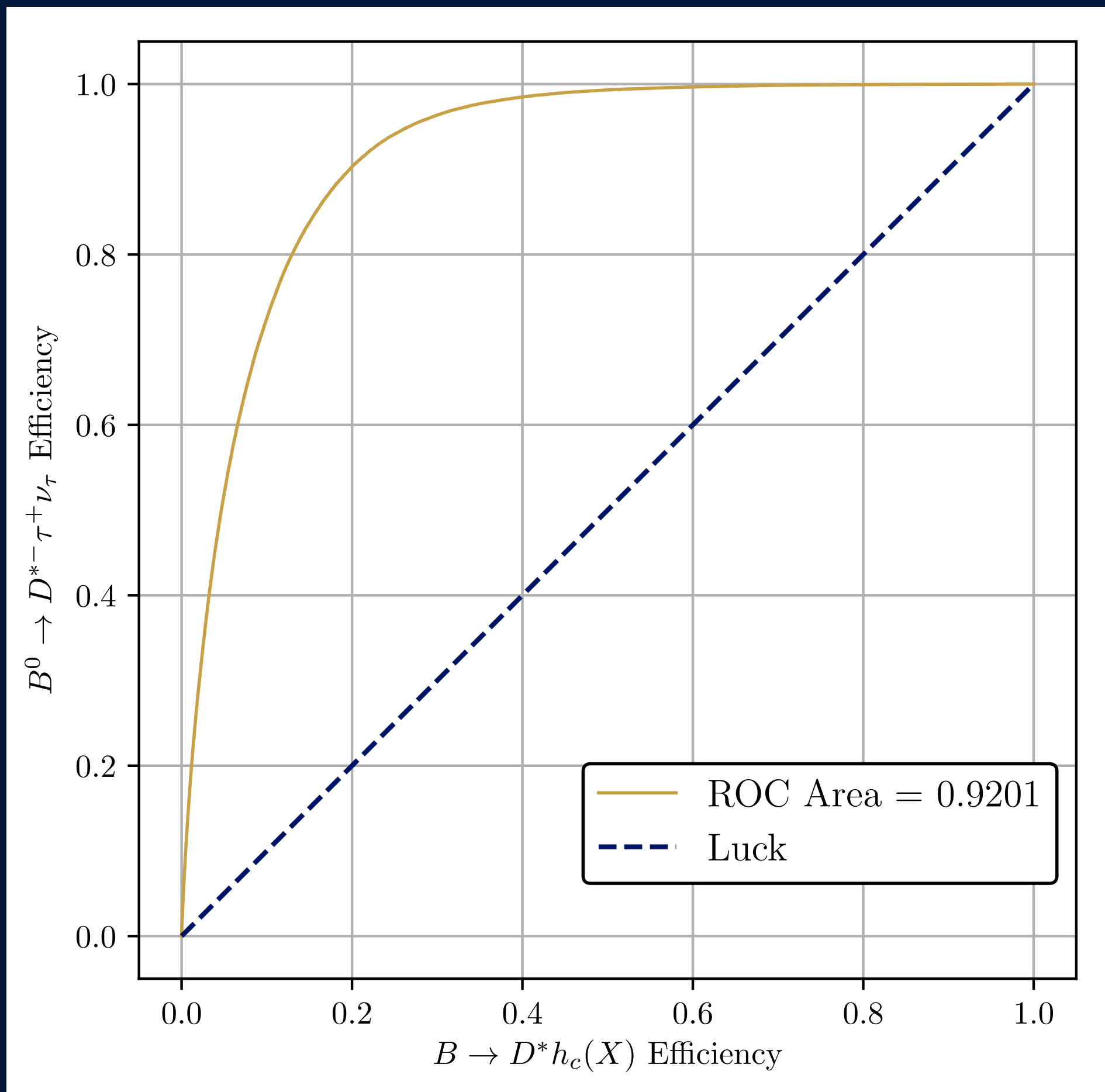


## TAU BDT - TRAINING





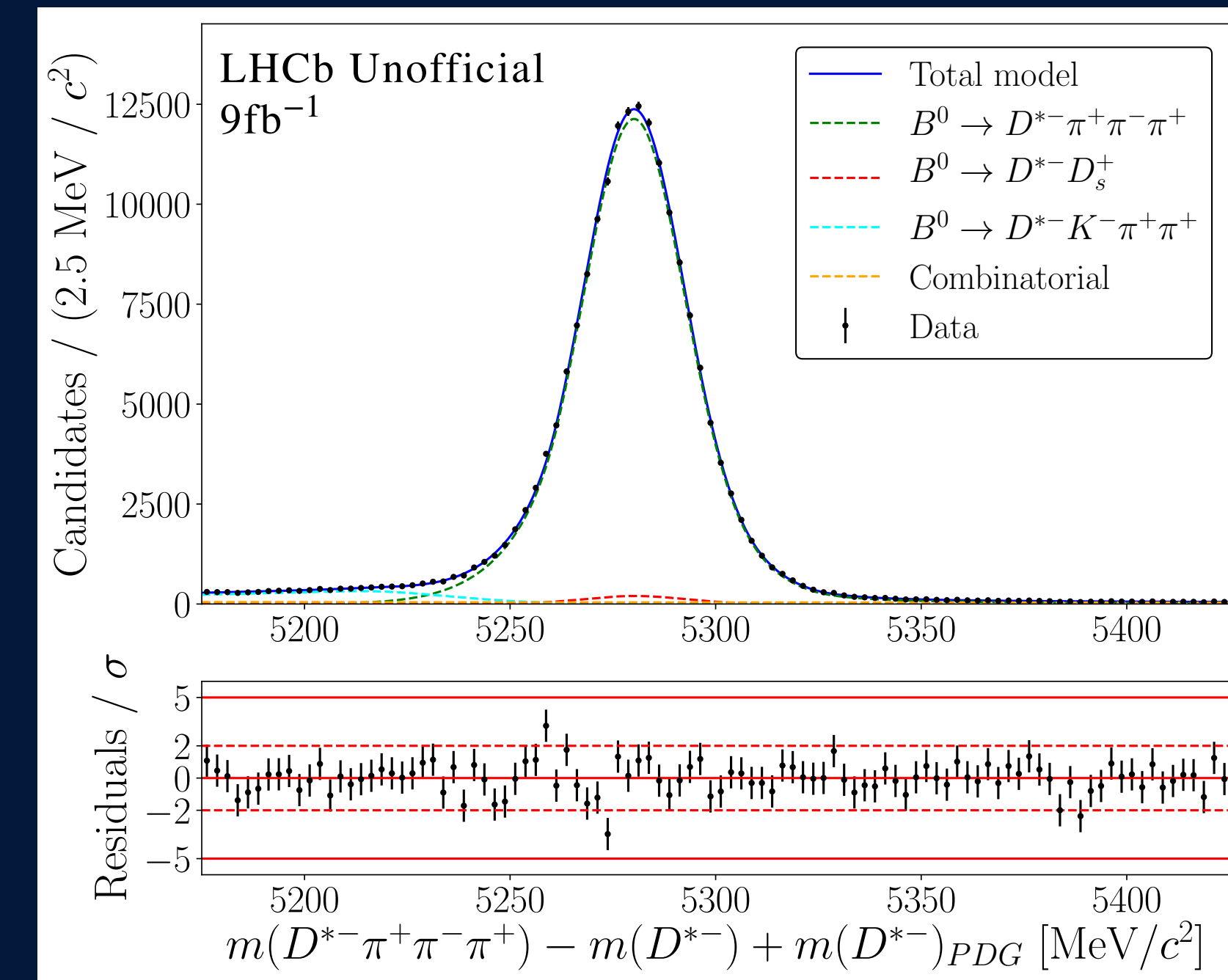
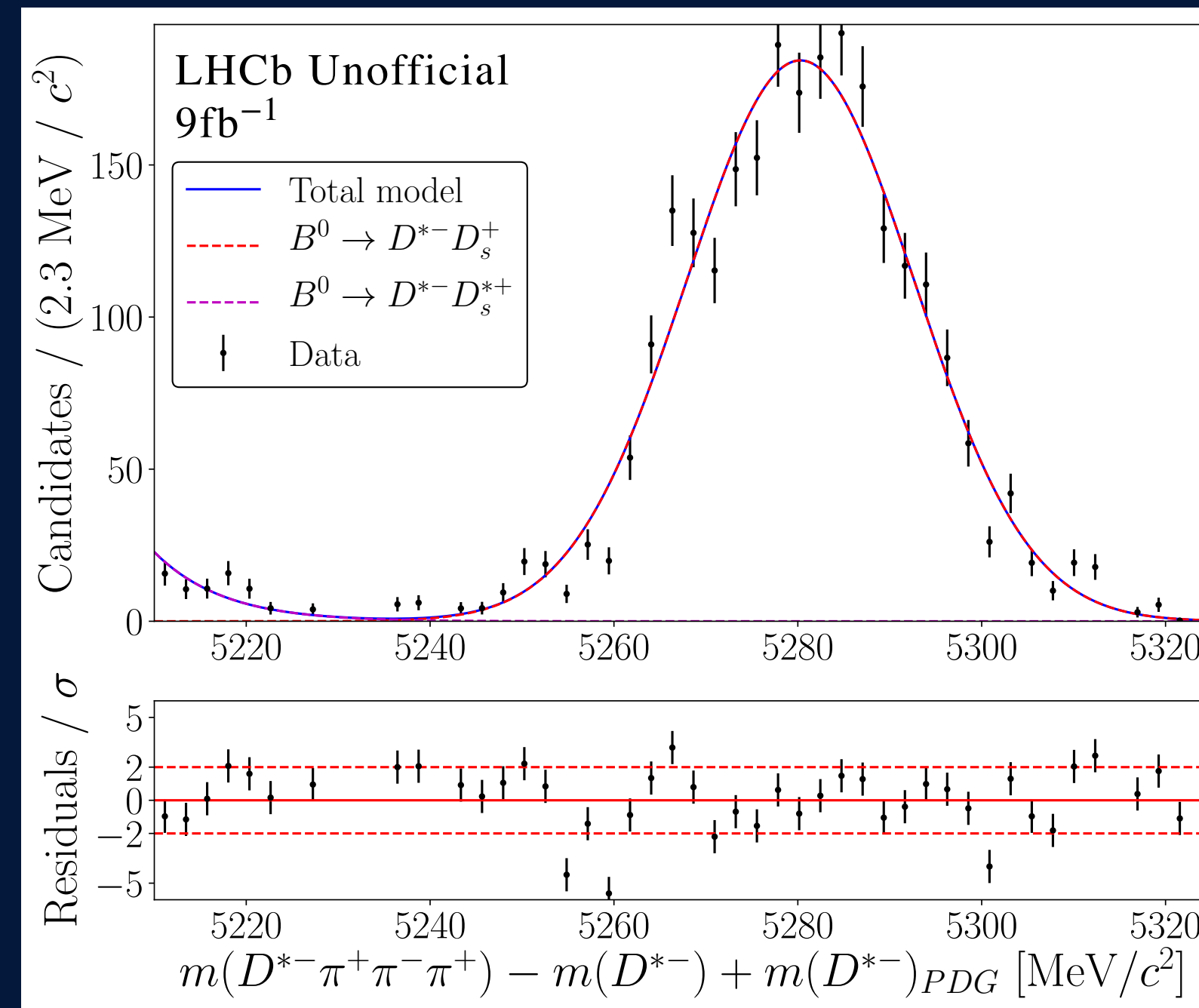
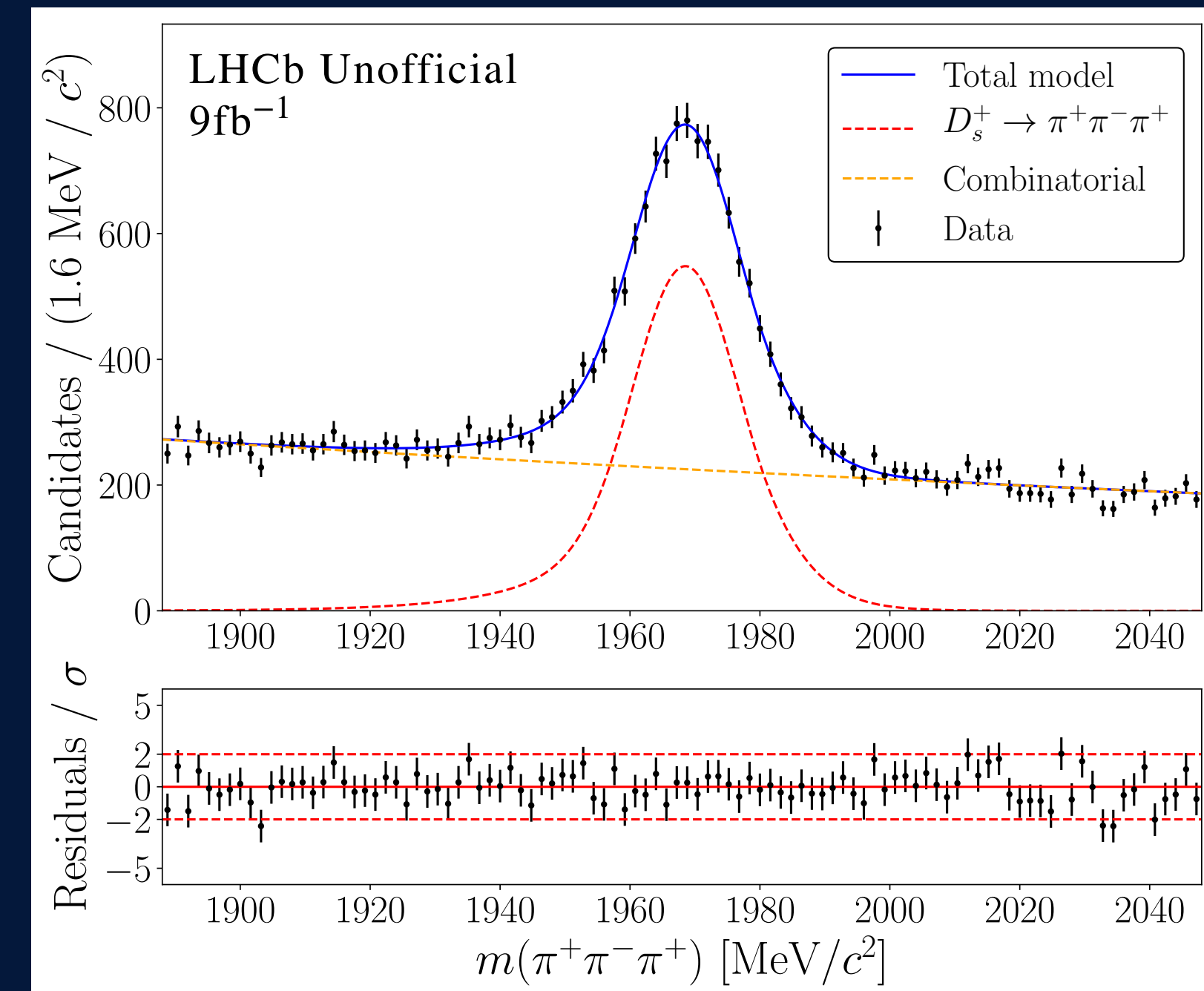
## ISOLATION BDT - TRAINING



A particle physics diagram showing a particle interaction. A wavy line at the top represents an incoming particle, which splits into two paths. One path is a solid line that leads to a dashed line on the left. The other path is a solid line that leads to a wavy line, which then splits into two paths. One path is a solid line that leads to a series of circles, and the other path is a solid line that leads to another series of circles. The circles are arranged in a way that suggests a particle decay or a specific interaction process.

SELECTION  
OPTIMISATION AND  
NORMALISATION FITS

# FULL $m(D^{*-}\pi^+\pi^-\pi^+)$ FIT - TIGHT CUTS

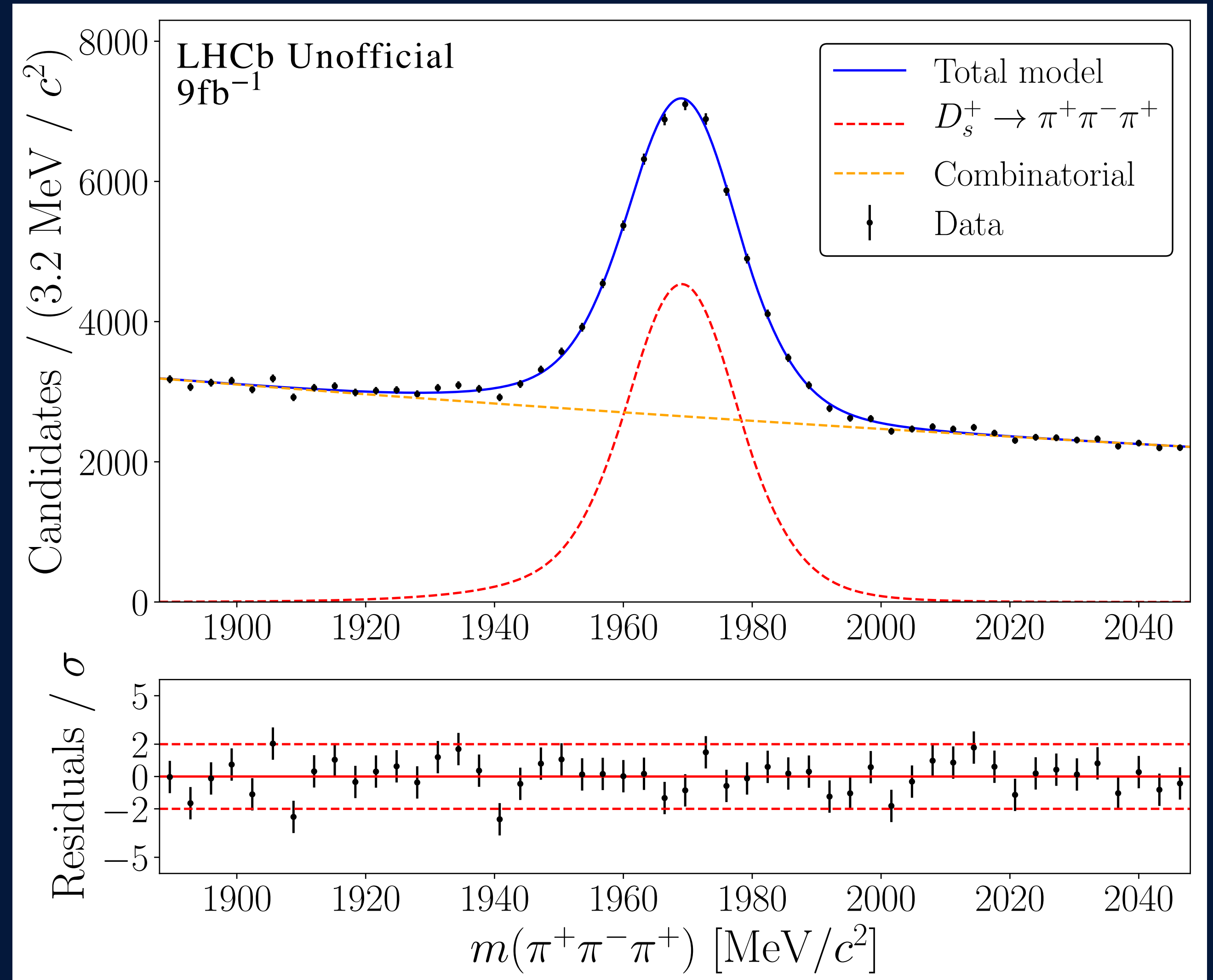


## ▶ Three normalisation fits

- ▶  $m(\pi^+\pi^-\pi^+)$  - measure  $D_s^+ \rightarrow \pi^+\pi^-\pi^+$  peak - calculate  $_s$ Weights
- ▶  $m(D^{*-}\pi^+\pi^-\pi^+)$  with  $_s$ Weights - measure  $B^0 \rightarrow D^{*-}D_s$  yield - can compare  $_s$ Weighted data and MC
- ▶  $m(D^{*-}\pi^+\pi^-\pi^+)$  - measure  $B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+$  yield
- ▶ Calculate estimate of optimised signal yield

# $m(\pi^+\pi^-\pi^+)$ FIT

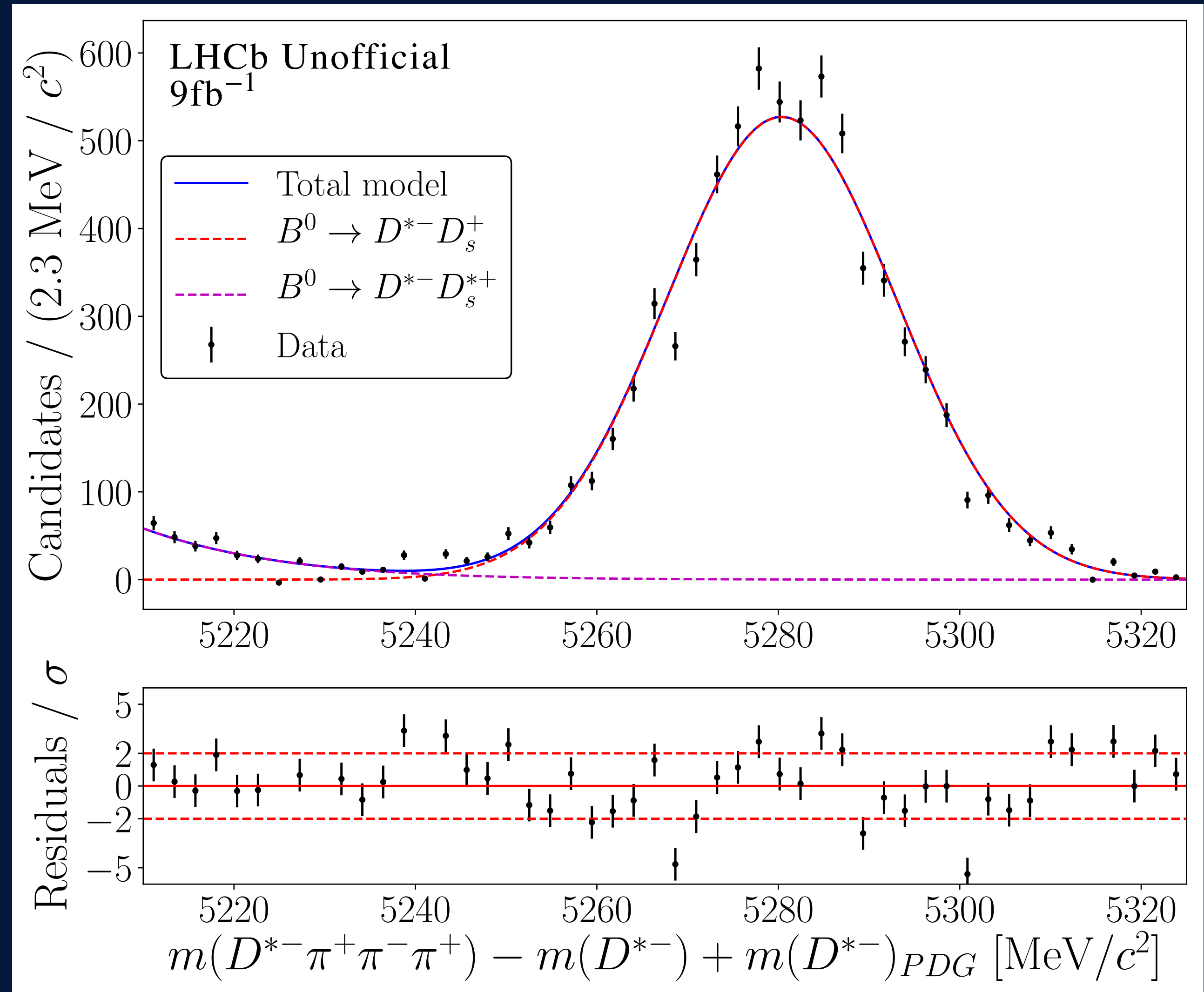
- ▶ Fit  $m(\pi^+\pi^-\pi^+)$  around mass of  $D_s$ 
  - ▶ Measure  $D_s^+ \rightarrow \pi^+\pi^-\pi^+$  peak
  - ▶ Calculate sWeights





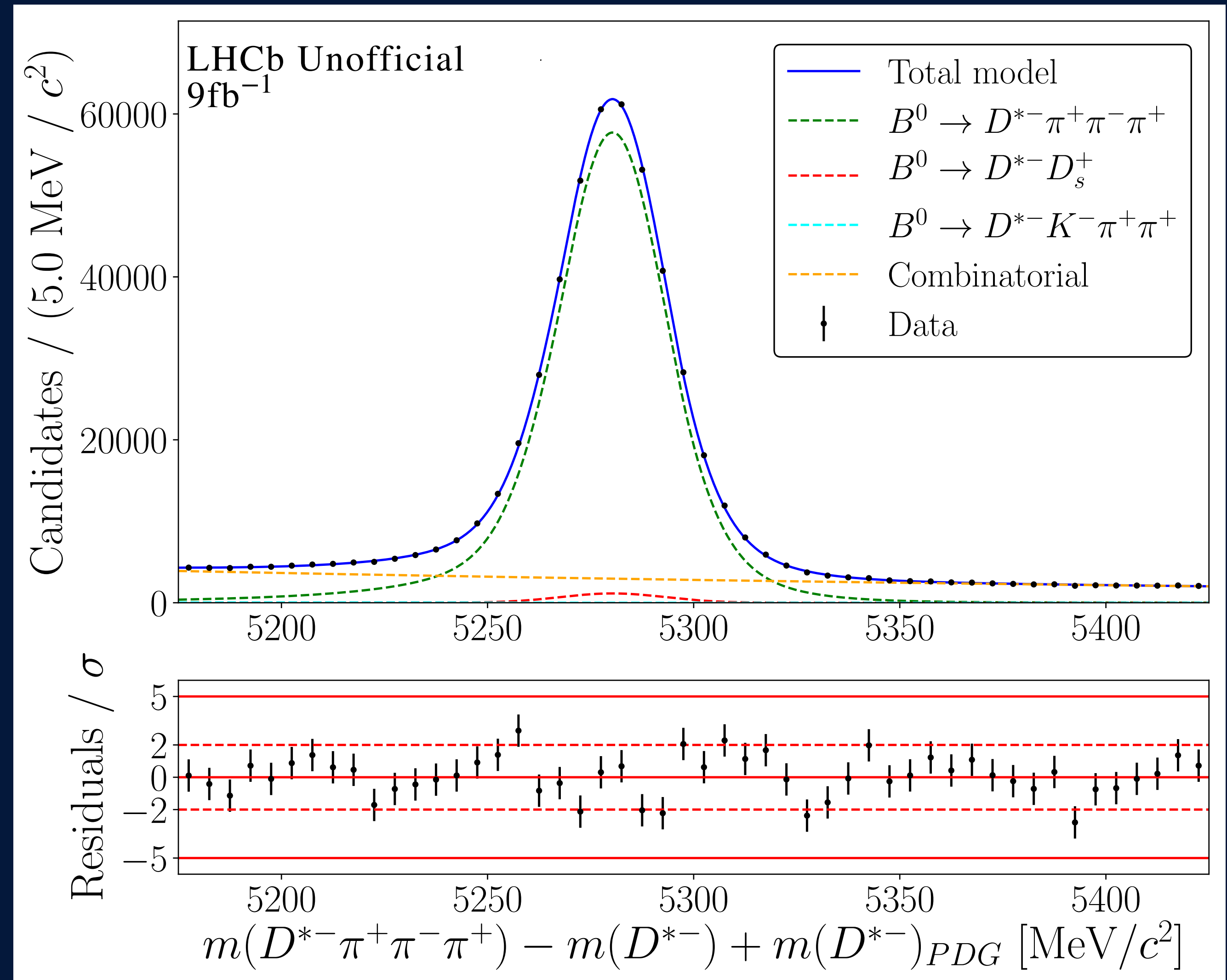
# SWEIGHTED $m(D^{*-}\pi^+\pi^-\pi^+)$ FIT

- ▶ Fit  $m(D^{*-}\pi^+\pi^-\pi^+)$  with  $m(\pi^+\pi^-\pi^+)$  around mass of  $D_s$
- ▶ Use sWeights so we only have  $B^0 \rightarrow D^{*-}D_s^+(X)$
- ▶ Measure pure  $B^0 \rightarrow D^{*-}D_s^+$  yield



# FULL $m(D^{*-}\pi^+\pi^-\pi^+)$ FIT

- ▶ Fit  $m(D^{*-}\pi^+\pi^-\pi^+)$  with  $B^0 \rightarrow D^{*-}D_s^+$  yield fixed
- ▶ No  $m(\pi^+\pi^-\pi^+)$  constraints
- ▶ No sWeights
- ▶ Measure  $B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+$  yield
- ▶ Optimisation loop then runs





A Feynman diagram illustrating a B meson decay. The B meson (represented by a wavy line) decays into a D\* meson (represented by a wavy line) and a lepton (represented by a straight line). The D\* meson then decays into a D meson (represented by a dashed line) and a lepton (represented by a straight line). The D meson further decays into a lepton (represented by a straight line) and a neutrino (represented by a straight line). The lepton from the D\* decay and the lepton from the D decay are shown as a pair of leptons (represented by straight lines) with a wavy line between them, indicating a lepton-lepton interaction. The neutrino from the D decay is shown as a straight line with a wavy line between it and the lepton from the D decay, indicating a neutrino-lepton interaction.

# REMOVING FAKE $D^*$

## SIGNAL SELECTION

Variable	Condition
Trigger	(B0_L0HadronDecision_TOS or B0_L0Global_TIS) and (B0_Hlt1TrackMVADecision_TOS or B0_Hlt1TwoTrackMVADecision_TOS) and (B0_Hlt2Topo2BodyDecision_TOS or B0_Hlt2Topo3BodyDecision_TOS or B0_Hlt2Topo4BodyDecision_TOS)
PV( $\tau^+$ )	= PV( $D^0$ )
$V_z(\tau^+) - V_z(\text{PV})/\text{error}$	> 10.0
$m(\pi^+\pi^-\pi^+)$	< 1600 MeV/ $c^2$
$m(D^{*-}\pi^+\pi^-\pi^+)$	< 4700.0 MeV/ $c^2$
$m(D^* - D^0)$	$\in [140.0, 160.0]$ MeV/ $c^2$
$m(D^0)$	$\in m(D^0)_{\text{PDG}} \pm 40.0$ MeV/ $c^2$
$\tau$ flight distance significance	> 3.0
Combinatorial BDT	> 0.6690
$\tau$ BDT	> 0.4816
Isolation BDT	> 0.8296

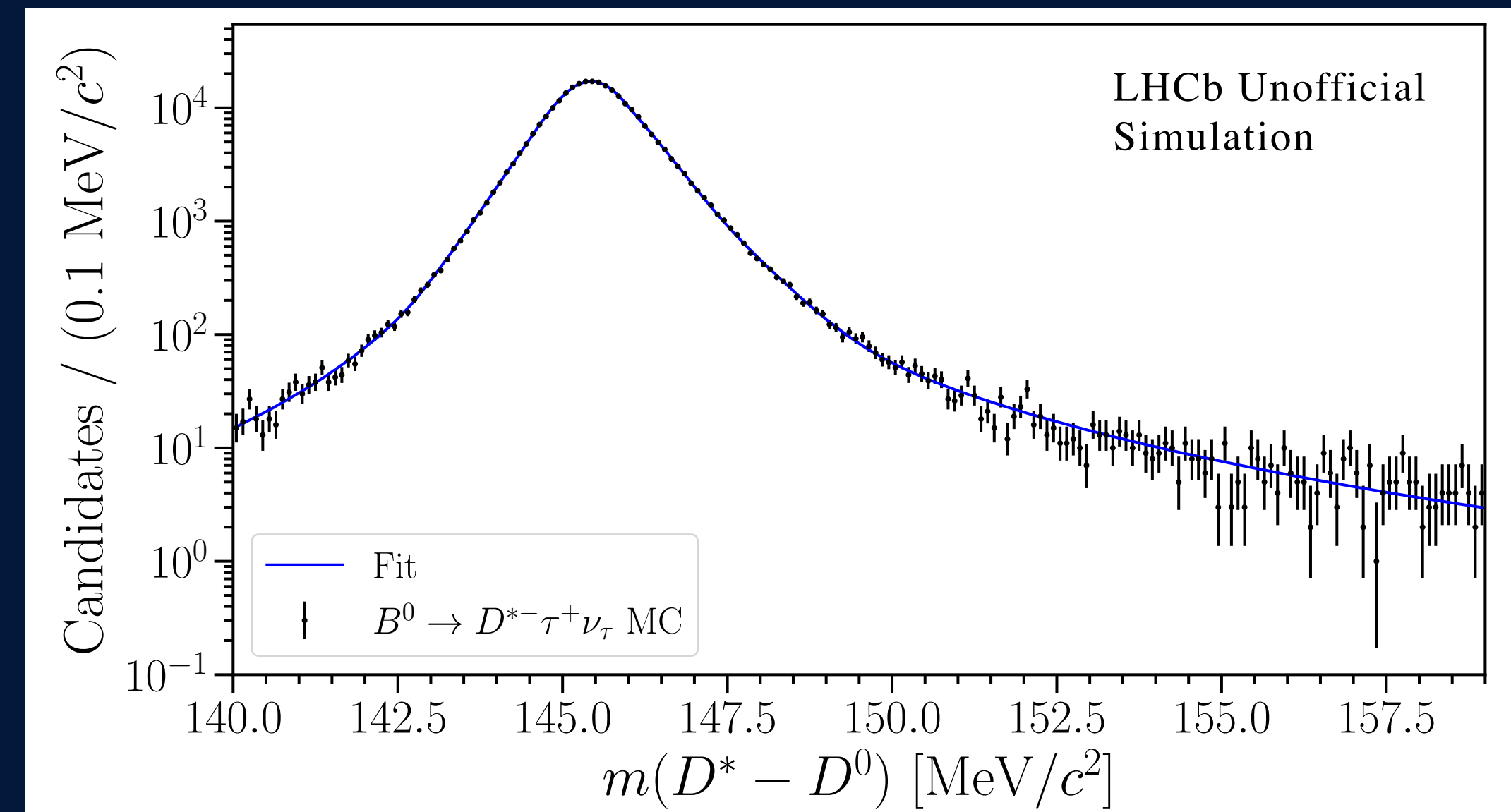
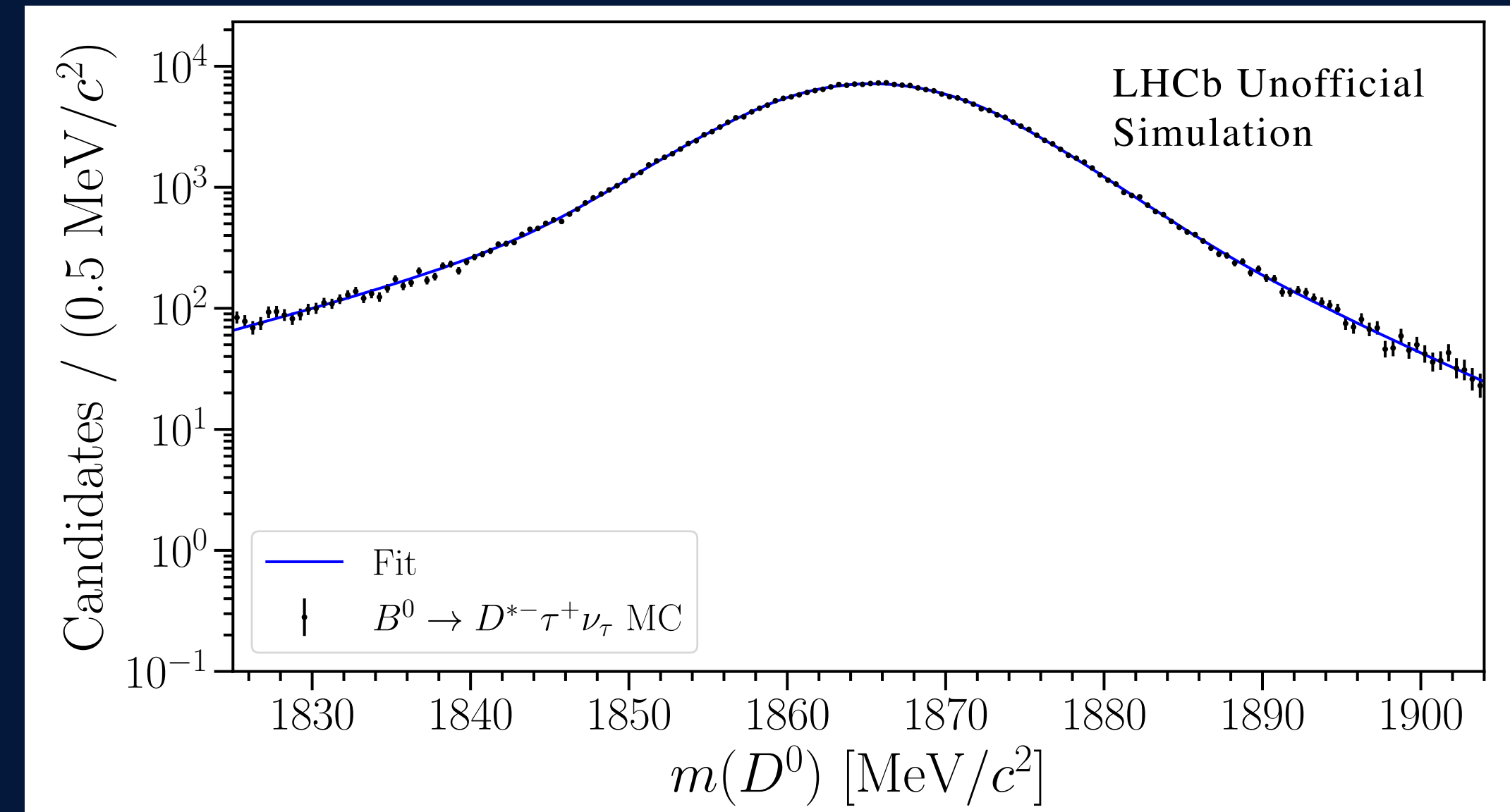
$D_s \rightarrow \pi^+ \pi^- \pi^+(X)$  PID SELECTION

Variable		Condition
$\pi^+$	PIDK	$< 4$
	$p$	$\in [3000, 100,000] \text{ MeV}/c$
	$p_T$	$\in [300, 10,000] \text{ MeV}/c$
$\pi^-$	PIDK	$< 1$
	$p$	$\in [3000, 100,000] \text{ MeV}/c$
	$p_T$	$\in [300, 10,000] \text{ MeV}/c$



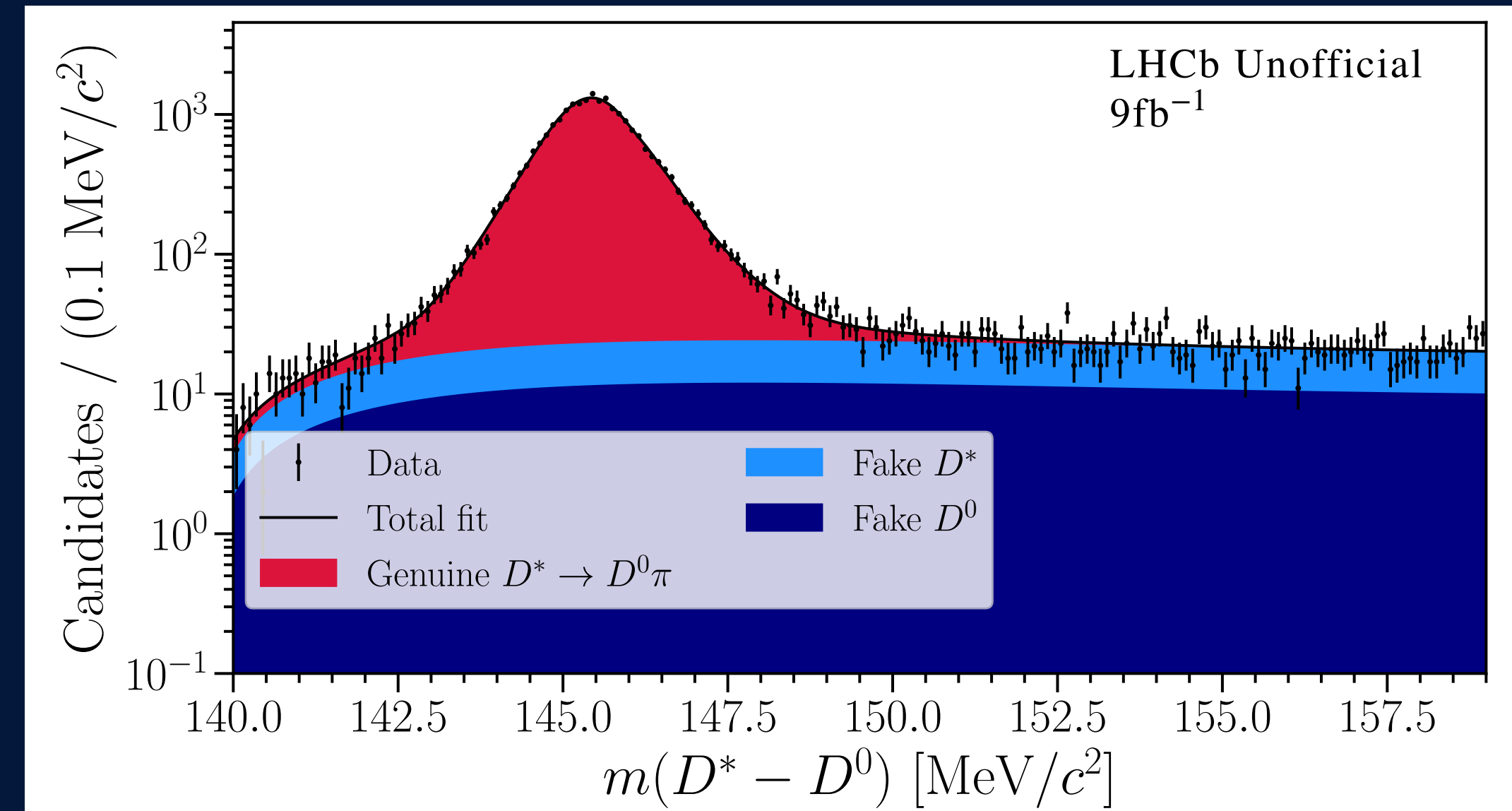
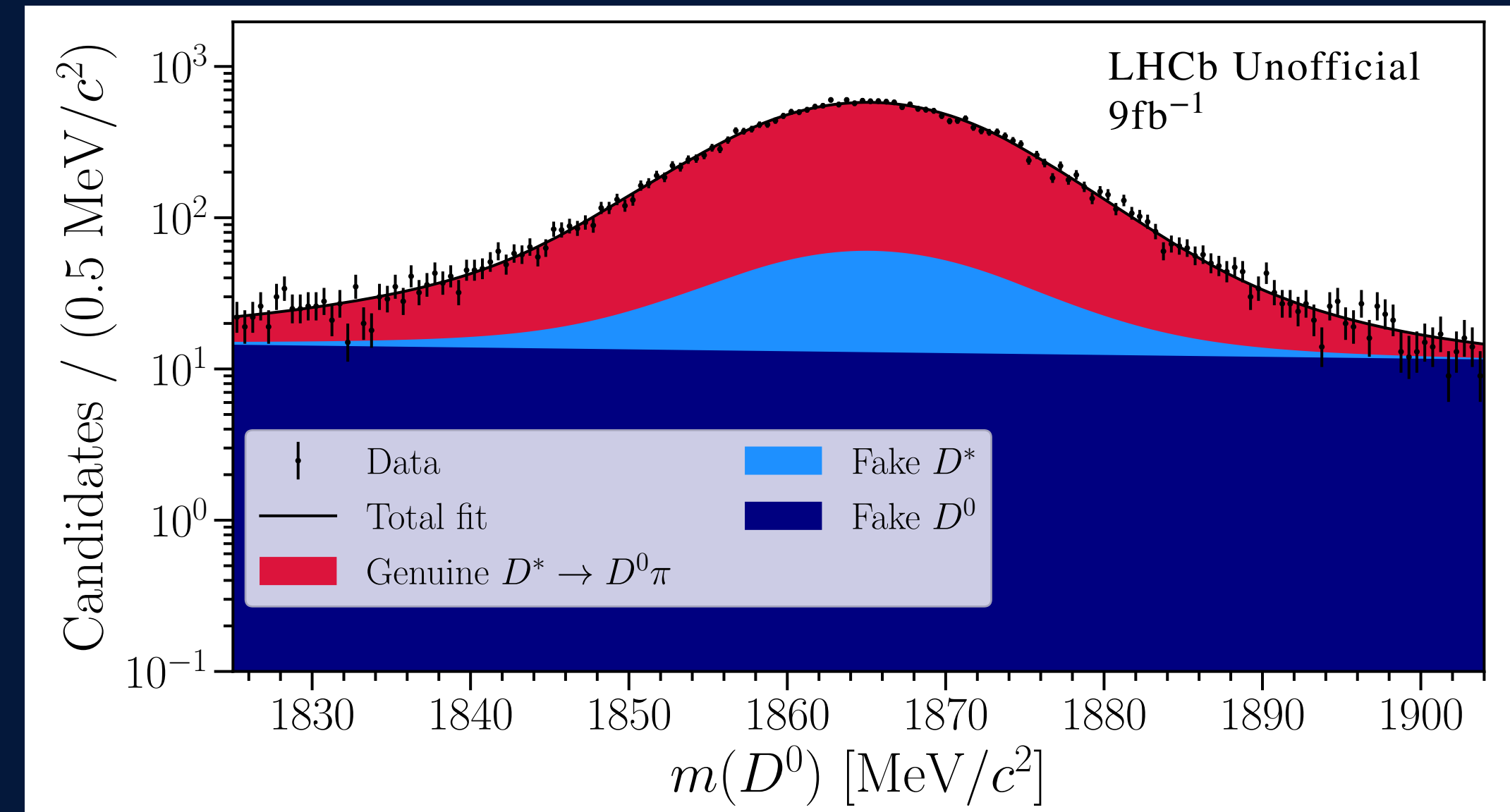
## MEASURING FAKE $D^*$ RATE - SIGNAL PDF

- ▶ After full selection the  $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$  dataset still contains some fake  $D^*$  and  $D^0$  combinatorial background
- ▶ Measure this rate with 2D fit to  $m(D^0)$  and  $m(D^* - D^0)$  and use  $s$ Weights to subtract it
- ▶ Fit signal MC to measure PDF parameters for the true  $D^*$  component
  - ▶ Gaussian constrain tail parameters and internal PDF fractions
  - ▶ Means and widths vary freely
  - ▶ Signal true  $D^*$  PDF used to model all sources of true  $D^*$  in data



## MEASURING FAKE $D^*$ RATE - DATA FIT

- ▶ True  $D^*$  - peaks in both
- ▶ Fake  $D^*$  - peaks in  $m(D^0)$ , not in  $m(D^* - D^0)$
- ▶ Fake  $D^0$  - does not peak in either
- ▶ Use floating yields for each of these components
- ▶ Can remove combinatorial background that rectangular  $m(D^0)$ , and  $m(D^* - D^0)$  cuts wouldn't
- ▶ Still other sources of combinatorial background
  - ▶ True  $D^*$  + fake  $3\pi$  combinatorial - modelled with inclusive MC
  - ▶ B1B2 background - modelled with WS data after sWeight fit is performed on WS data





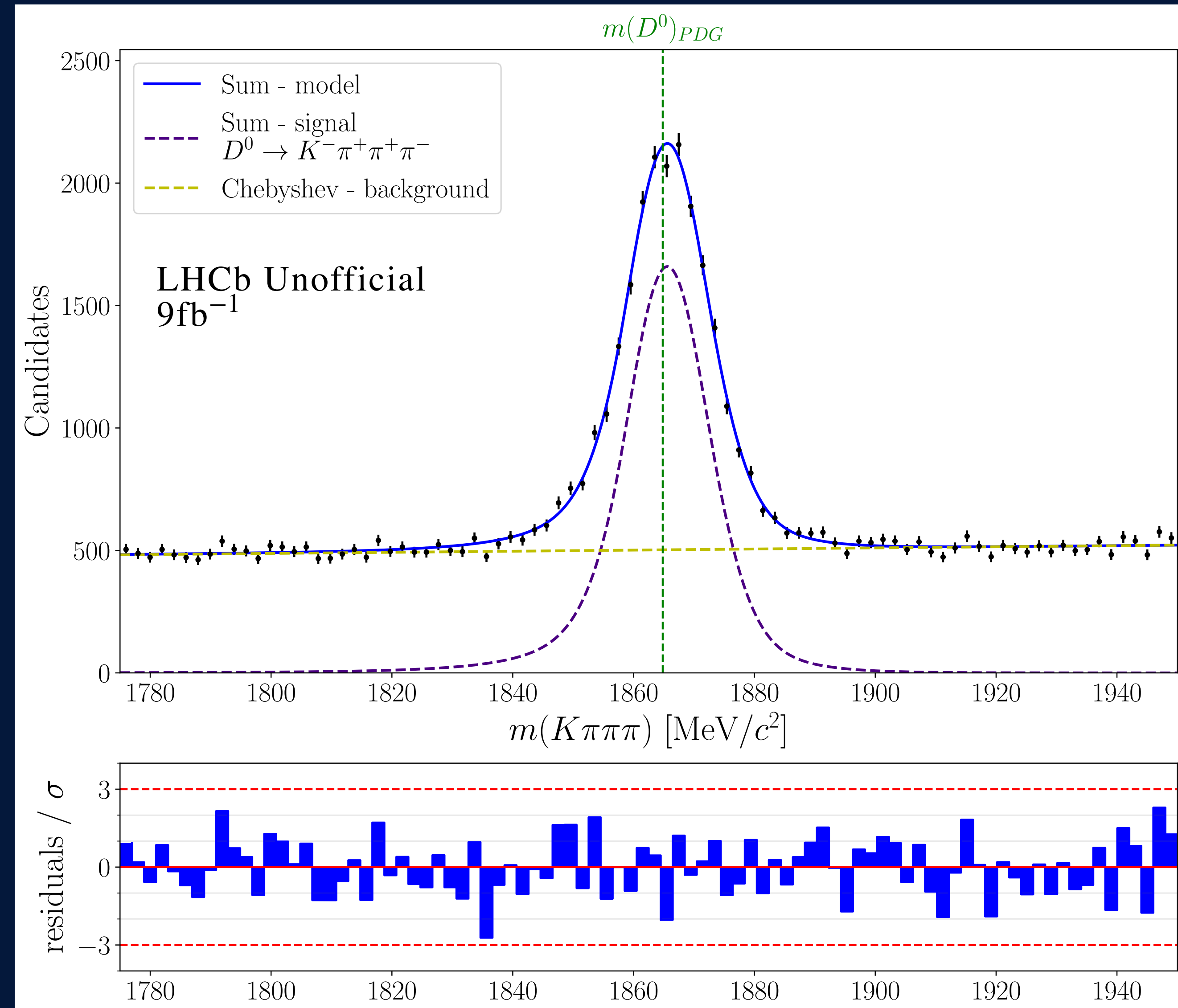
# CONTROL STUDIES

## CONTROL STUDIES

- ▶ Several control studies
  - ▶  $B \rightarrow D^{*-}D^0(X)$  : Weights for data/MC agreement
    - ▶ Isolate  $B \rightarrow D^{*-}D^0(X)$  via  $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$  using  $s$ Weights
  - ▶  $B \rightarrow D^{*-}D^+(X)$  : Weights for data/MC agreement
    - ▶ Isolate  $B \rightarrow D^{*-}D^+(X)$  via  $D^+ \rightarrow K^-\pi^+\pi^+$  using  $s$ Weights
  - ▶  $B \rightarrow D^{*-}D_s(X)$  : Weights for data/MC agreement and for relative decay fractions
    - ▶ Isolate  $D_s \rightarrow \pi^+\pi^-\pi^+$  using  $s$ Weights
    - ▶ Fit  $m(D^{*-}D_s)$  to measure decay fractions
  - ▶  $D_s \rightarrow \pi^+\pi^-\pi^+(X)$  : Weights for relative decay fractions
    - ▶ Simultaneous fit in four variables to measure decay fractions
- ▶ Methodology aligned with the Run 1  $\mathcal{R}(D^*)$  measurement [PRL 120 \(2018\) 171802](#), [PRD 97 \(2018\) 072013](#)

## $B \rightarrow D^* D^0(X)$ CONTROL STUDY

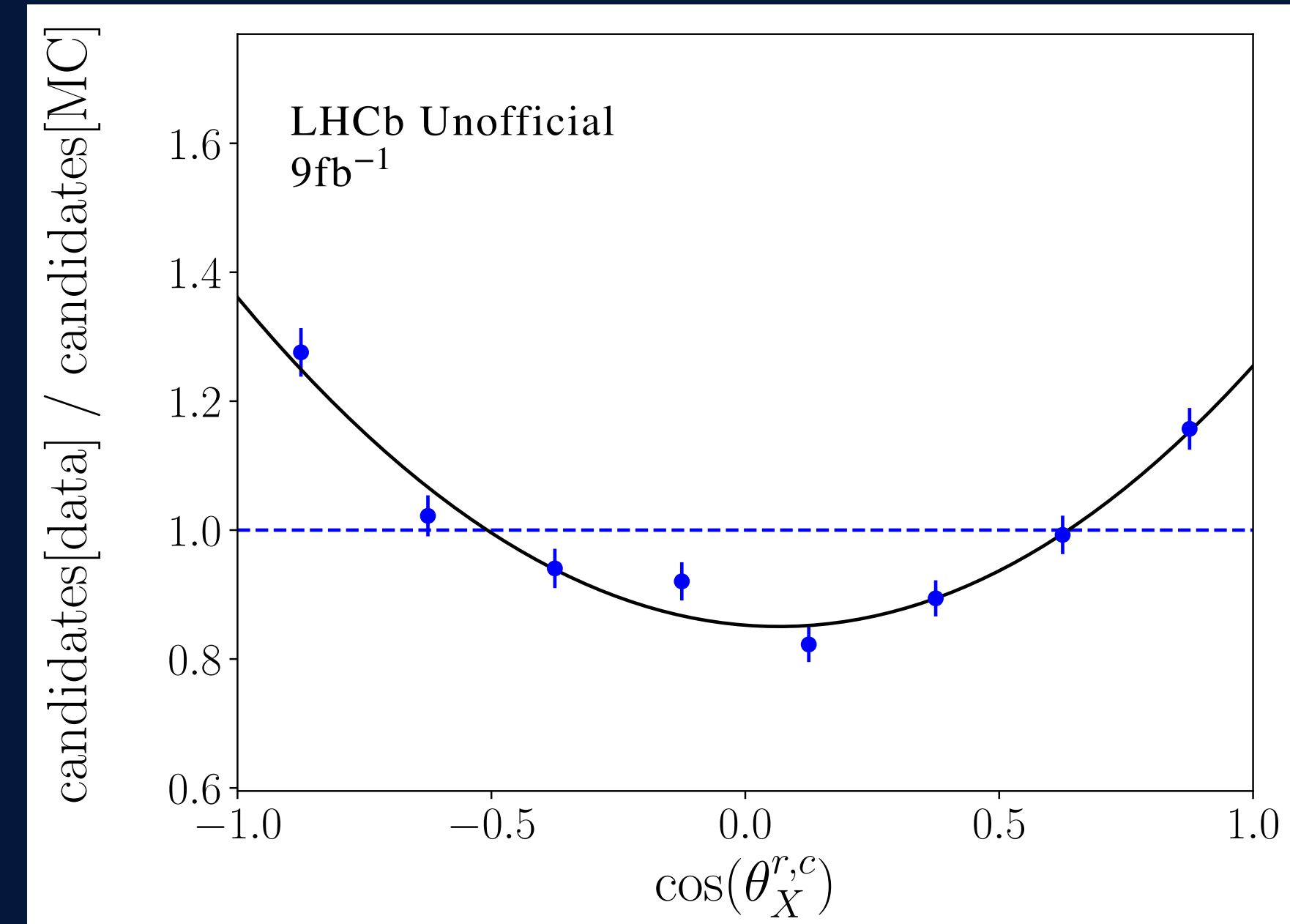
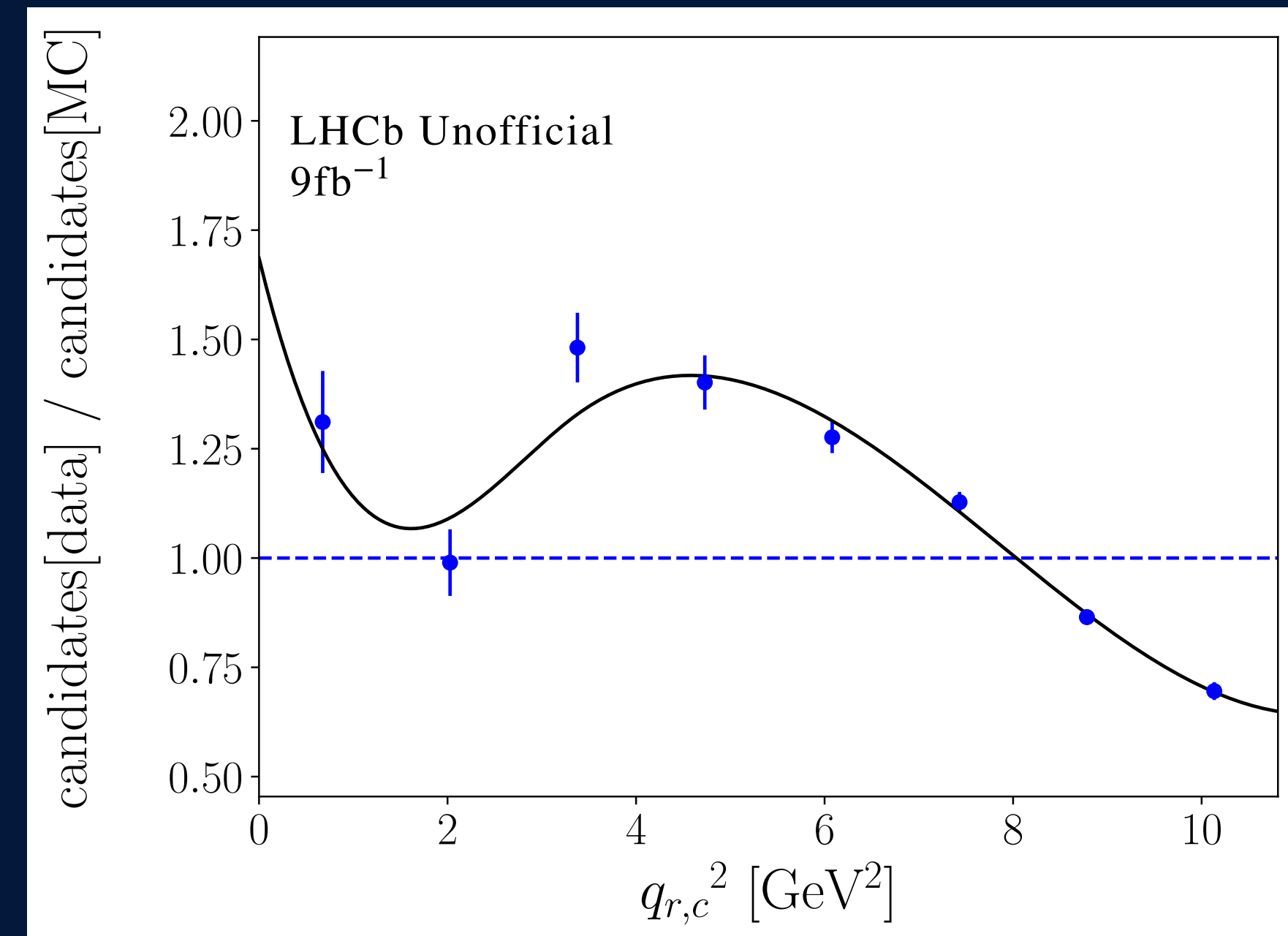
- ▶ Isolate  $B \rightarrow D^* D^0(X)$  via  $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ 
  - ▶  $m(K^- \pi^+ \pi^- \pi^+) \in m(D^0)_{\text{PDG}} \pm 200.0 \text{ MeV}/c^2$
- ▶ Fit  $m(K^- \pi^+ \pi^- \pi^+)$  in MC for shape
- ▶ Fit  $m(K^- \pi^+ \pi^- \pi^+)$  in data to measure peak
- ▶ sWeight  $m(K^- \pi^+ \pi^- \pi^+)$  peak to obtain pure  $B \rightarrow D^* D^0(X)$
- ▶ Perform data/MC reweighting to correct  $B \rightarrow D^* D^0(X)$  MC



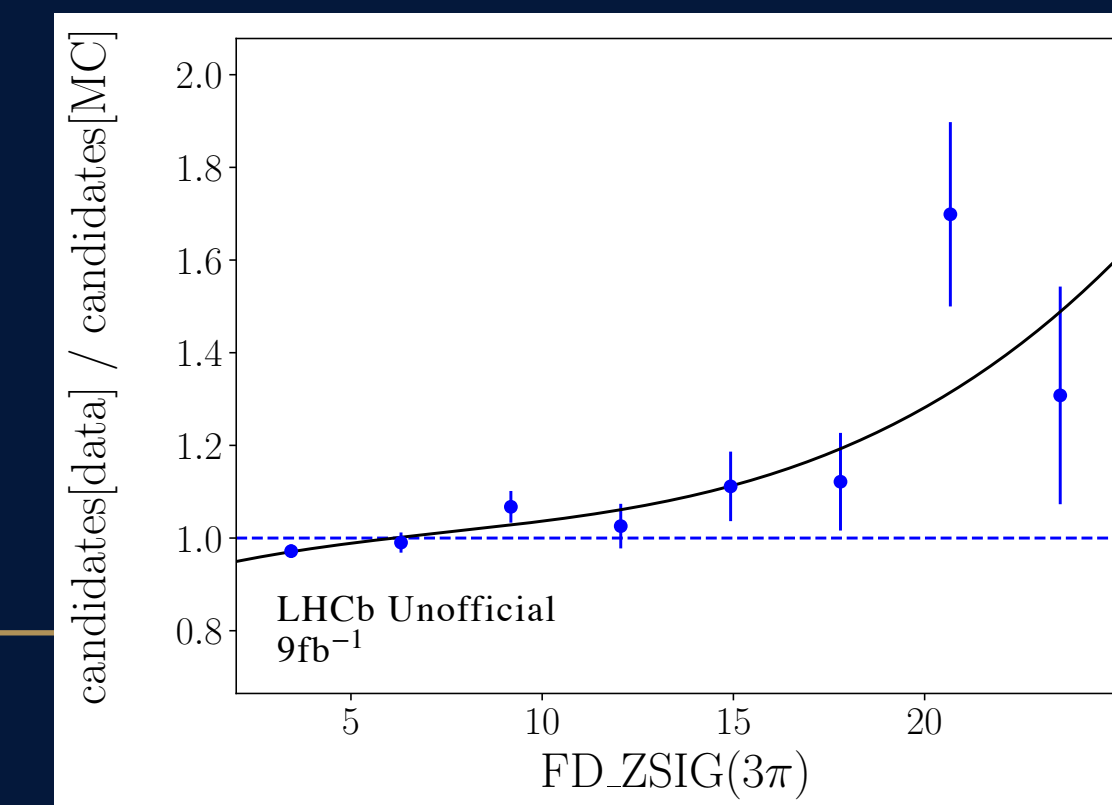
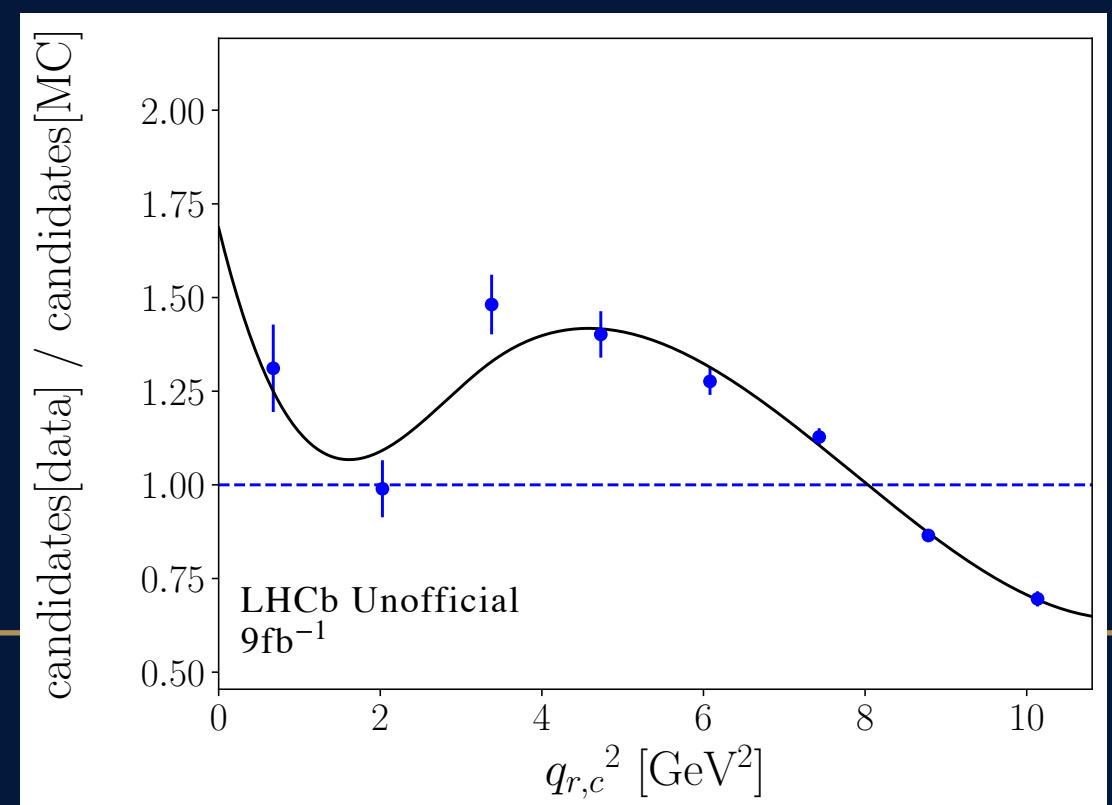
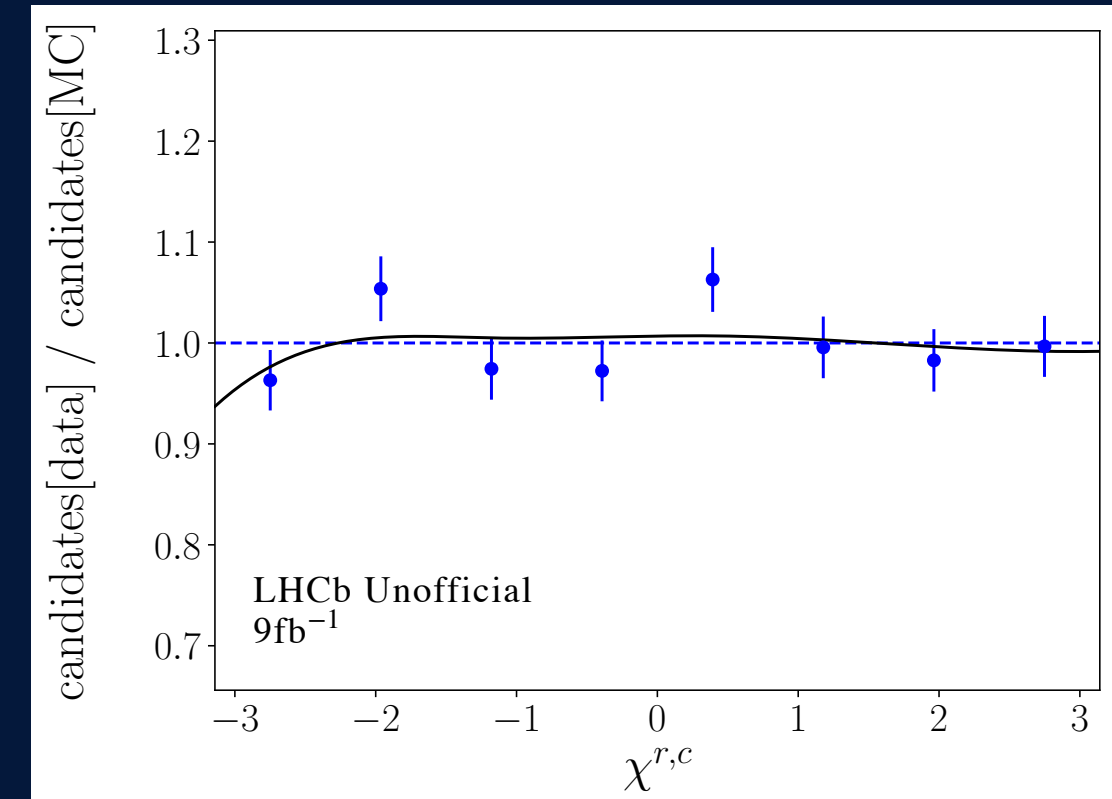
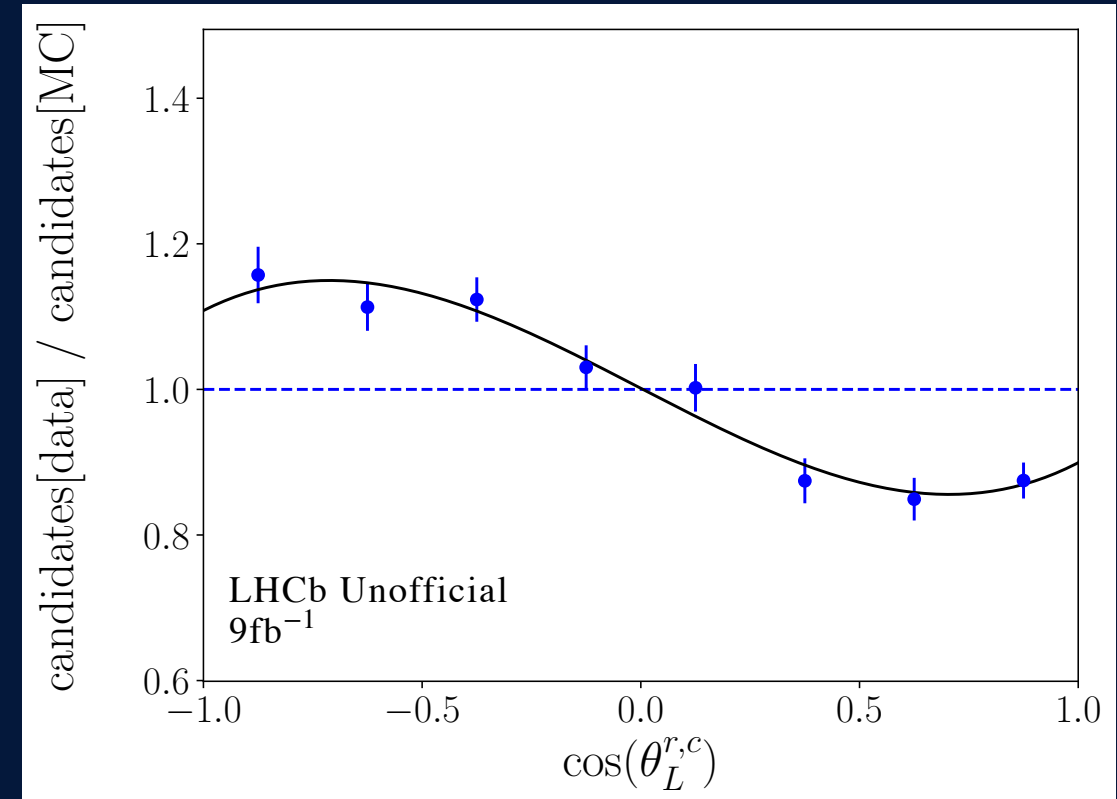
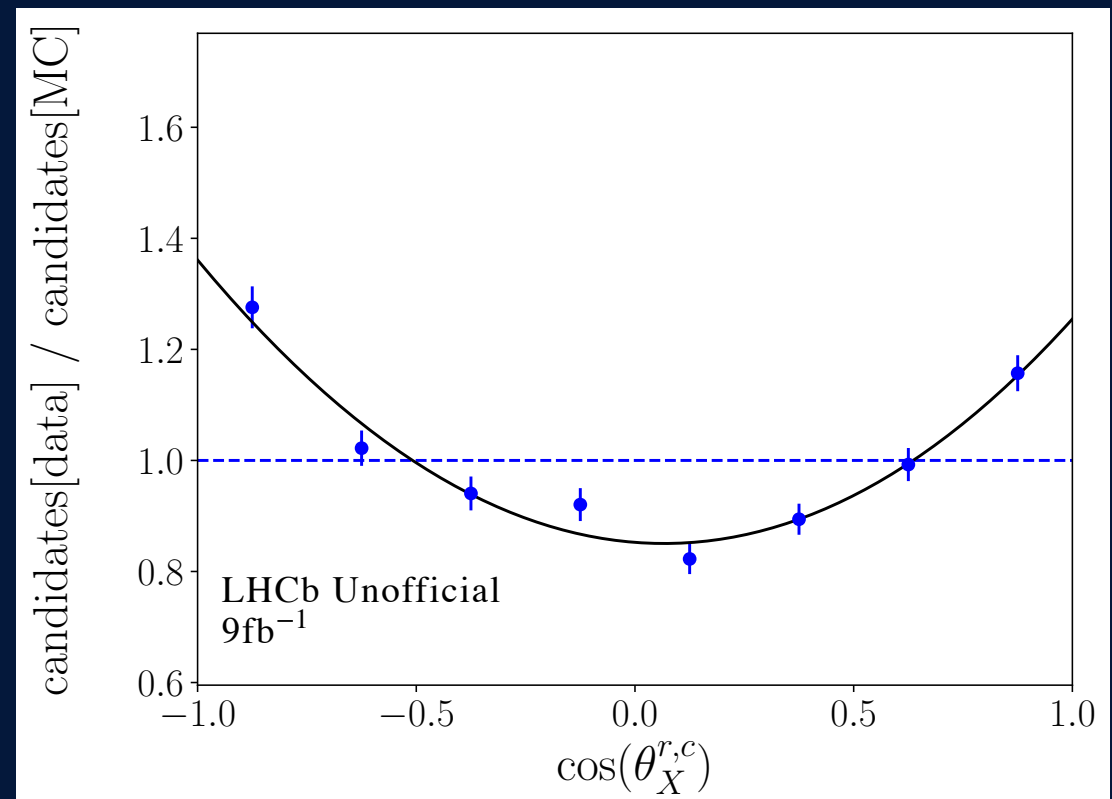
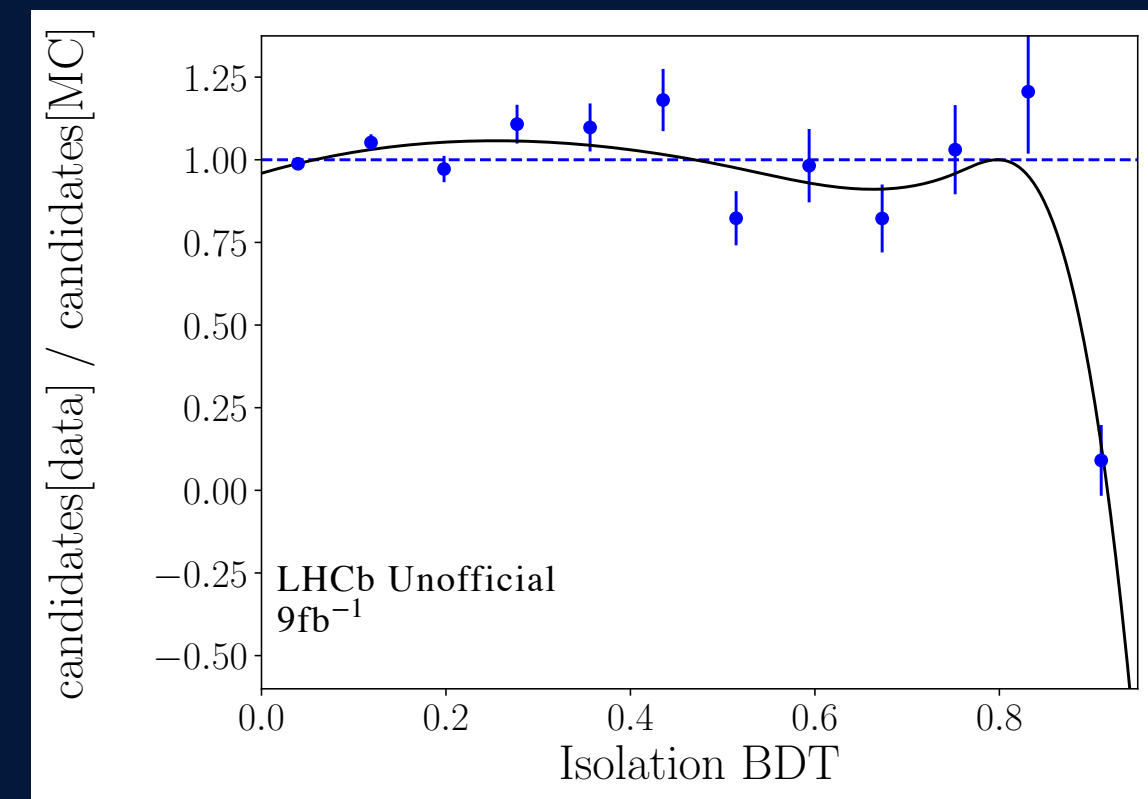
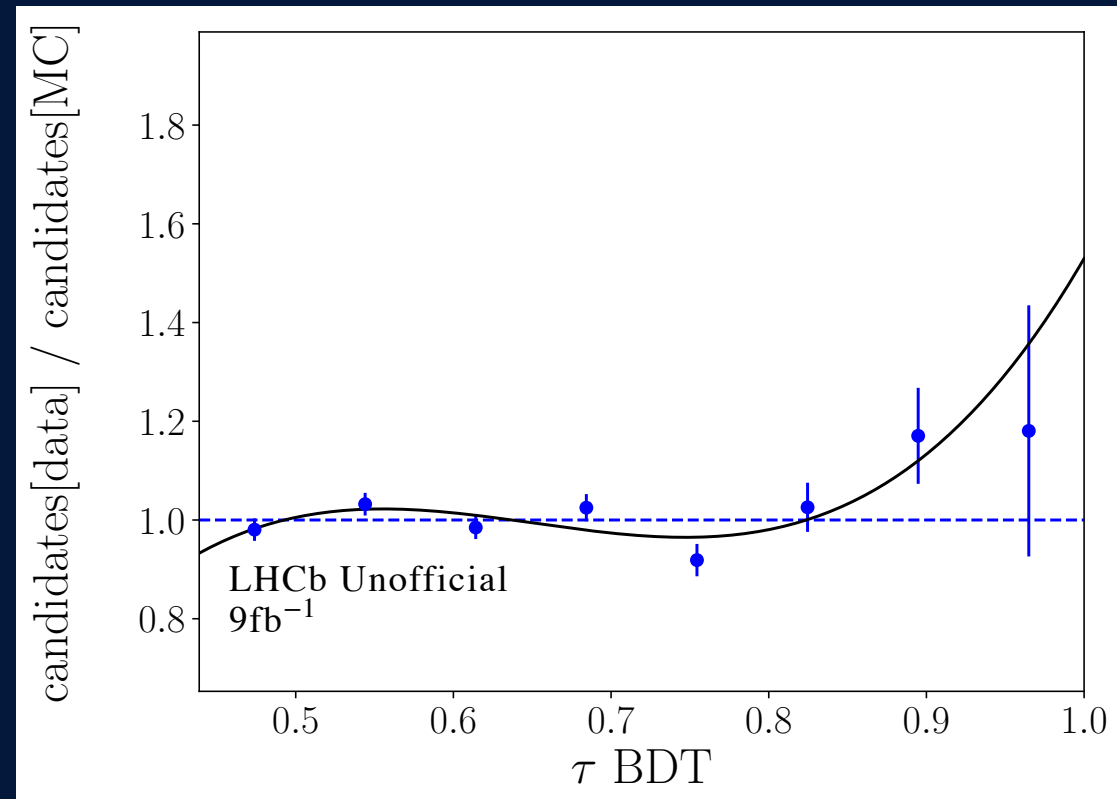
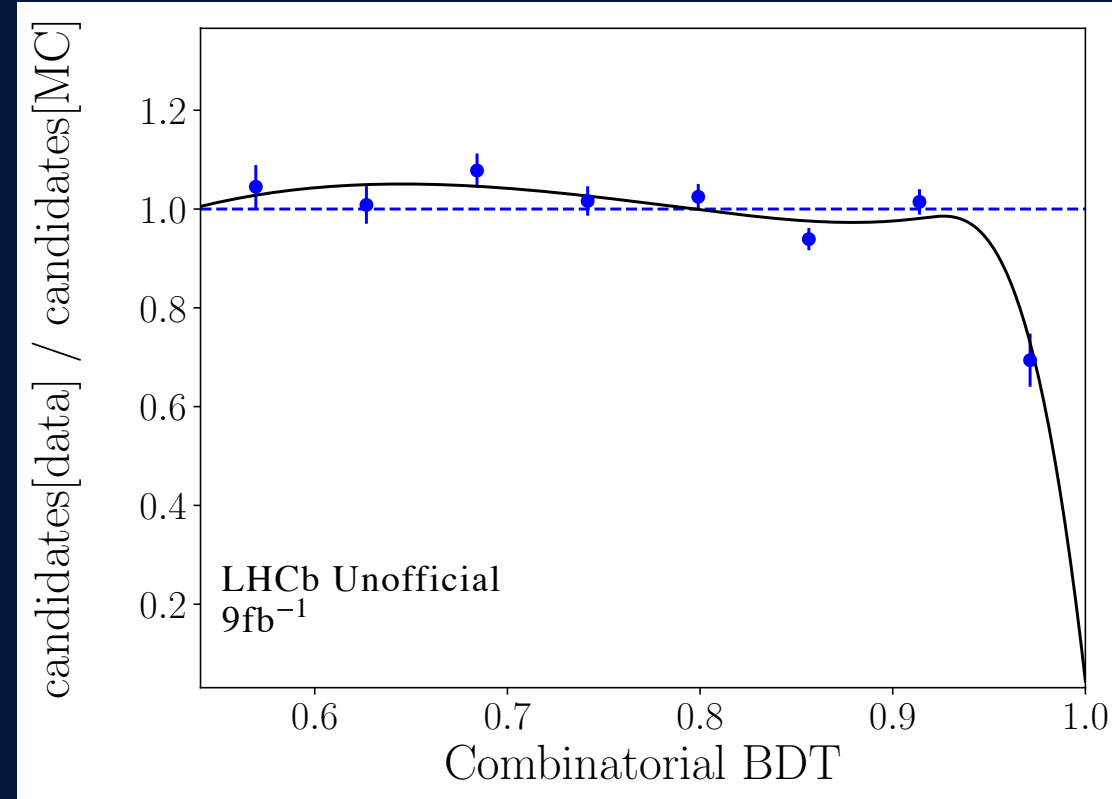


## $B \rightarrow D^*D^0(X)$ REWEIGHTING

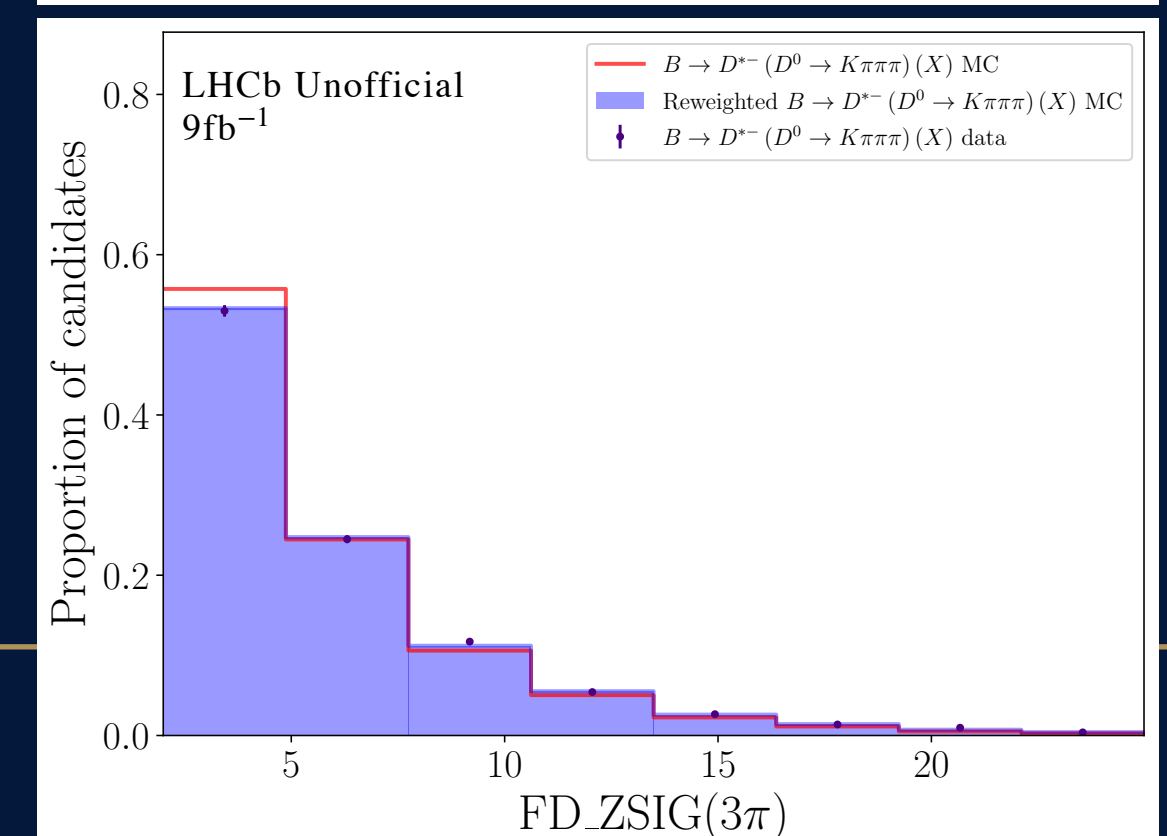
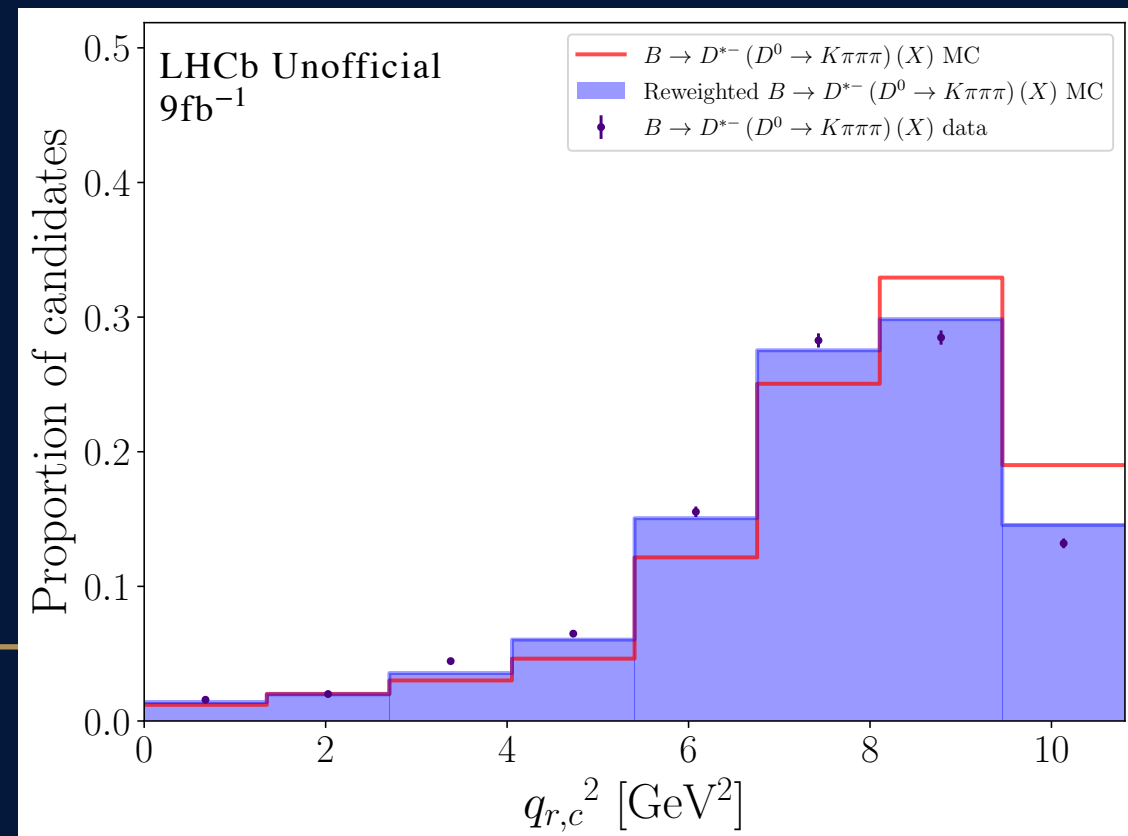
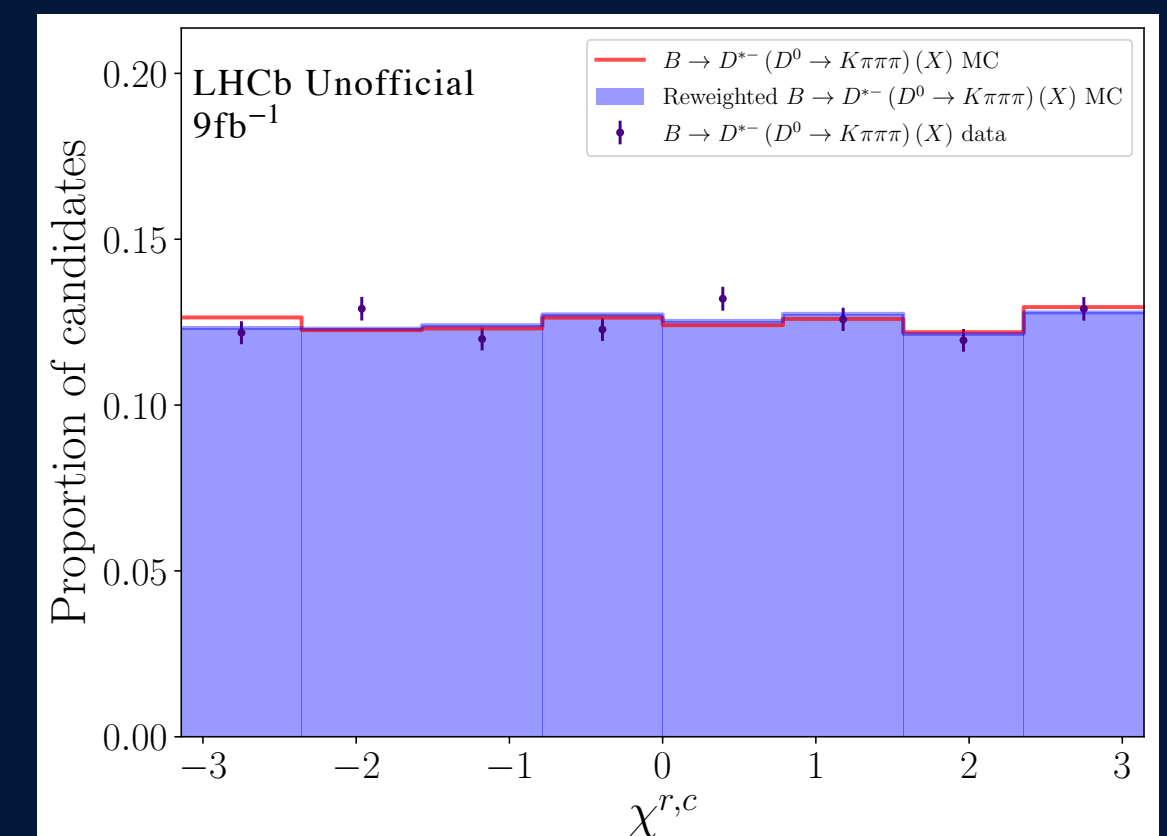
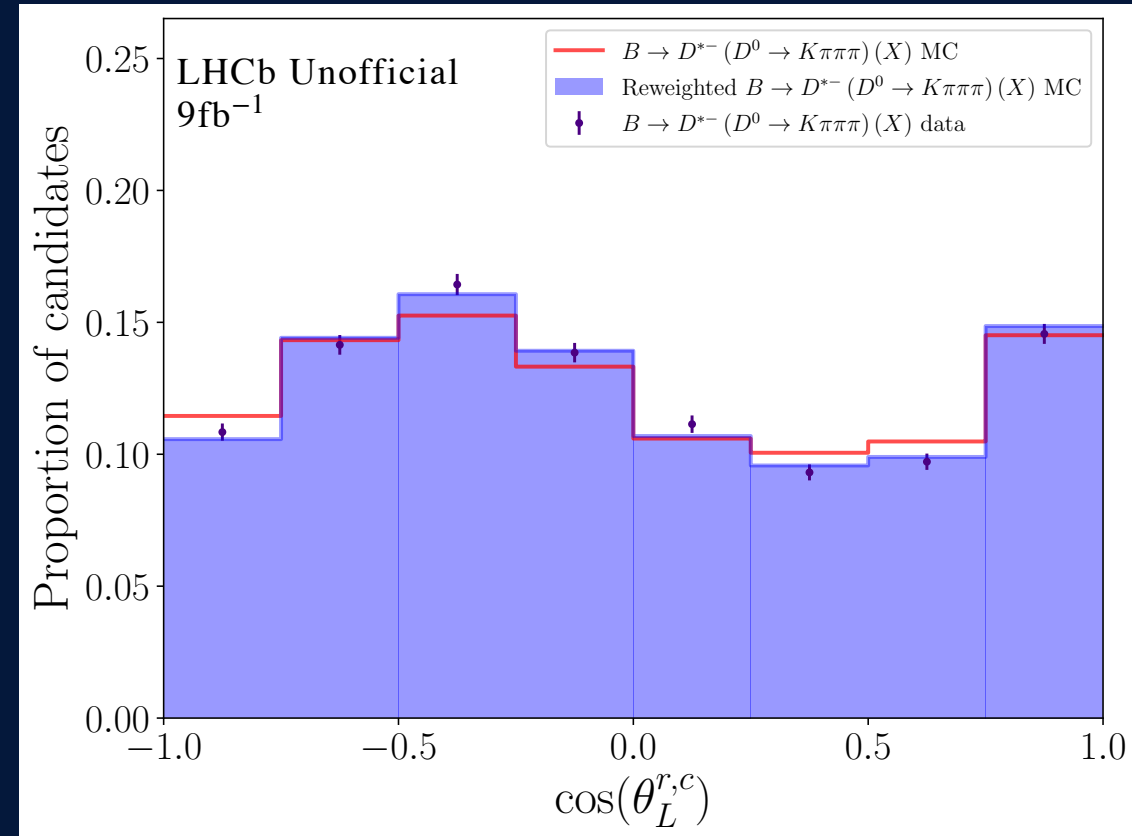
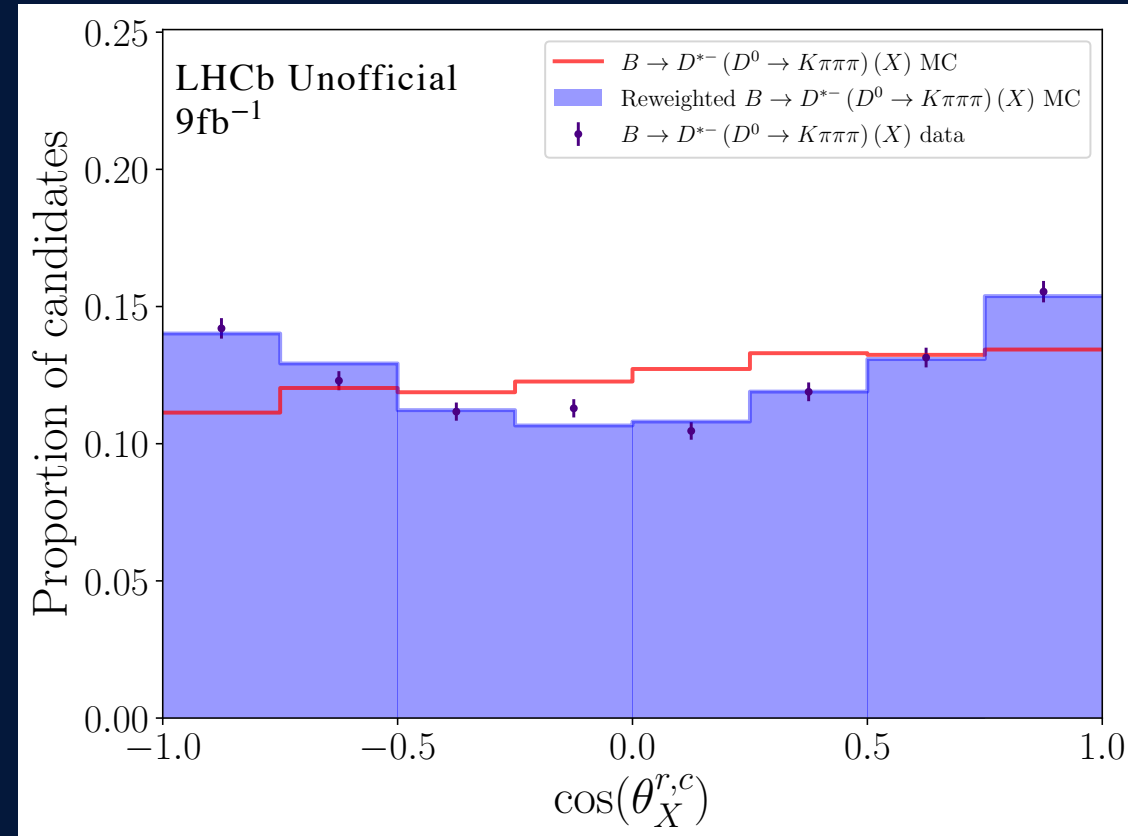
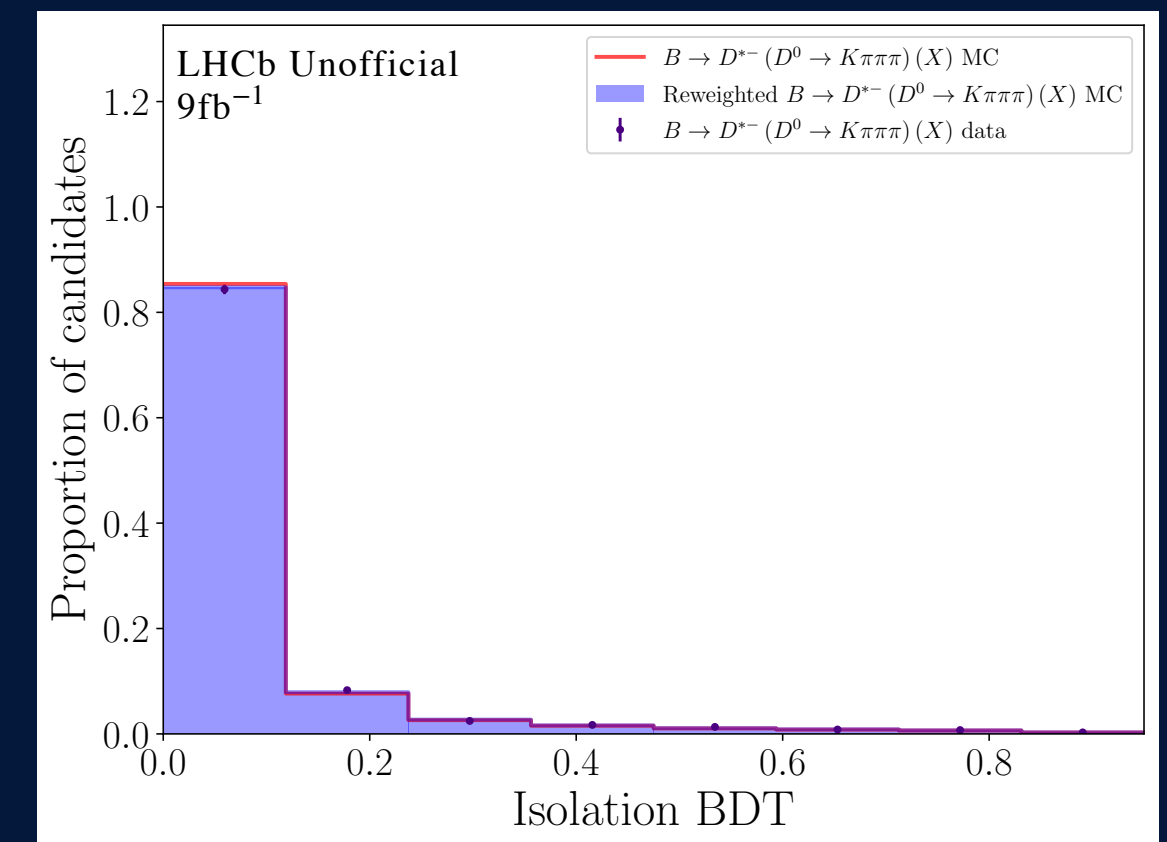
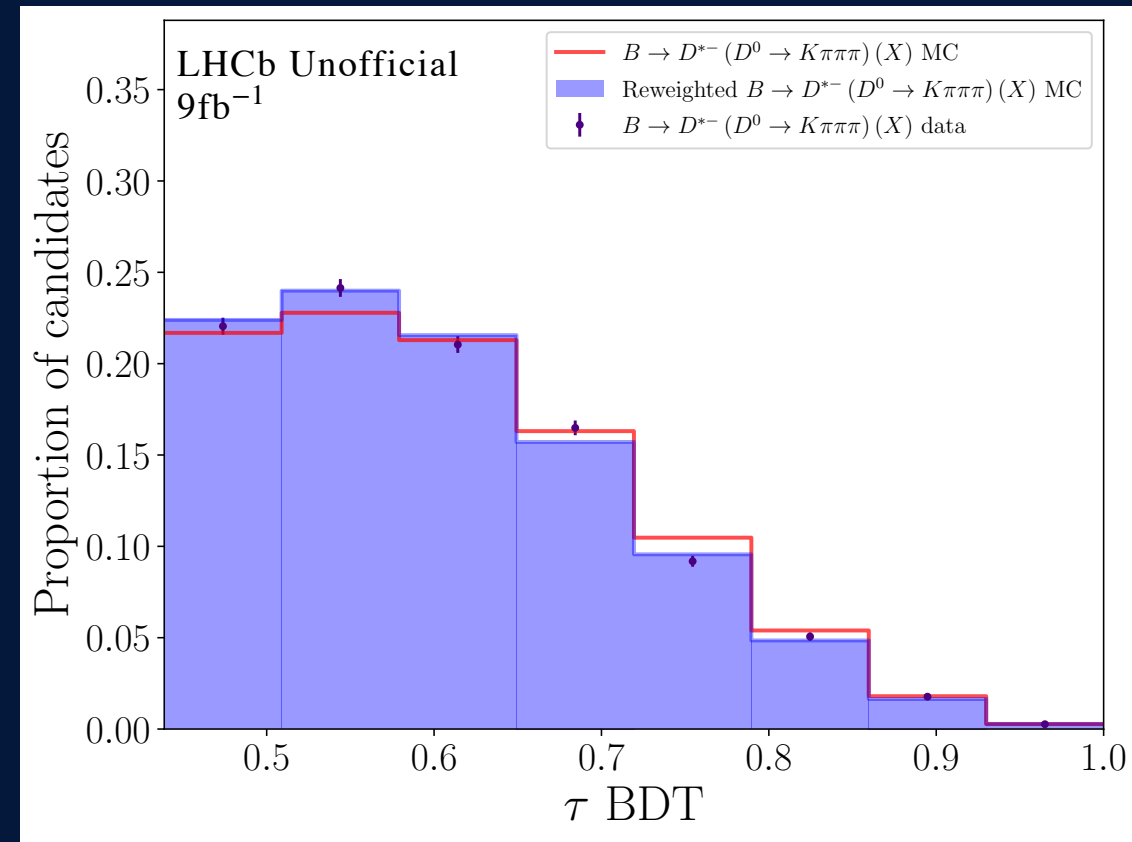
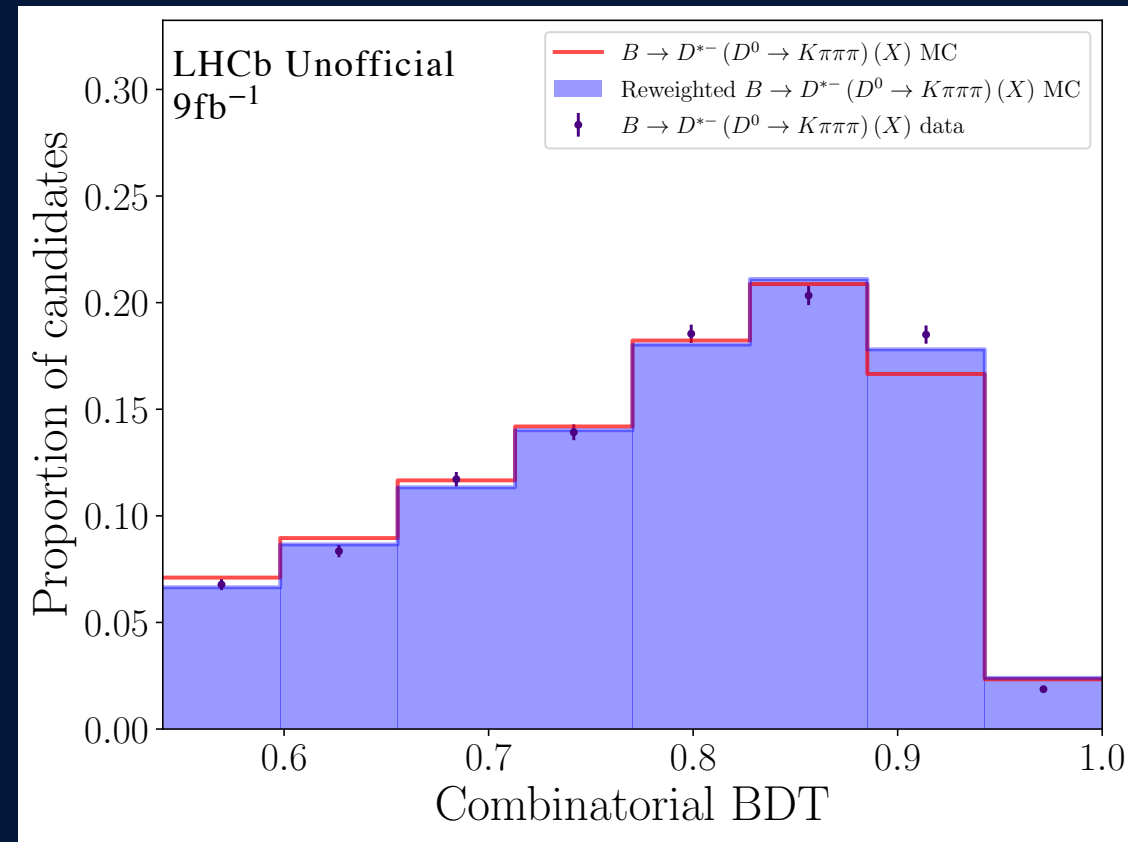
- ▶ Sequential reweighting using several variables
- ▶ Take data/MC ratio and fit using a cubic spline
  - ▶ Spline fit accounts for errors on each point
  - ▶ Smoothed to avoid features due to fluctuations
  - ▶ More robust than just using the ratio histograms
- ▶ Use spline to calculate weight for each MC event
  - ▶ Value of the spline at the variable value is used
  - ▶ Apply weight and move to next variable
    - ▶ Fit data/MC ratio with spline and update the weight
- ▶ Obtain single weight that corrects MC
  - ▶ Derived from  $B \rightarrow D^*(D^0 \rightarrow K^-\pi^+\pi^-\pi^+)(X)$ , but applied to all  $B \rightarrow D^*D^0(X)$



# $B \rightarrow D^* D^0(X)$ DATA/MC RATIO FITS



# $B \rightarrow D^* D^0(X)$ VARIABLES AFTER REWEIGHTING

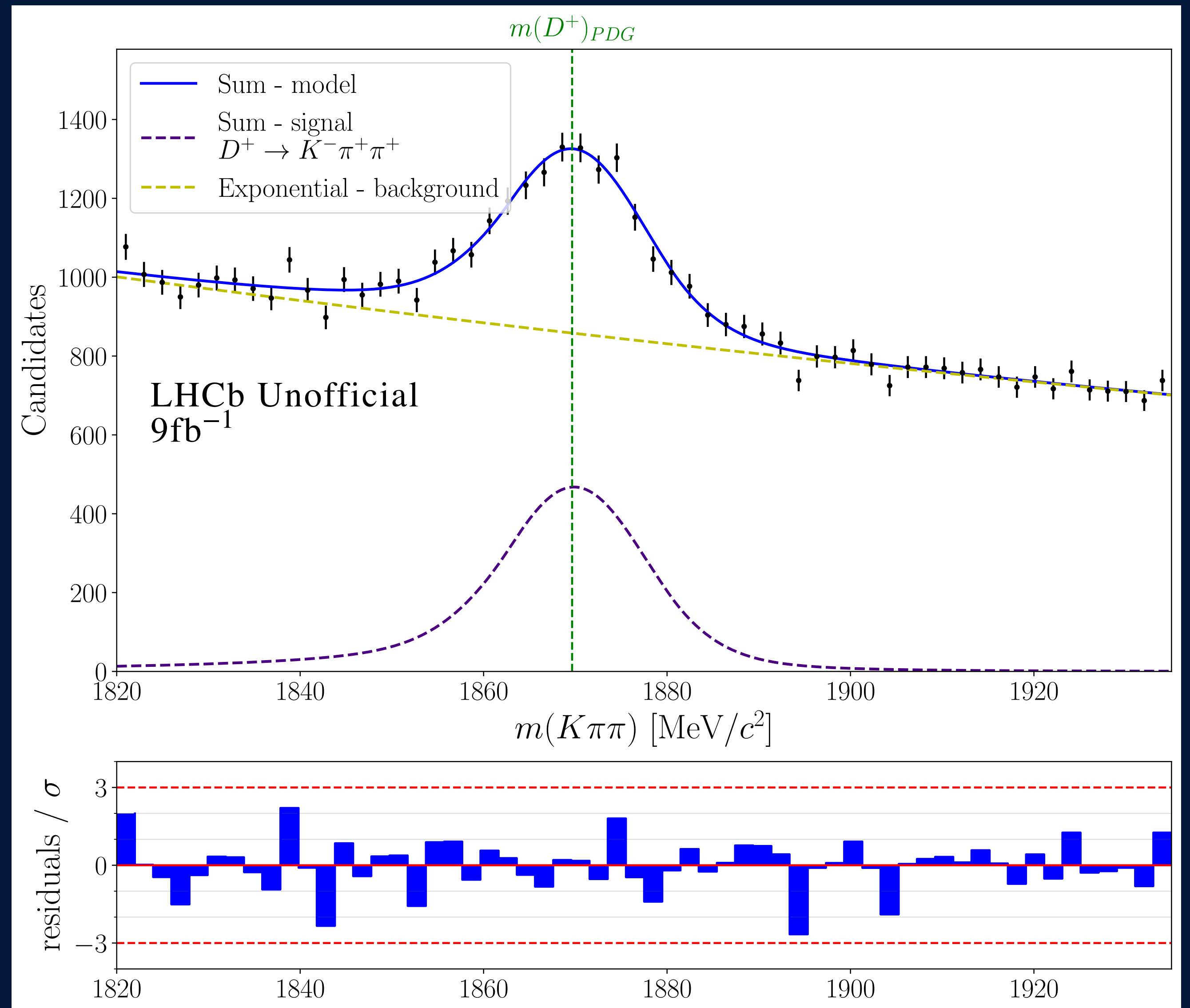


## CONTROL STUDIES

- ▶ Several control studies
  - ▶  $B \rightarrow D^{*-}D^0(X)$  : Weights for data/MC agreement
    - ▶ Isolate  $B \rightarrow D^{*-}D^0(X)$  via  $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$  using  $s$ Weights
  - ▶  $B \rightarrow D^{*-}D^+(X)$  : Weights for data/MC agreement
    - ▶ Isolate  $B \rightarrow D^{*-}D^+(X)$  via  $D^+ \rightarrow K^-\pi^+\pi^+$  using  $s$ Weights
  - ▶  $B \rightarrow D^{*-}D_s(X)$  : Weights for data/MC agreement and for relative decay fractions
    - ▶ Isolate  $D_s \rightarrow \pi^+\pi^-\pi^+$  using  $s$ Weights
    - ▶ Fit  $m(D^{*-}D_s)$  to measure decay fractions
  - ▶  $D_s \rightarrow \pi^+\pi^-\pi^+(X)$  : Weights for relative decay fractions
    - ▶ Simultaneous fit in four variables to measure decay fractions
- ▶ Methodology aligned with the Run 1  $\mathcal{R}(D^*)$  measurement [PRL 120 \(2018\) 171802](#), [PRD 97 \(2018\) 072013](#)

## $B \rightarrow D^*D^+(X)$ CONTROL STUDY

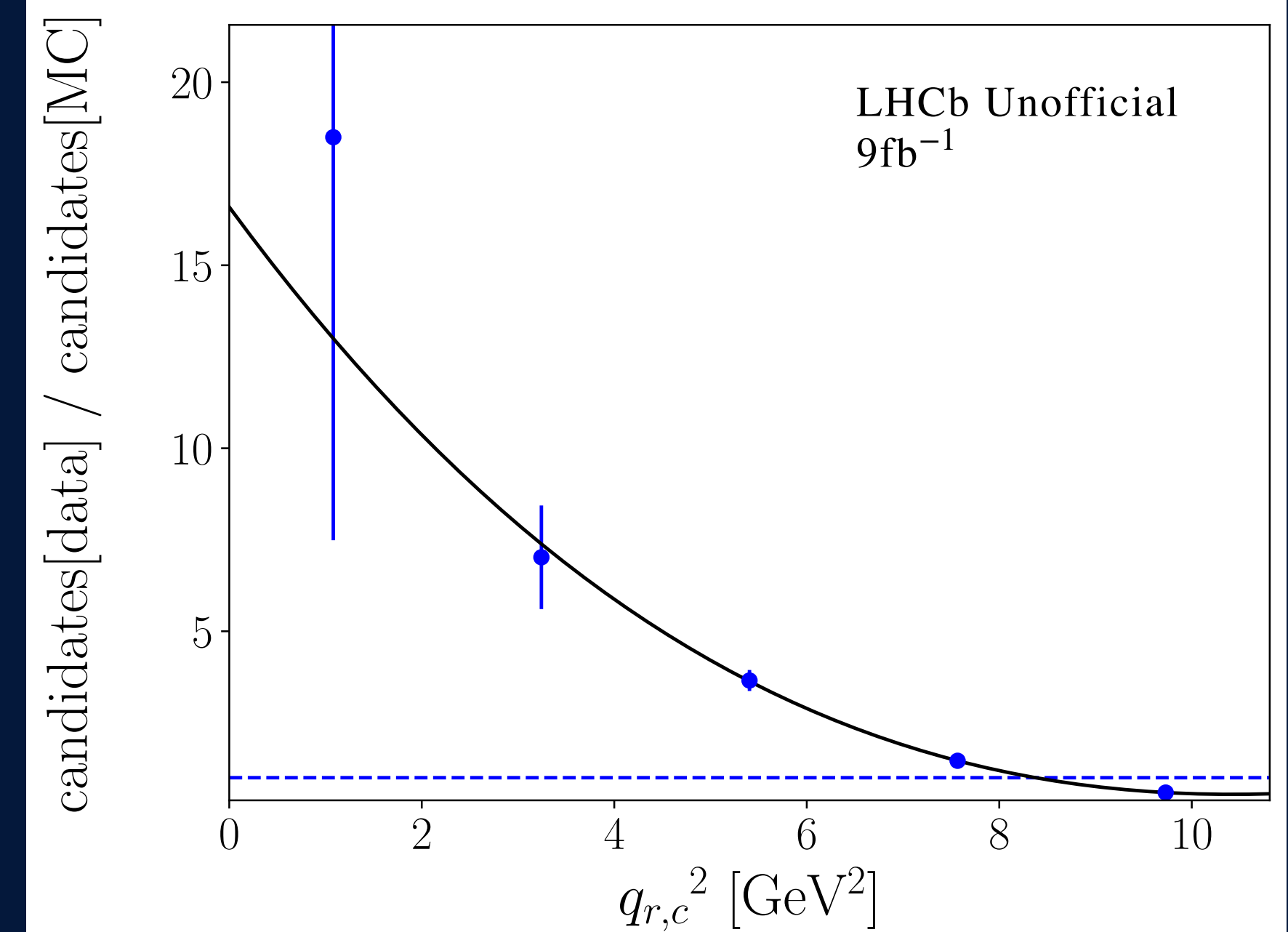
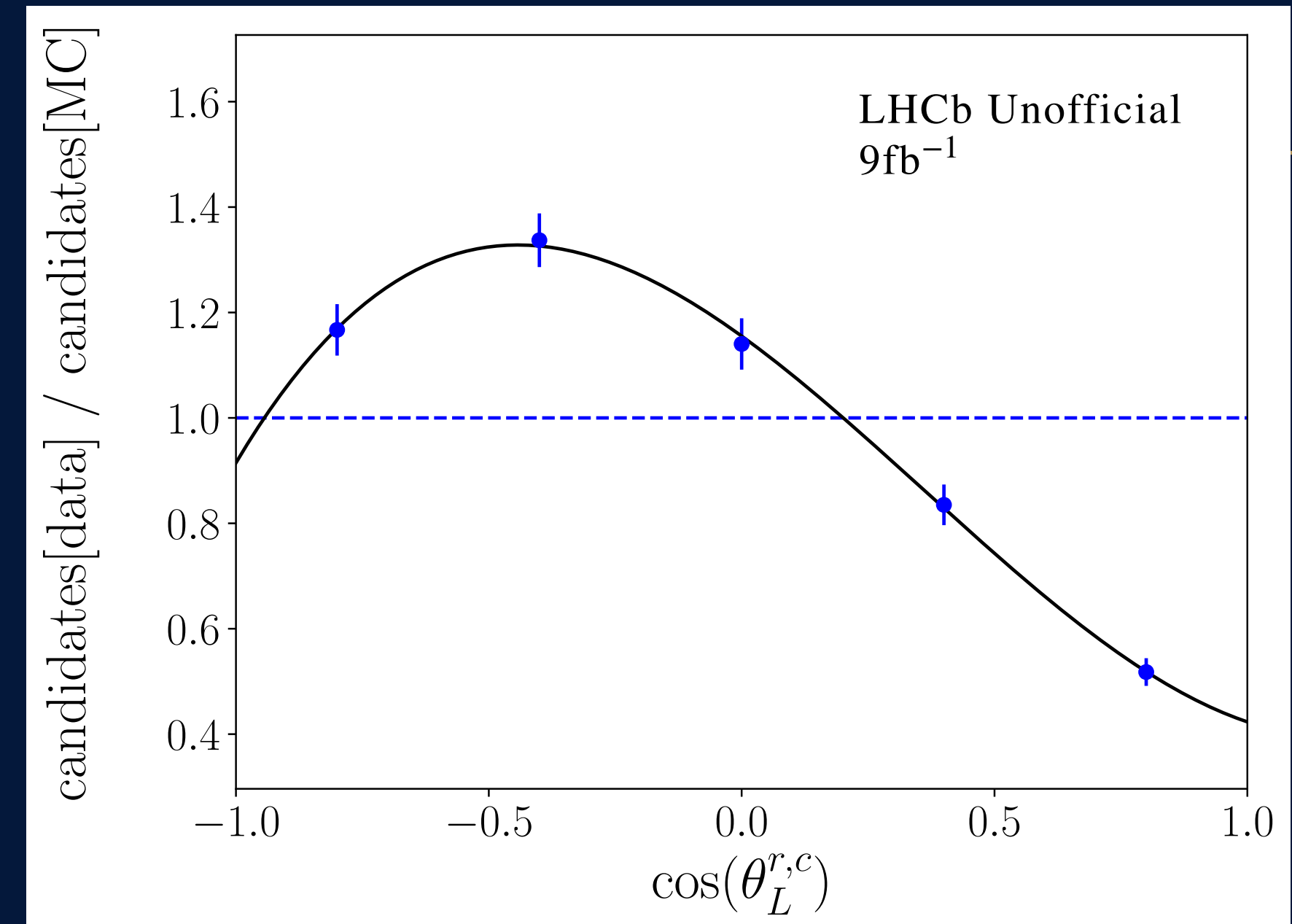
- ▶ Isolate  $B \rightarrow D^*D^+(X)$  via  $D^+ \rightarrow K^-\pi^+\pi^+$ 
  - ▶  $m(K^-\pi^+\pi^+) \in m(D^+)_{\text{PDG}} \pm 200.0 \text{ MeV}/c^2$
- ▶ Fit  $m(K^-\pi^+\pi^+)$  in MC for shape
- ▶ Fit  $m(K^-\pi^+\pi^+)$  in data to measure peak
- ▶ sWeight  $m(K^-\pi^+\pi^+)$  peak to obtain pure  $B \rightarrow D^*D^+(X)$
- ▶ Perform data/MC reweighting to correct  $B \rightarrow D^*D^+(X)$  MC



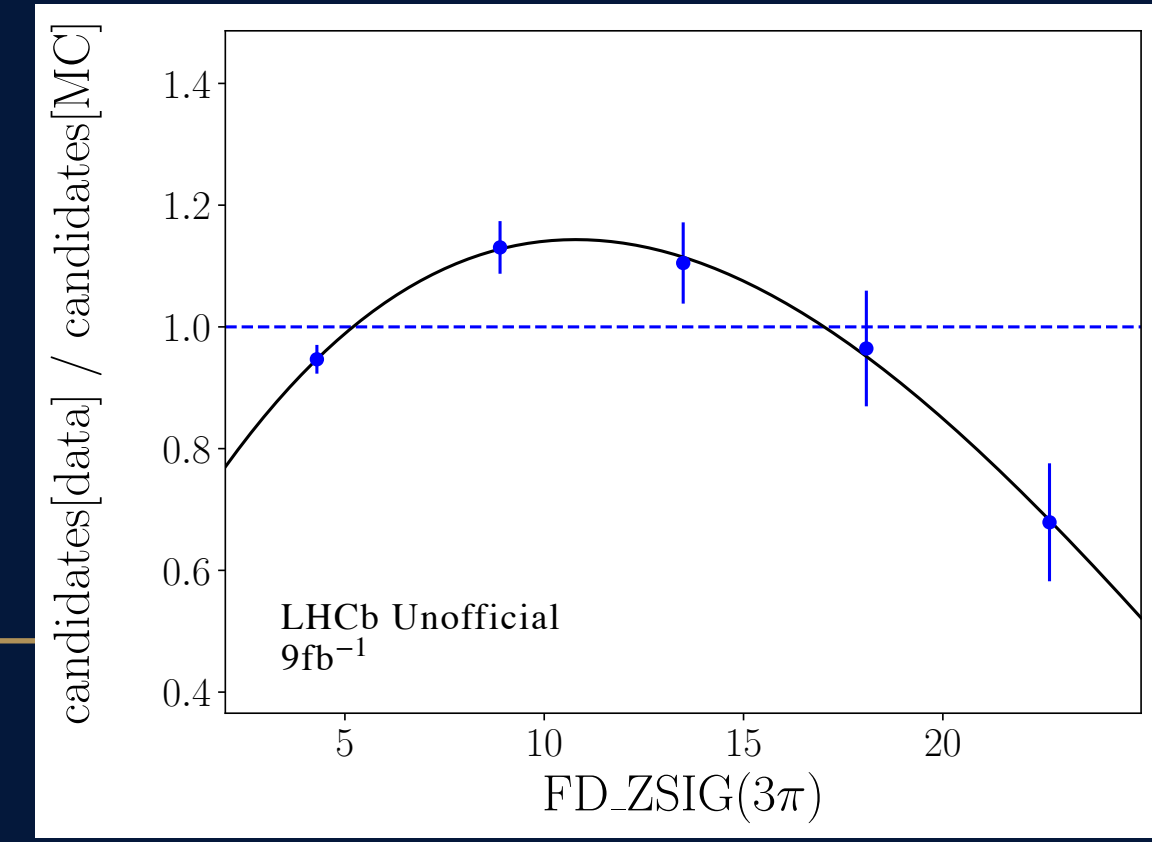
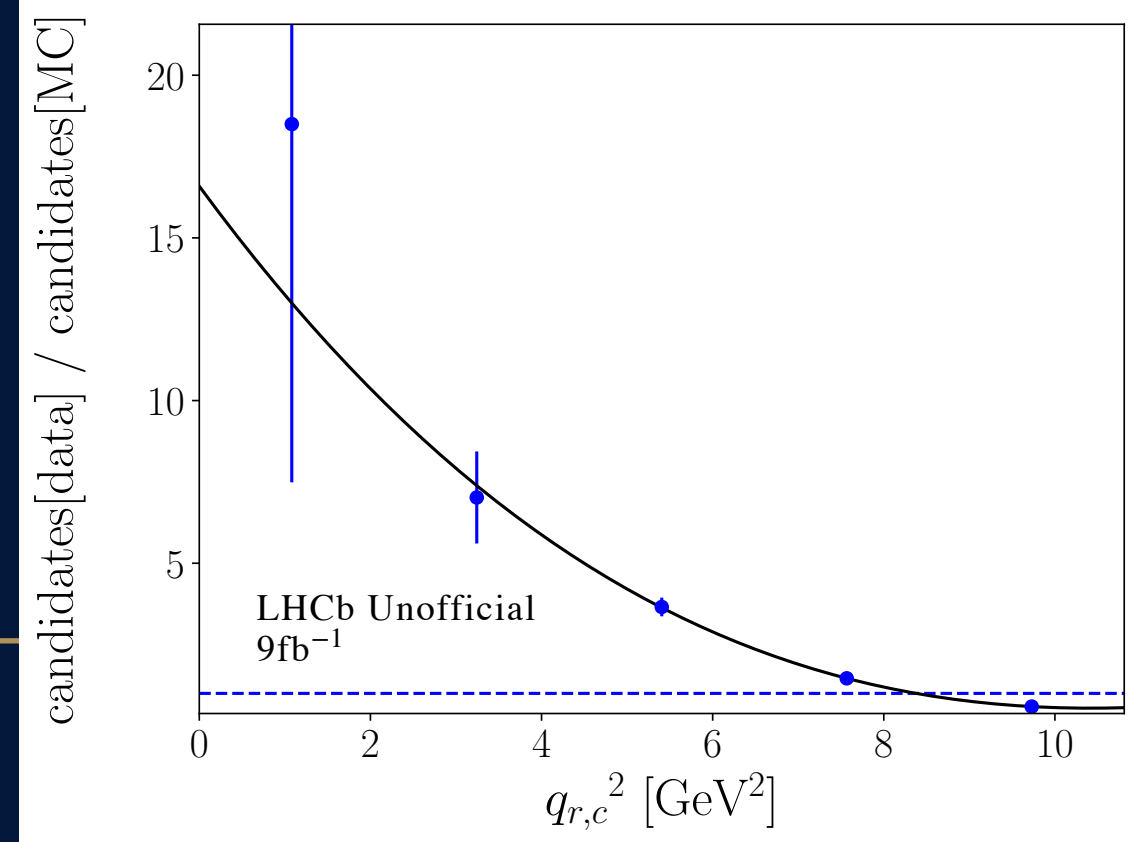
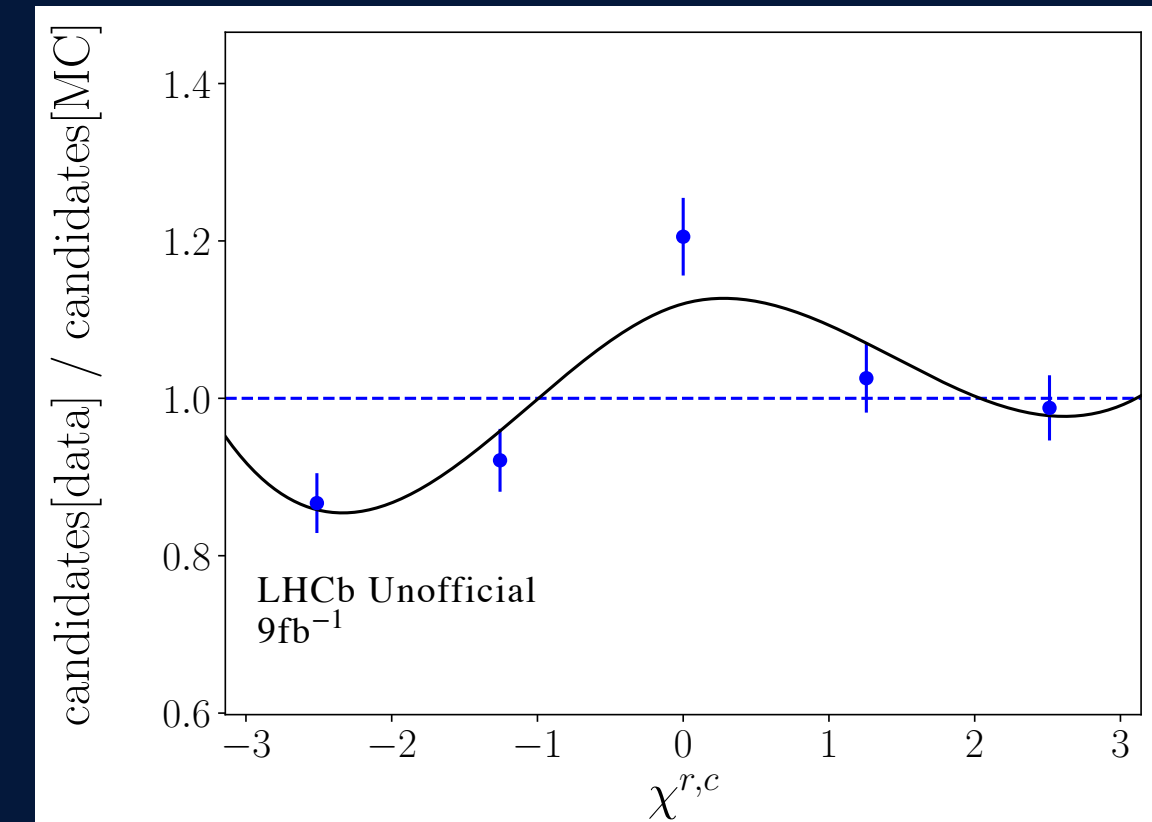
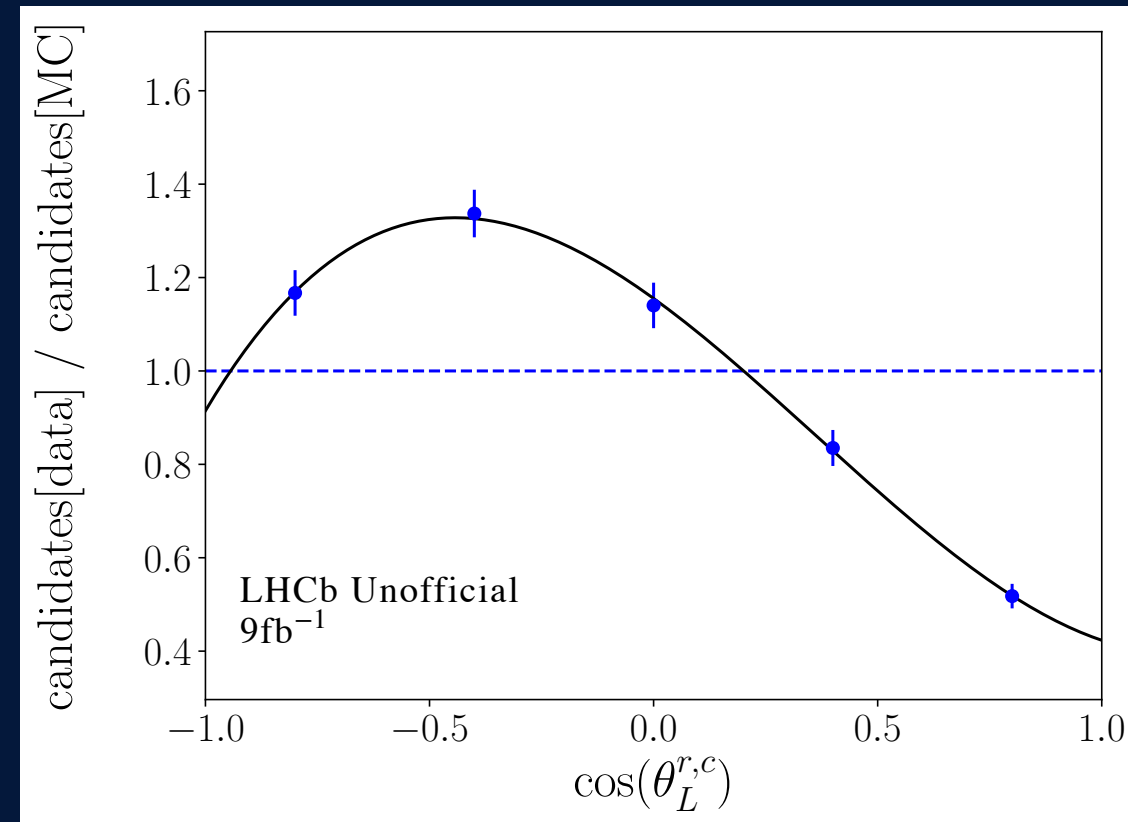
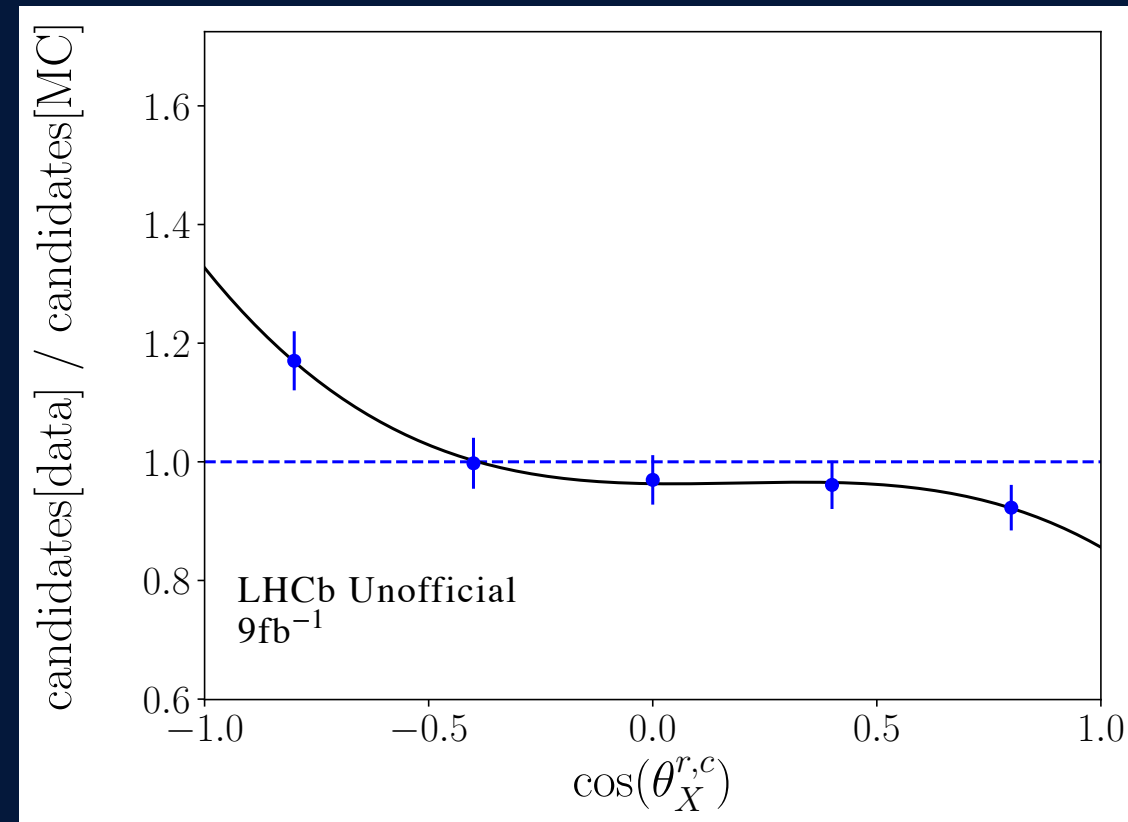
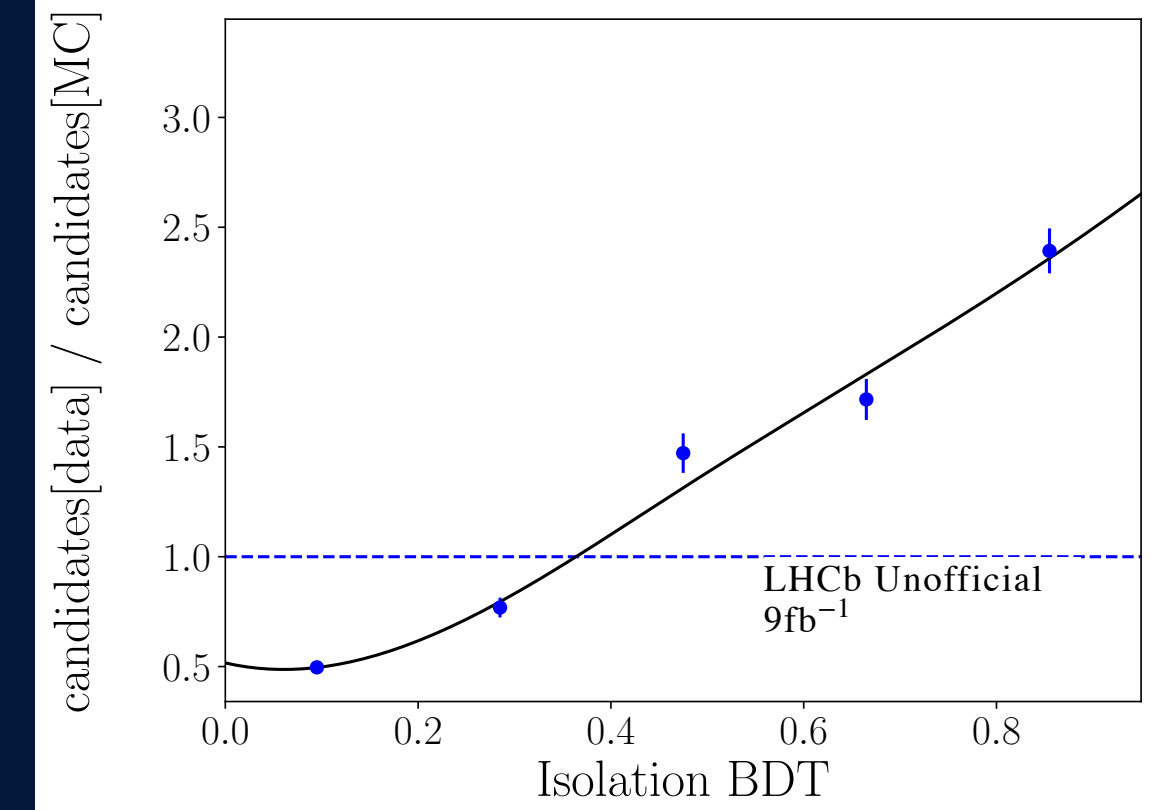
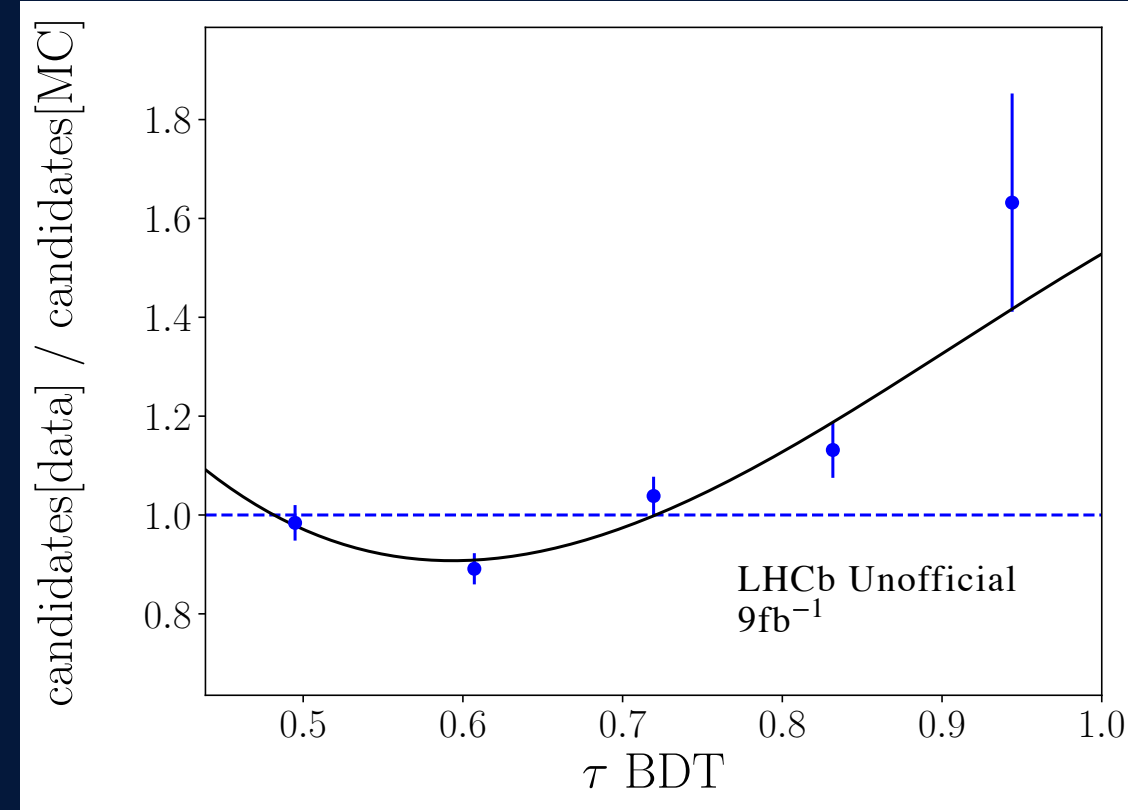
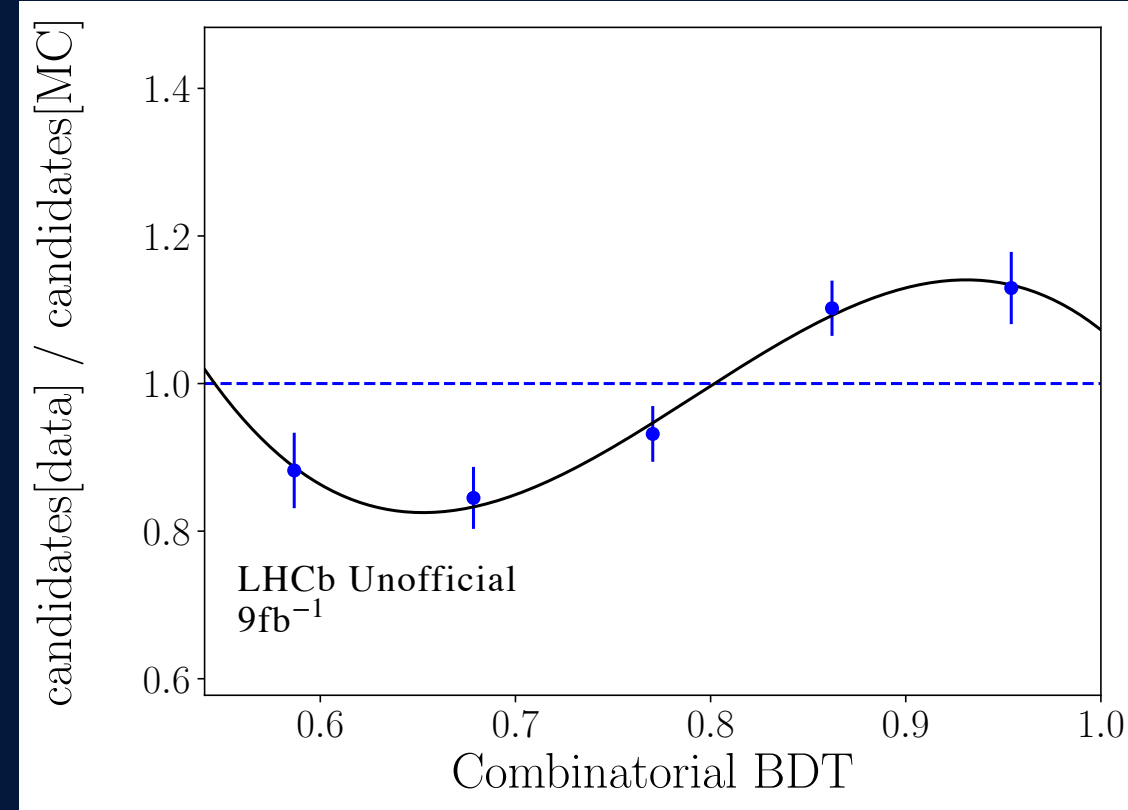


## $B \rightarrow D^*D^+(X)$ REWEIGHTING

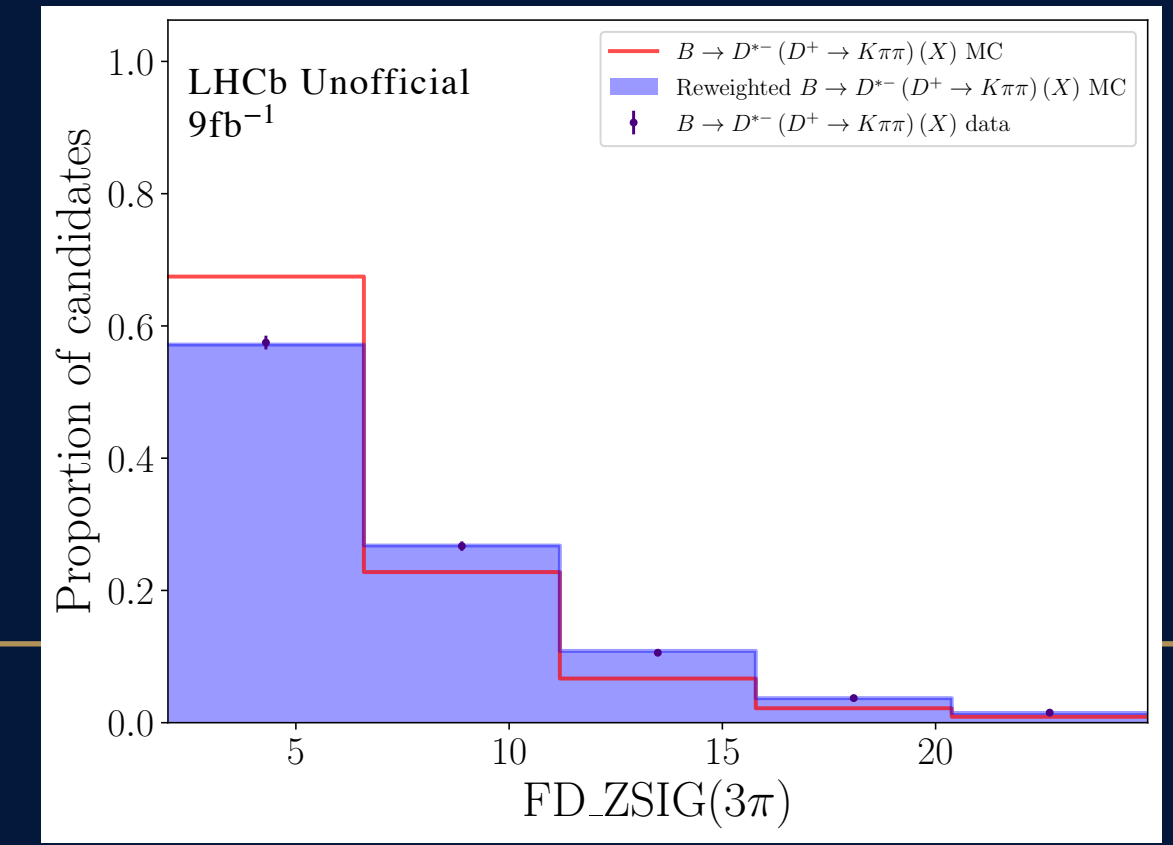
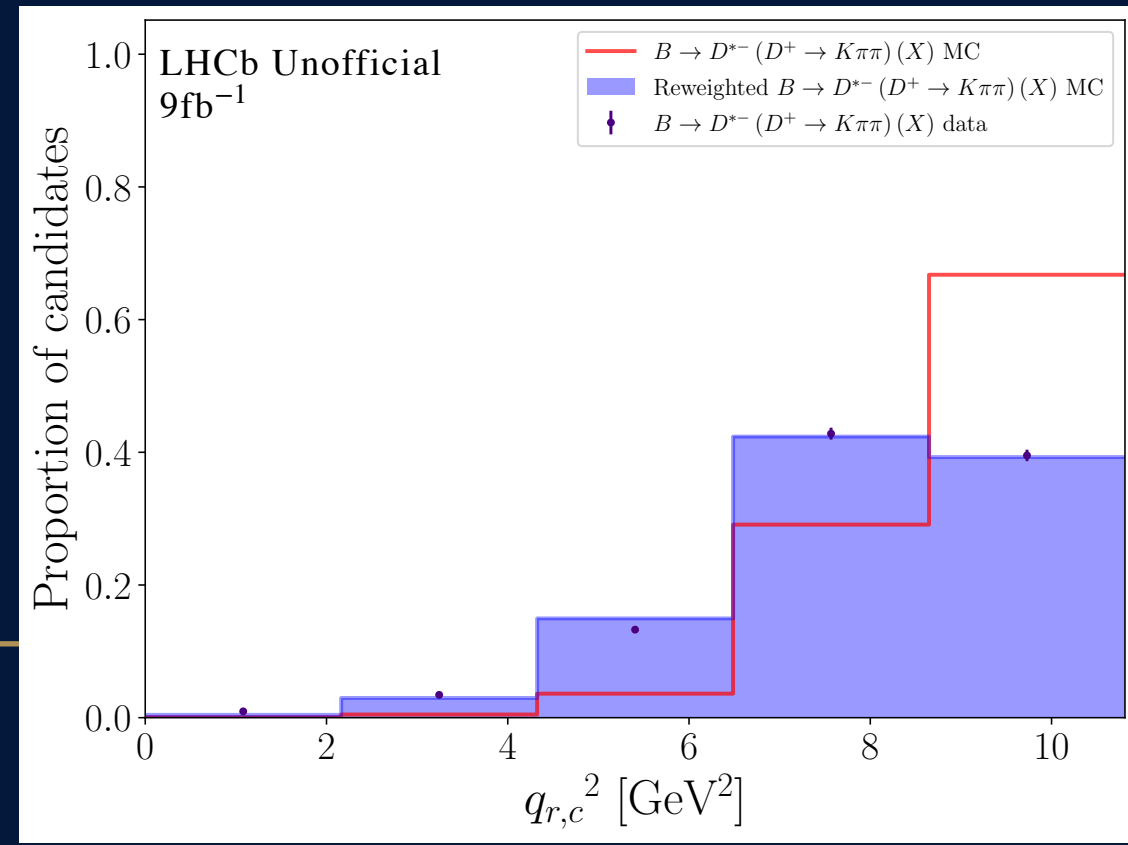
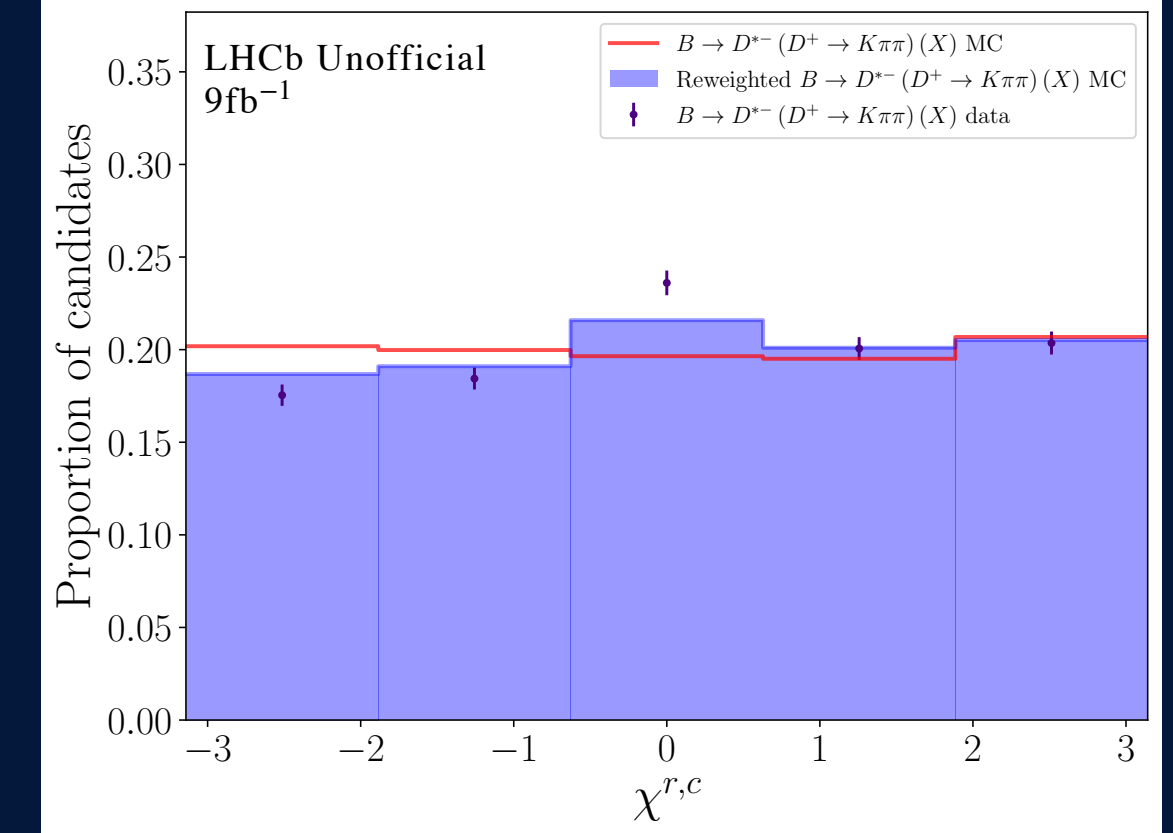
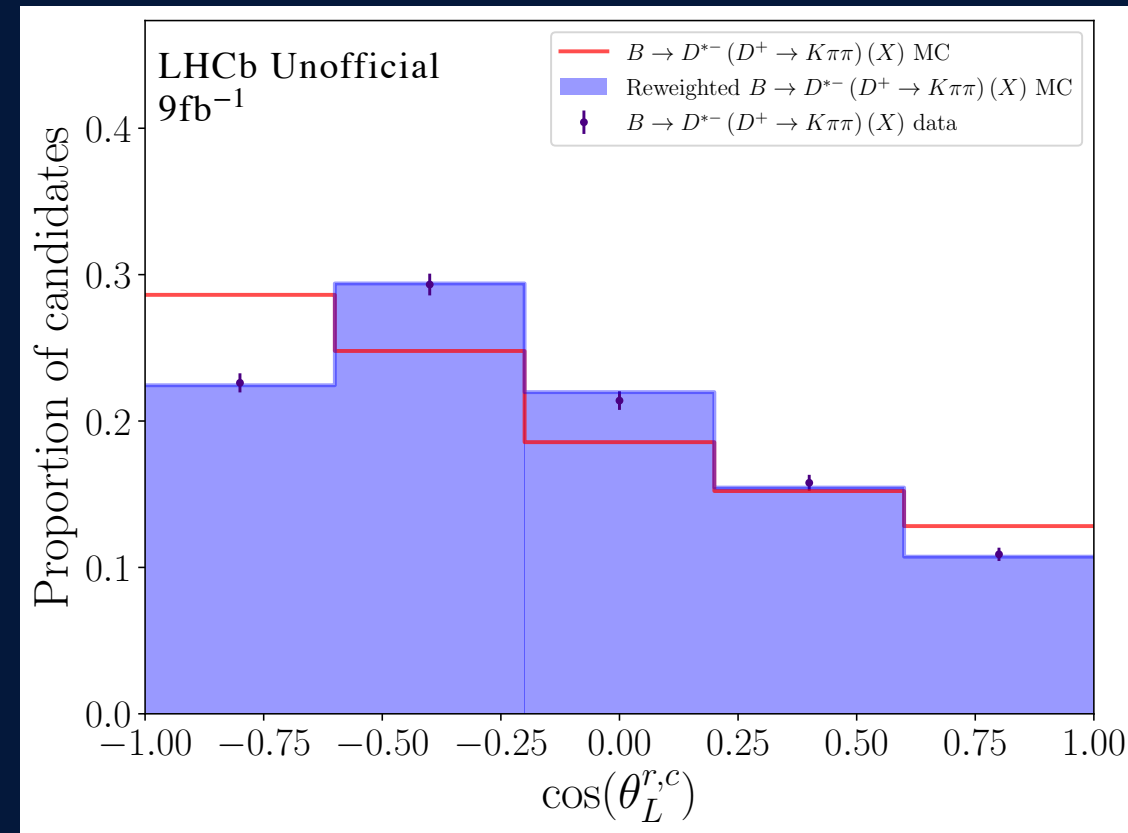
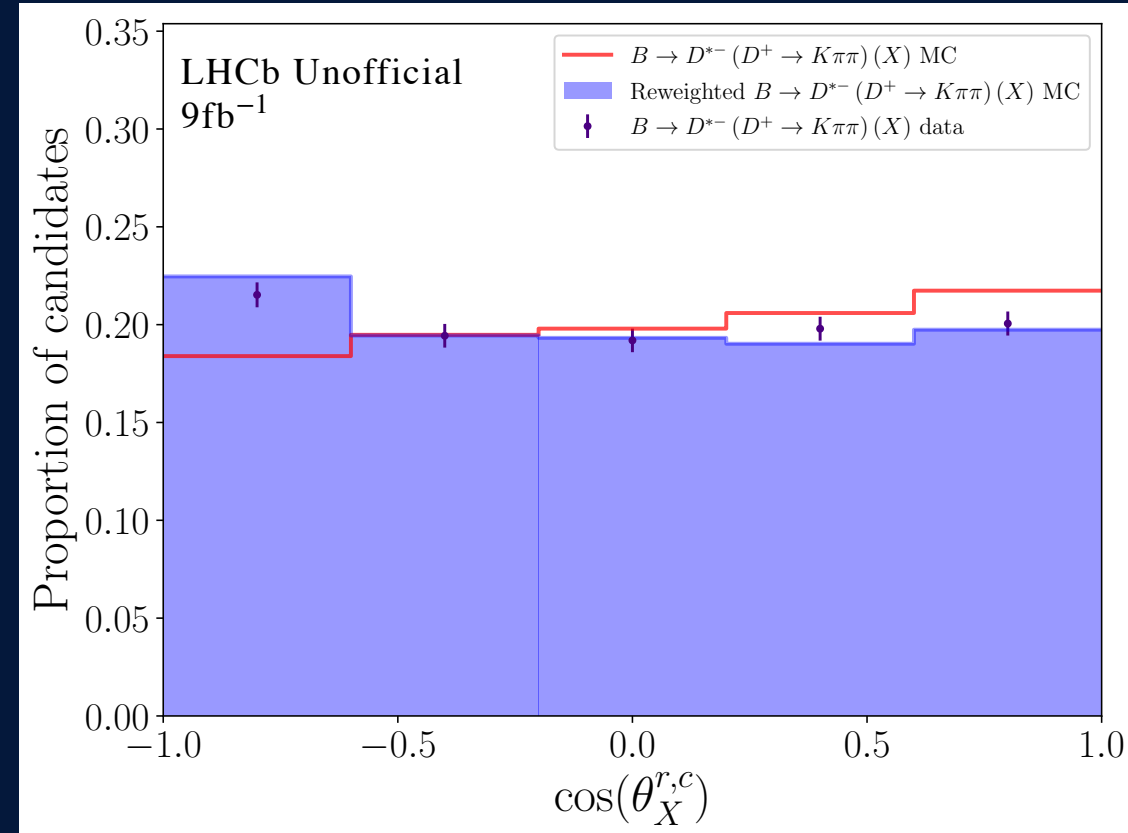
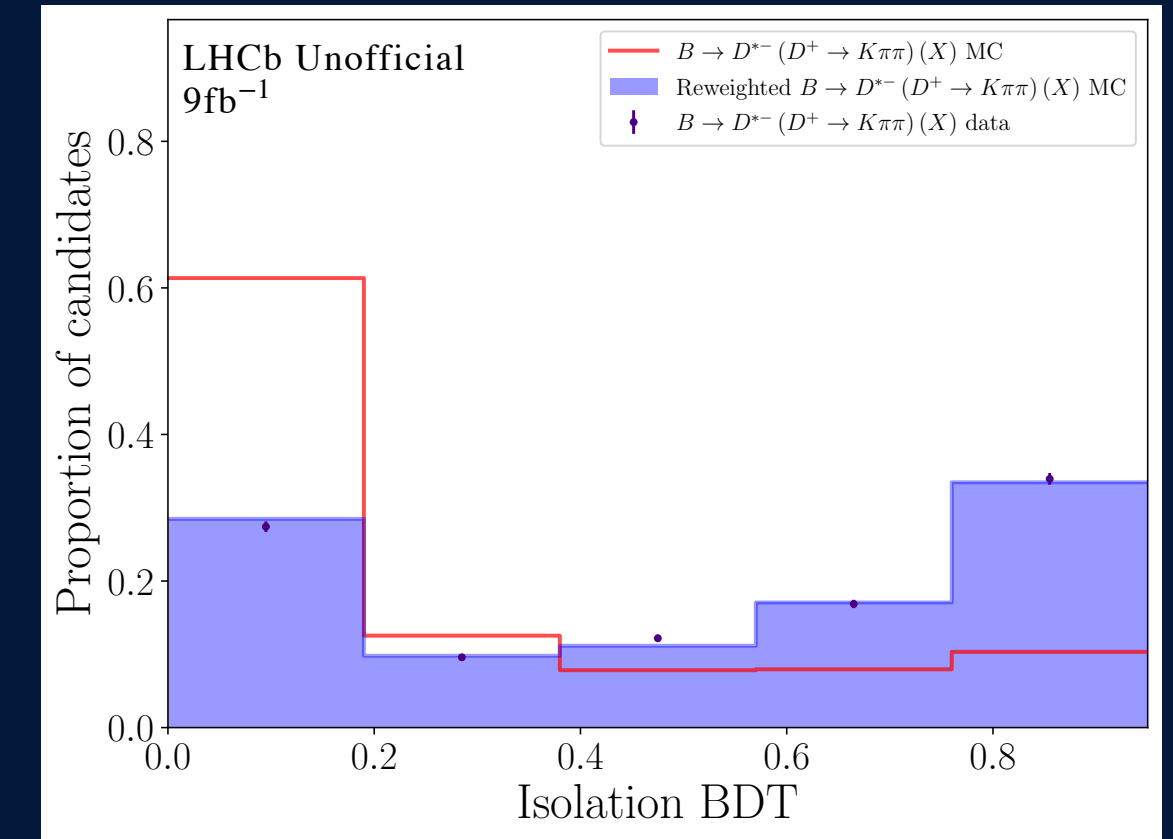
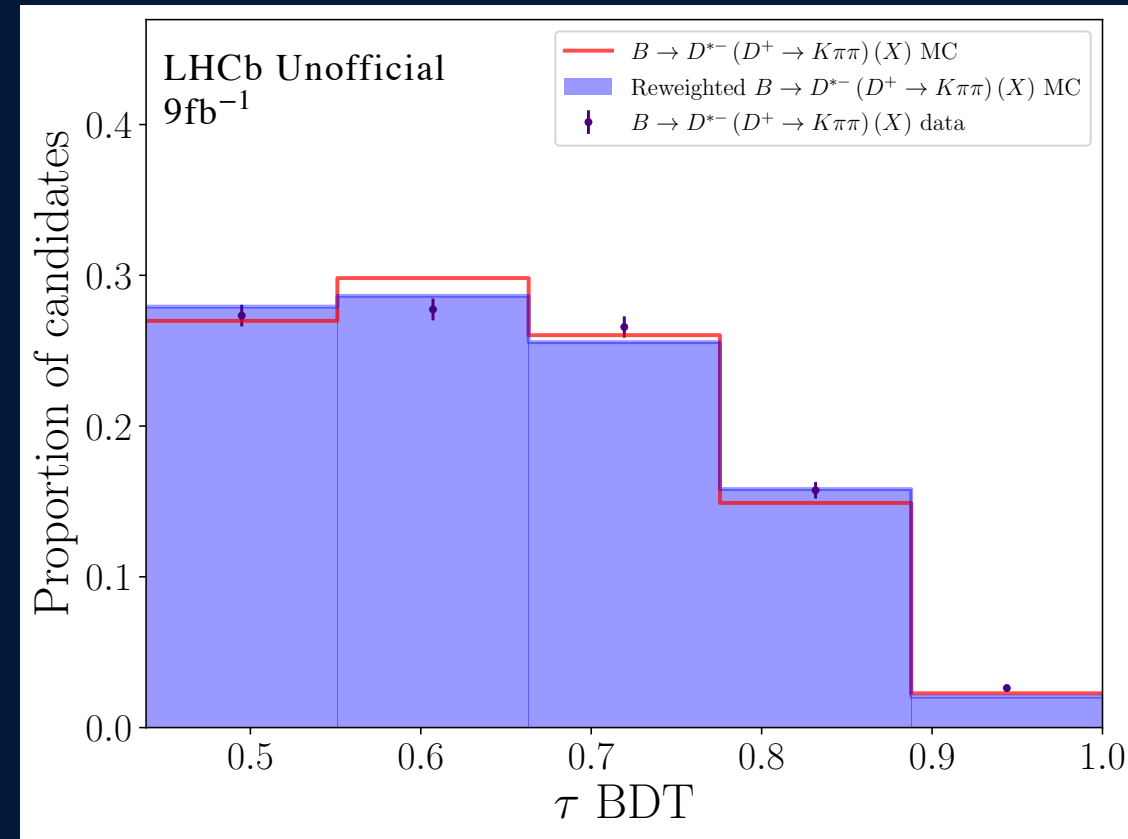
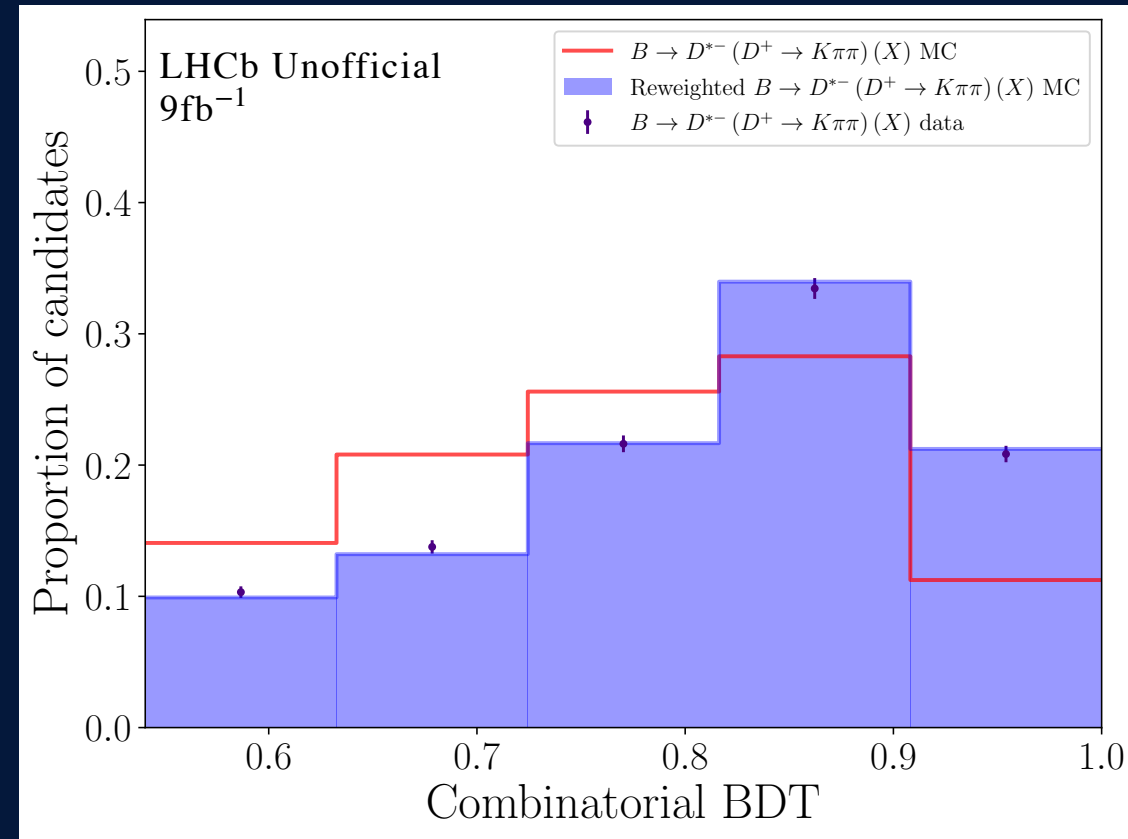
- ▶ Sequential reweighting using several variables
- ▶ Take data/MC ratio and fit using a cubic spline
  - ▶ Spline fit accounts for errors on each point
  - ▶ Smoothed to avoid features due to fluctuations
  - ▶ More robust than just using the ratio histograms
- ▶ Use spline to calculate weight for each MC event
  - ▶ Value of the spline at the variable value is used
  - ▶ Apply weight and move to next variable
    - ▶ Fit data/MC ratio with spline and update the weight
- ▶ Obtain single weight that corrects MC
  - ▶ Derived from  $B \rightarrow D^*(D^+ \rightarrow K^-\pi^+\pi^+)(X)$ , but applied to all  $B \rightarrow D^*D^+(X)$



# $B \rightarrow D^* D^+(X)$ DATA/MC RATIO FITS



# $B \rightarrow D^* D^+(X)$ VARIABLES AFTER REWEIGHTING

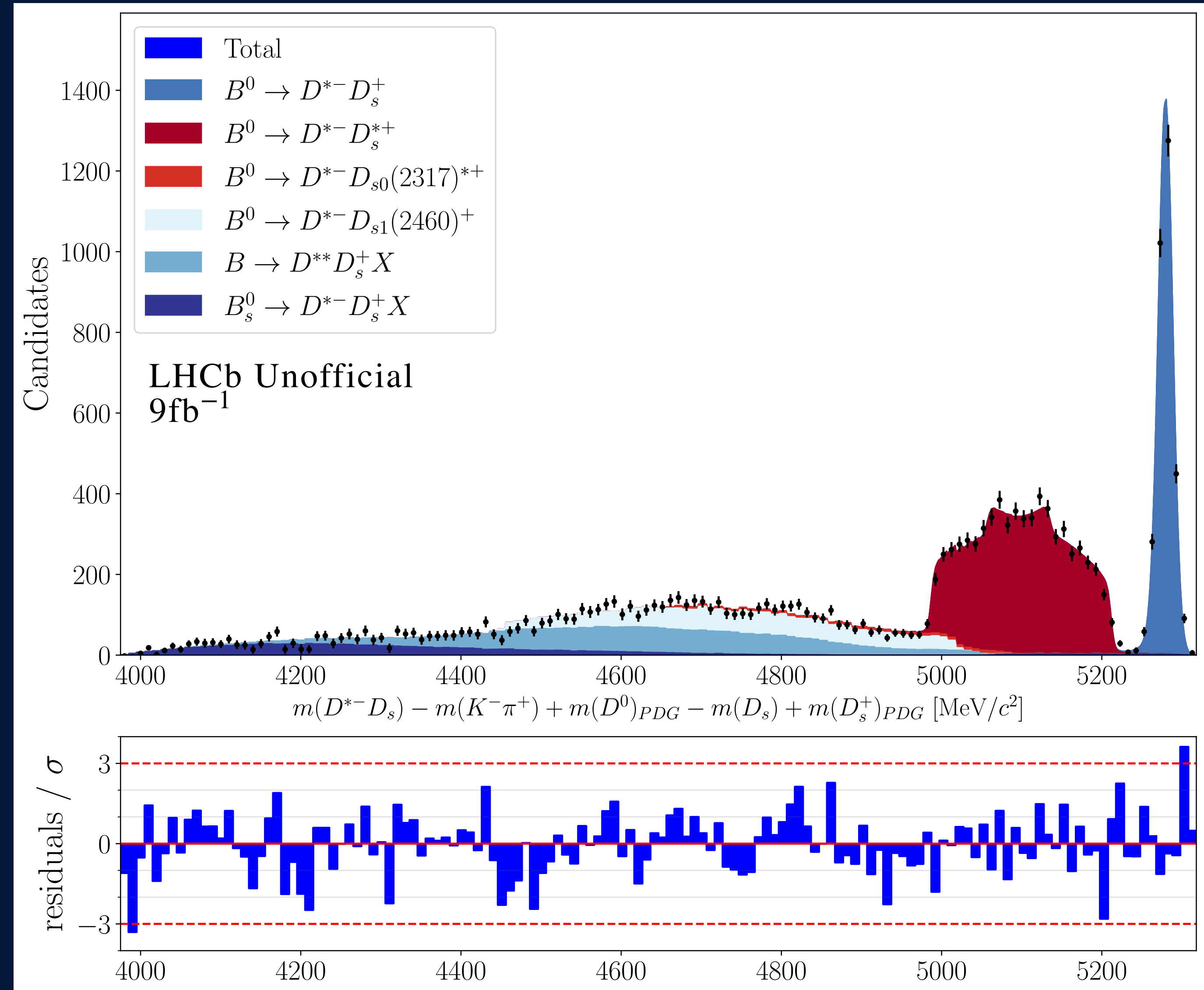


## CONTROL STUDIES

- ▶ Several control studies
  - ▶  $B \rightarrow D^{*-}D^0(X)$  : Weights for data/MC agreement
    - ▶ Isolate  $B \rightarrow D^{*-}D^0(X)$  via  $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$  using  $s$ Weights
  - ▶  $B \rightarrow D^{*-}D^+(X)$  : Weights for data/MC agreement
    - ▶ Isolate  $B \rightarrow D^{*-}D^+(X)$  via  $D^+ \rightarrow K^-\pi^+\pi^+$  using  $s$ Weights
  - ▶  $B \rightarrow D^{*-}D_s(X)$  : Weights for data/MC agreement and for relative decay fractions
    - ▶ Isolate  $D_s \rightarrow \pi^+\pi^-\pi^+$  using  $s$ Weights
    - ▶ Fit  $m(D^{*-}D_s)$  to measure decay fractions
  - ▶  $D_s \rightarrow \pi^+\pi^-\pi^+(X)$  : Weights for relative decay fractions
    - ▶ Simultaneous fit in four variables to measure decay fractions
- ▶ Methodology aligned with the Run 1  $\mathcal{R}(D^*)$  measurement [PRL 120 \(2018\) 171802](#), [PRD 97 \(2018\) 072013](#)

## $B \rightarrow D^* D_s(X)$ CONTROL STUDY

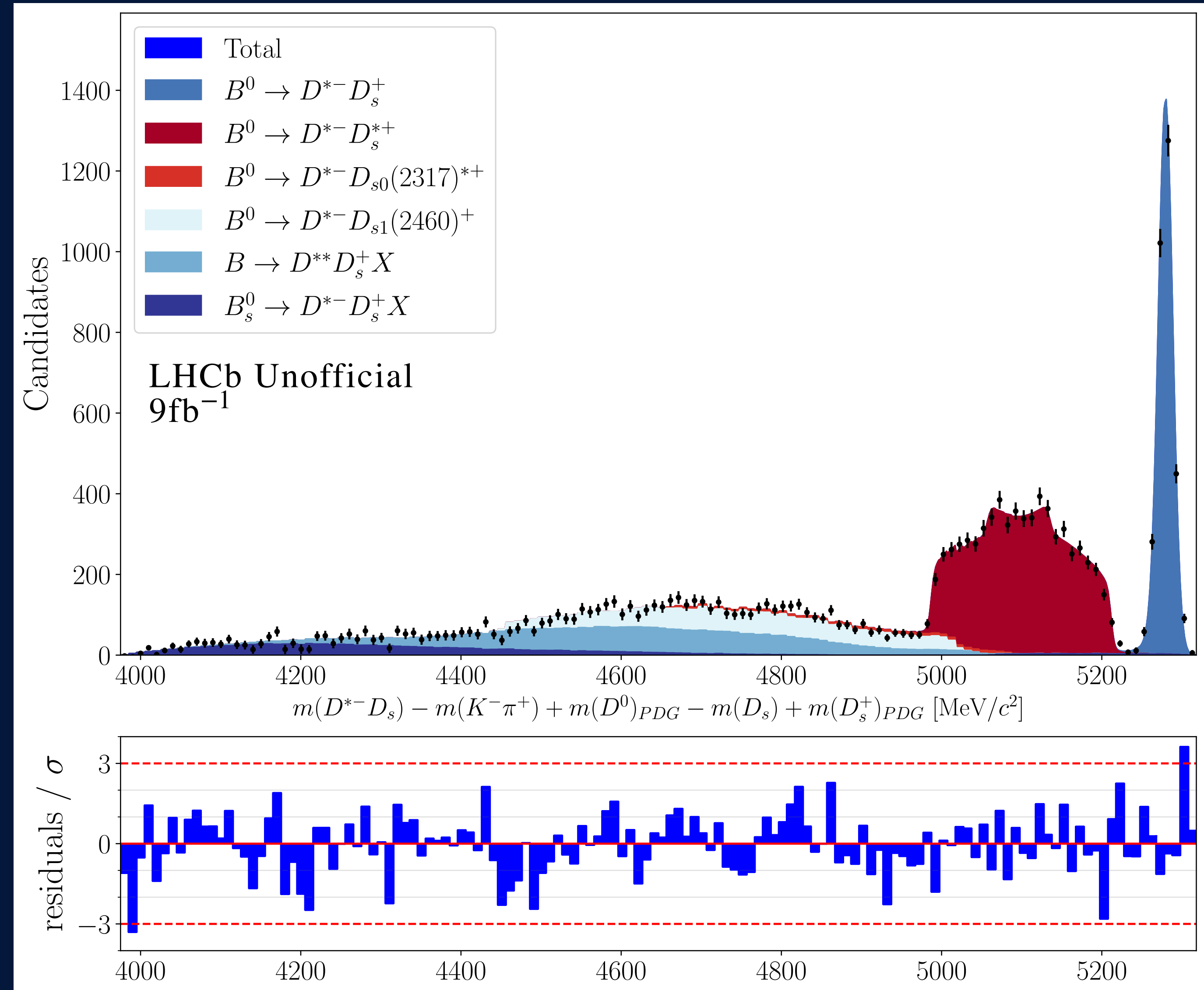
- ▶ Isolate  $D_s \rightarrow \pi^+ \pi^- \pi^+$  with  $m(\pi^+ \pi^- \pi^+)$  fit and sWeights
  - ▶  $m(\pi^+ \pi^- \pi^+) \in m(D_s)_{\text{PDG}} \pm 200.0 \text{ MeV}/c^2$
- ▶ Fit  $m(D^* \pi^+ \pi^- \pi^+)$  with control selection applied
- ▶ Measure fractions of different  $B \rightarrow D^* D_s(X)$  decays
- ▶ Compare to fractions of  $B \rightarrow D^* D_s(X)$  decays generated in MC
- ▶ Calculate weights to correct these fractions





## $B \rightarrow D^* D_s(X)$ TEMPLATES AND PDFS

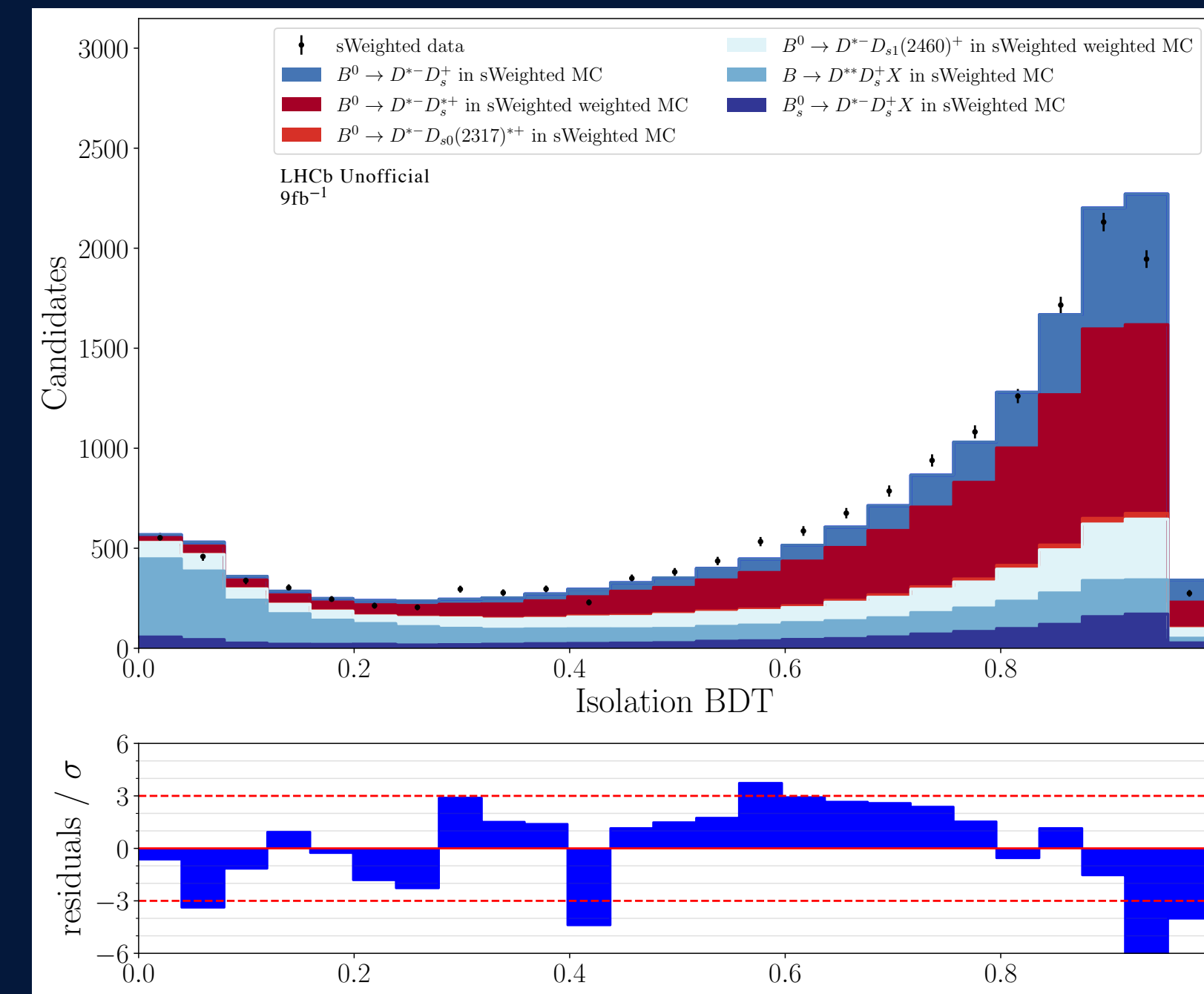
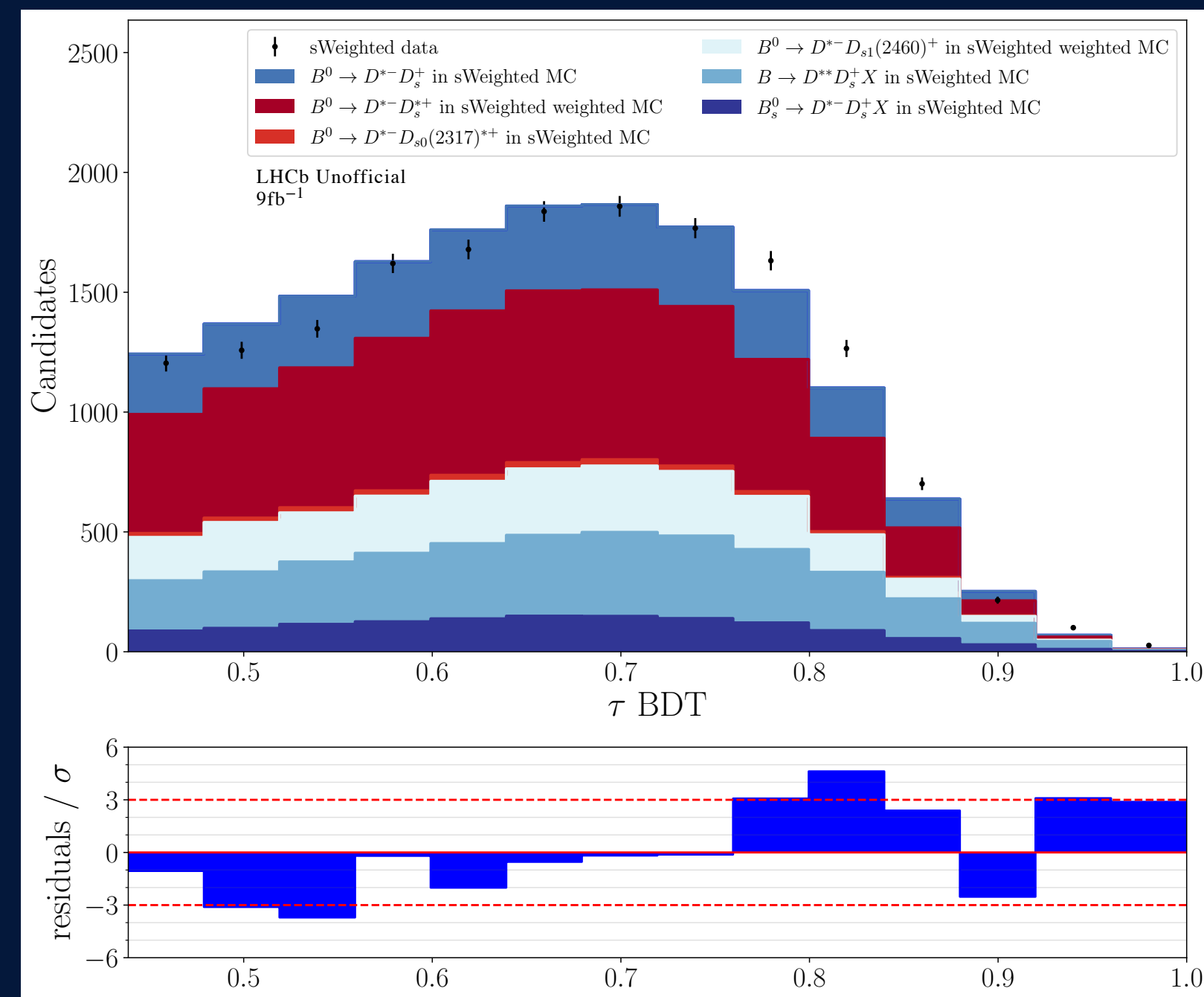
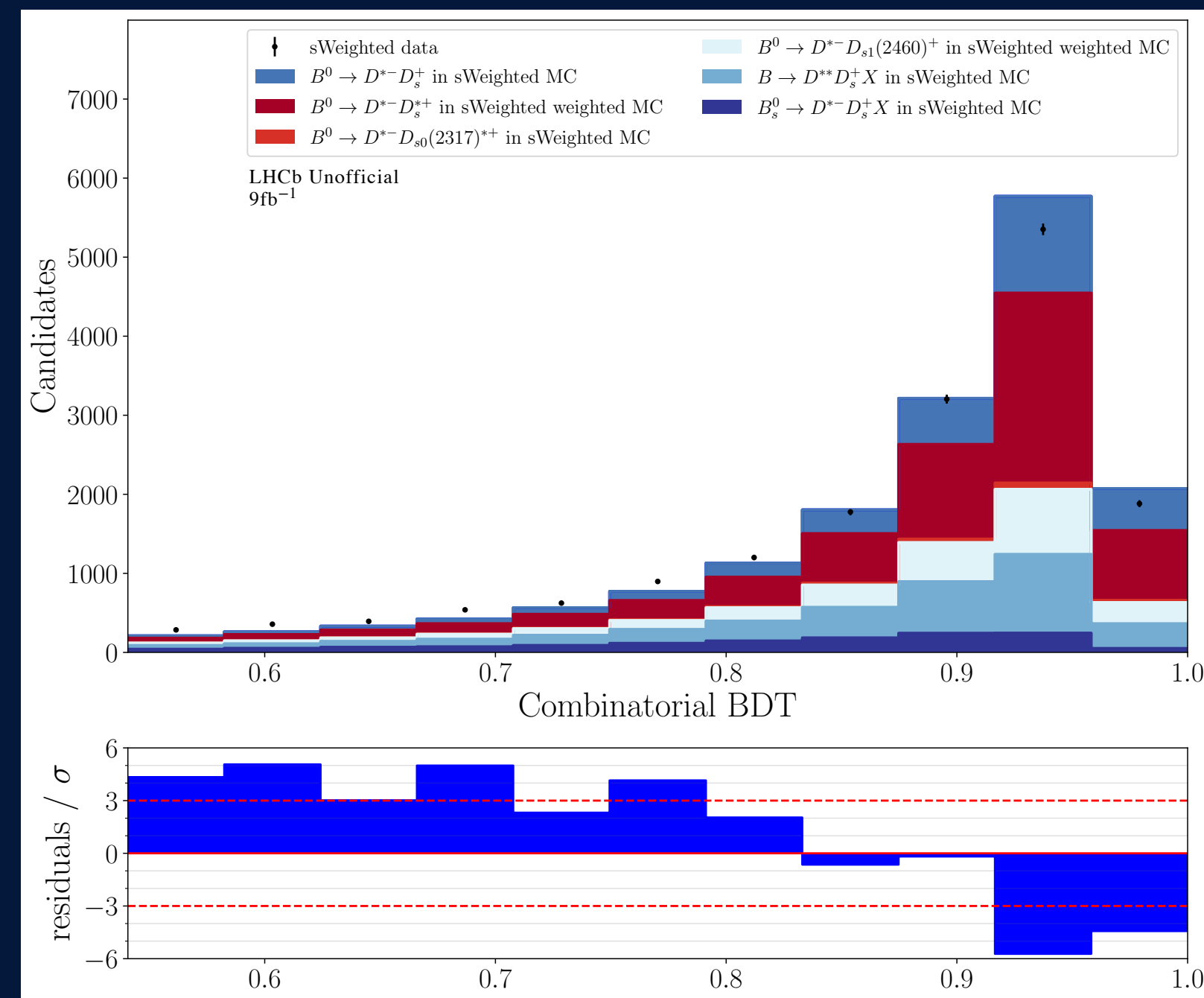
- ▶ Fit  $B^0 \rightarrow D^* D_s^*$  RooHORNSdini and RooHILLdini PDFs from the published  $B^0 \rightarrow D^* D_s^*$  analysis: <https://arxiv.org/abs/2105.02596>
  - ▶ Also use  $f_L = 0.578$  from that analysis
- ▶ Fit  $B^0 \rightarrow D^* D_s$  using a sum of Crystal Balls
- ▶ Lower mass components are templates taken from MC



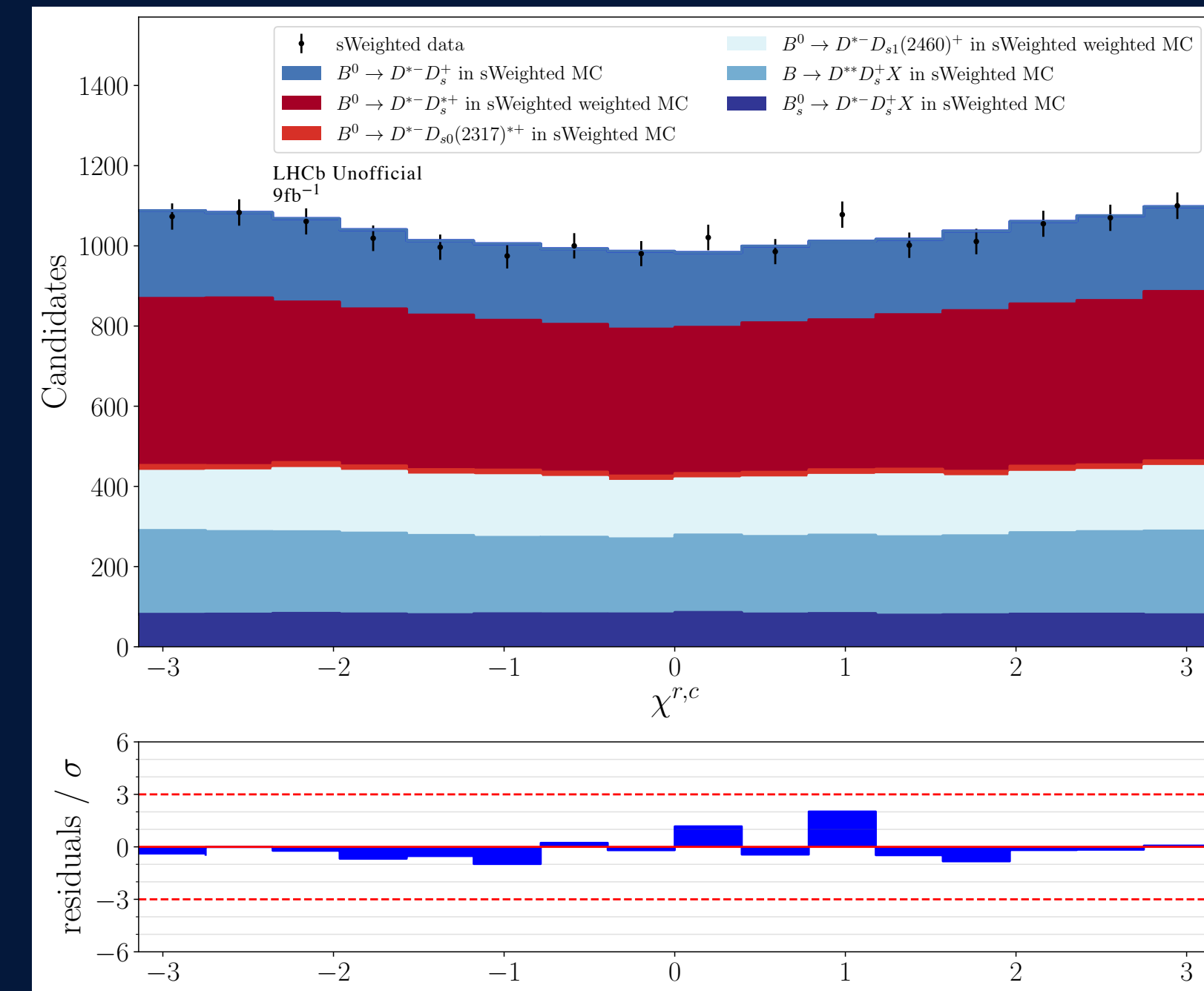
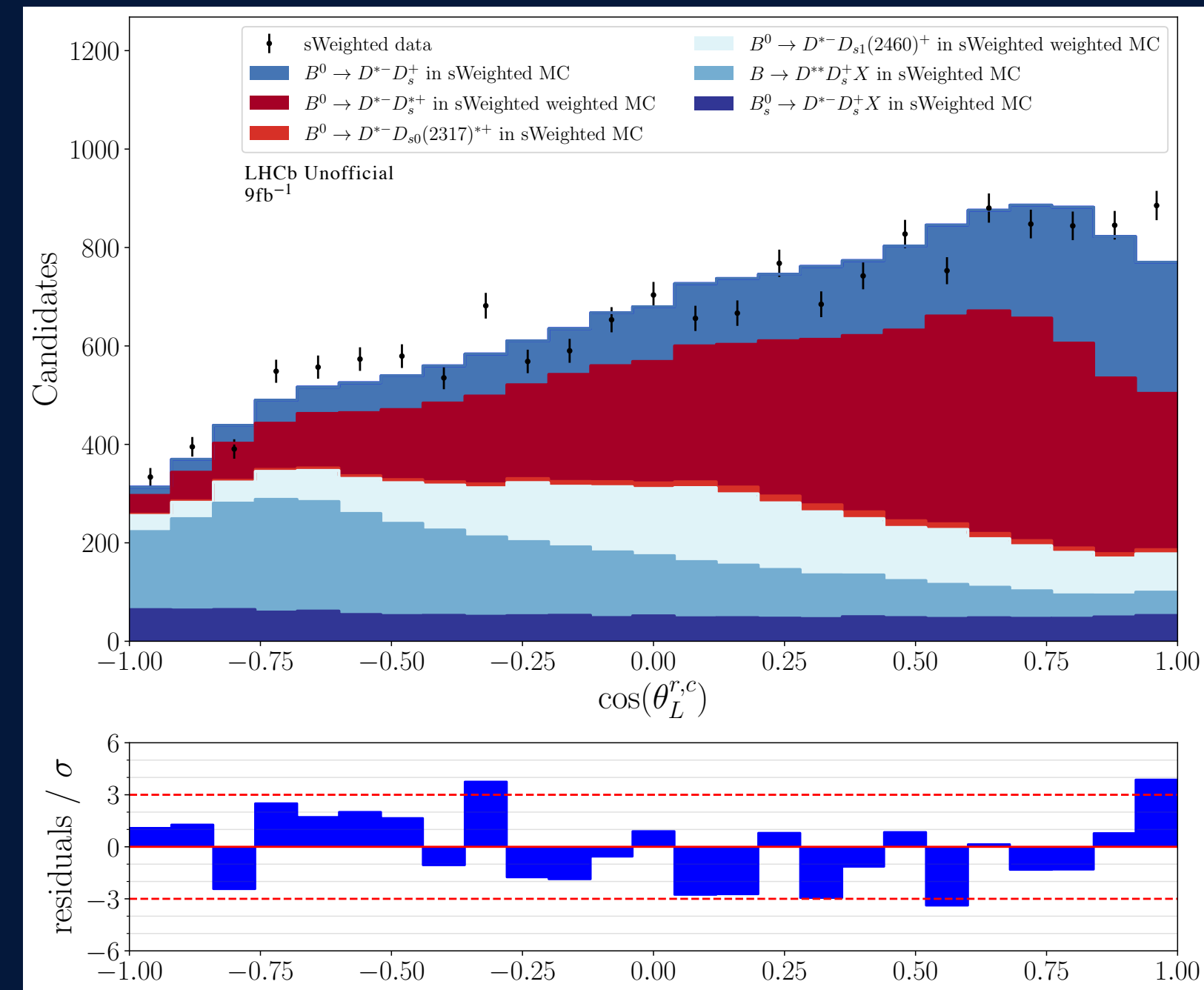
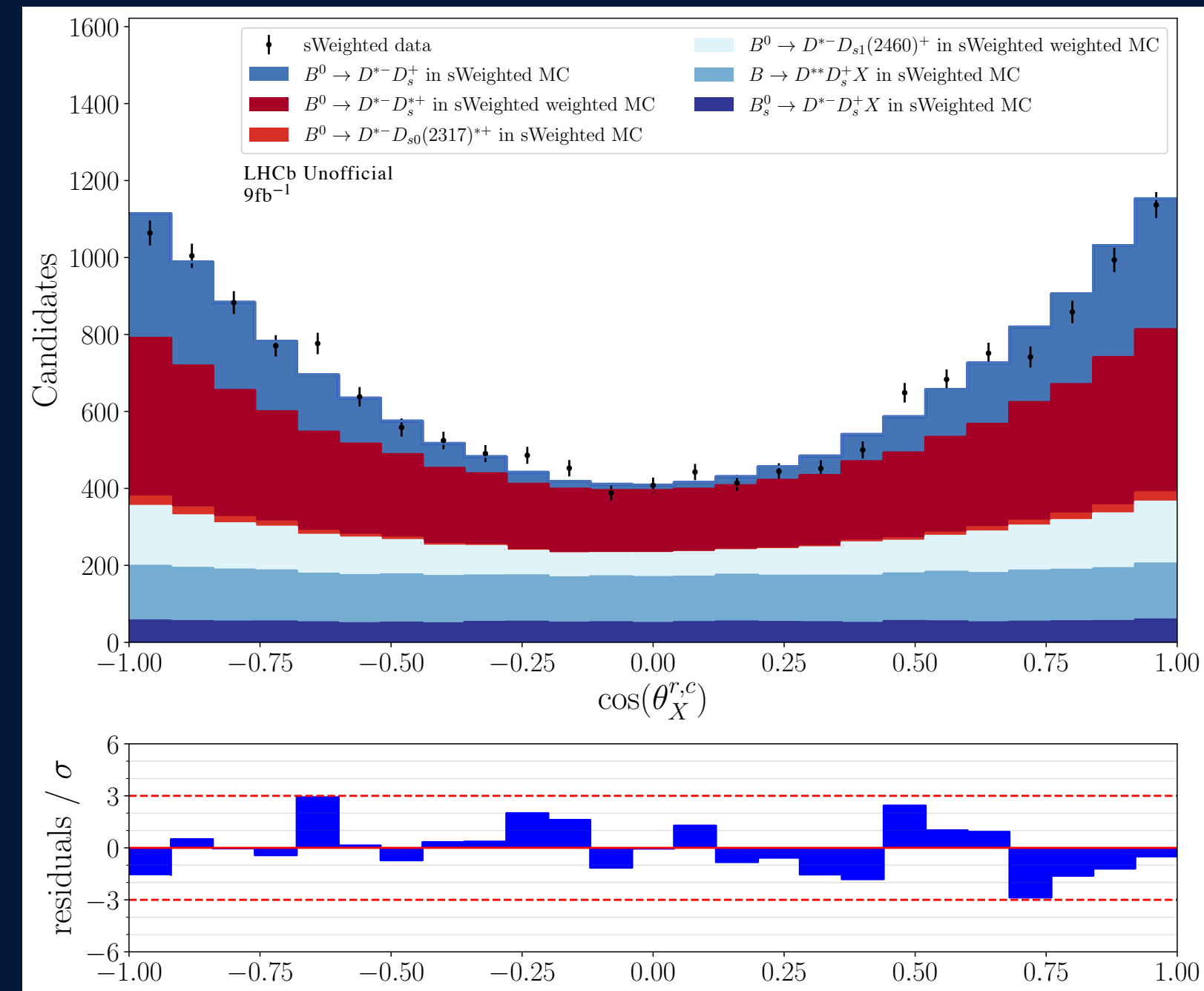
# $B \rightarrow D^* D_s(X)$ CONTROL STUDY - BDTs

▶  $B \rightarrow D^*(D_s \rightarrow \pi^+ \pi^- \pi^+)(X)$  data

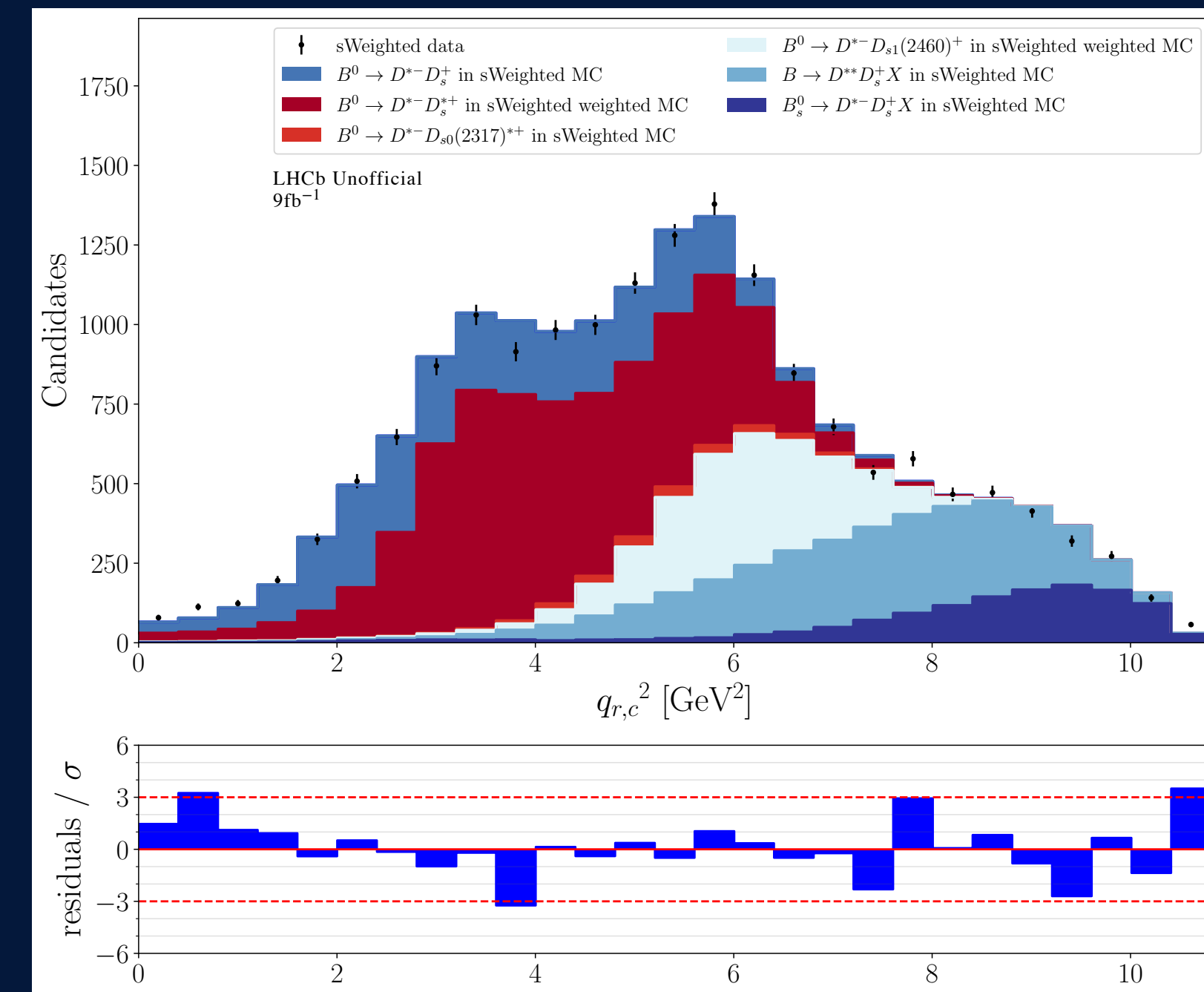
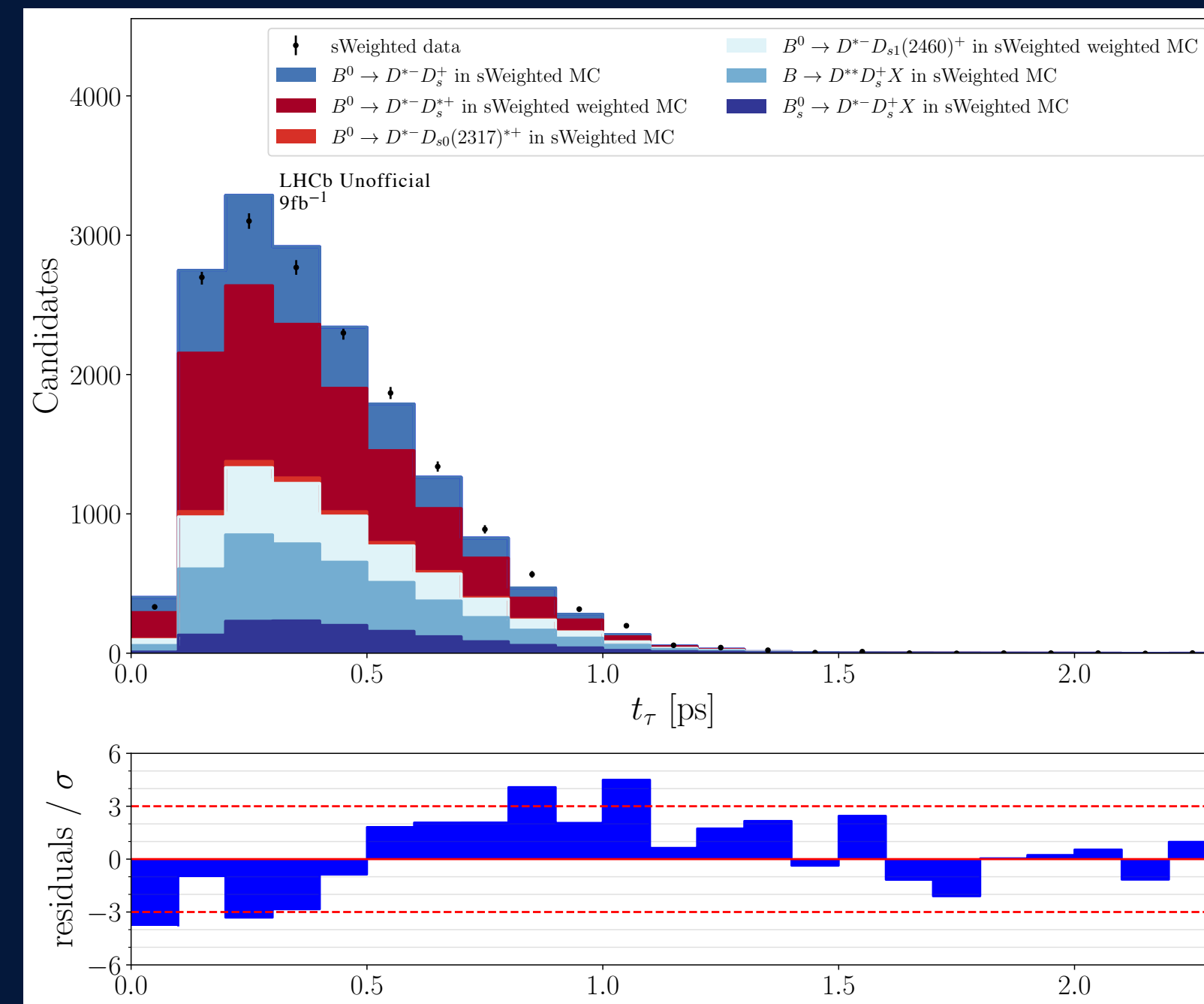
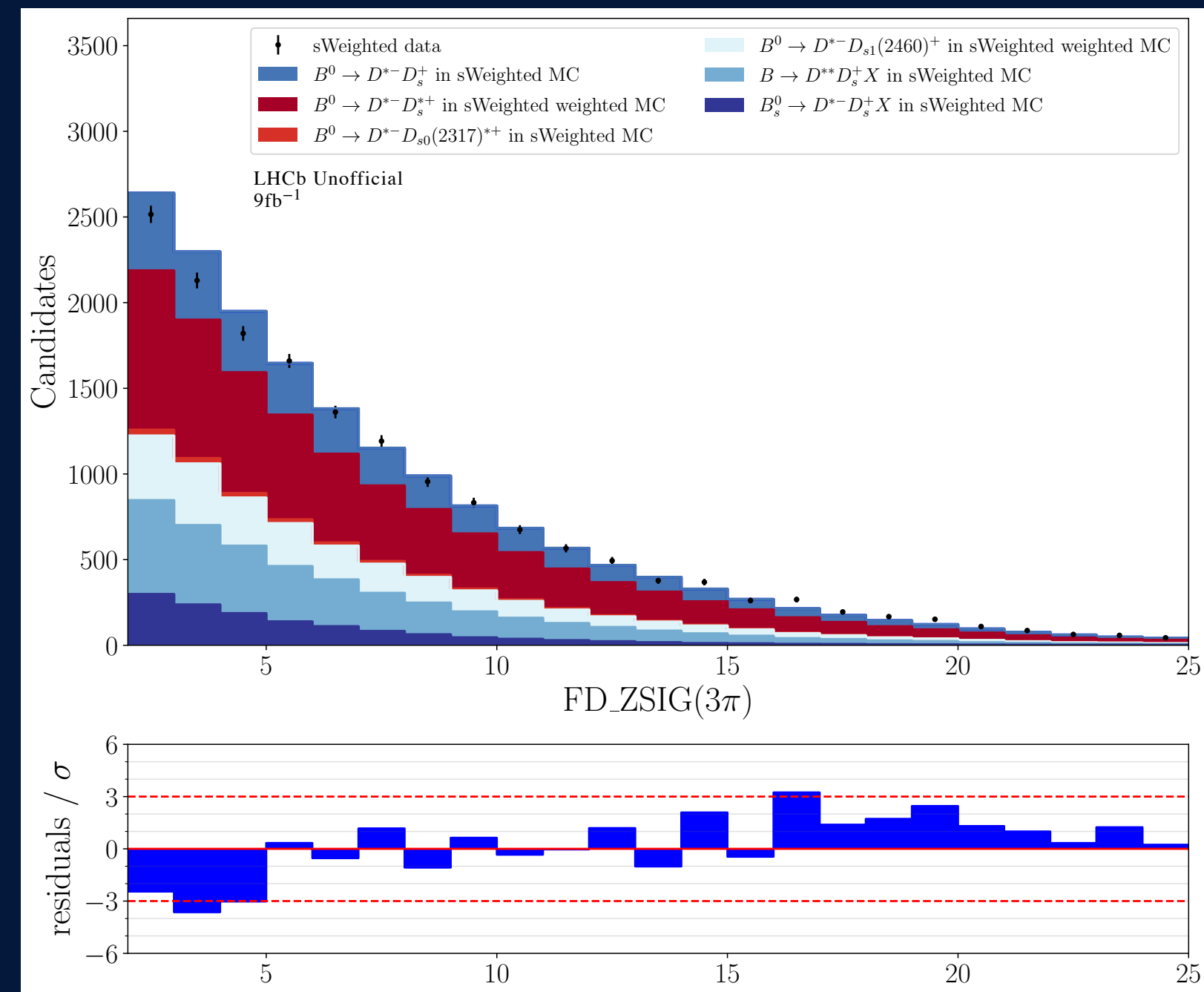
▶  $B \rightarrow D^*(D_s \rightarrow \pi^+ \pi^- \pi^+)(X)$  MC summed using the fractions measured in  $m(D^* \pi^+ \pi^- \pi^+)$  fit



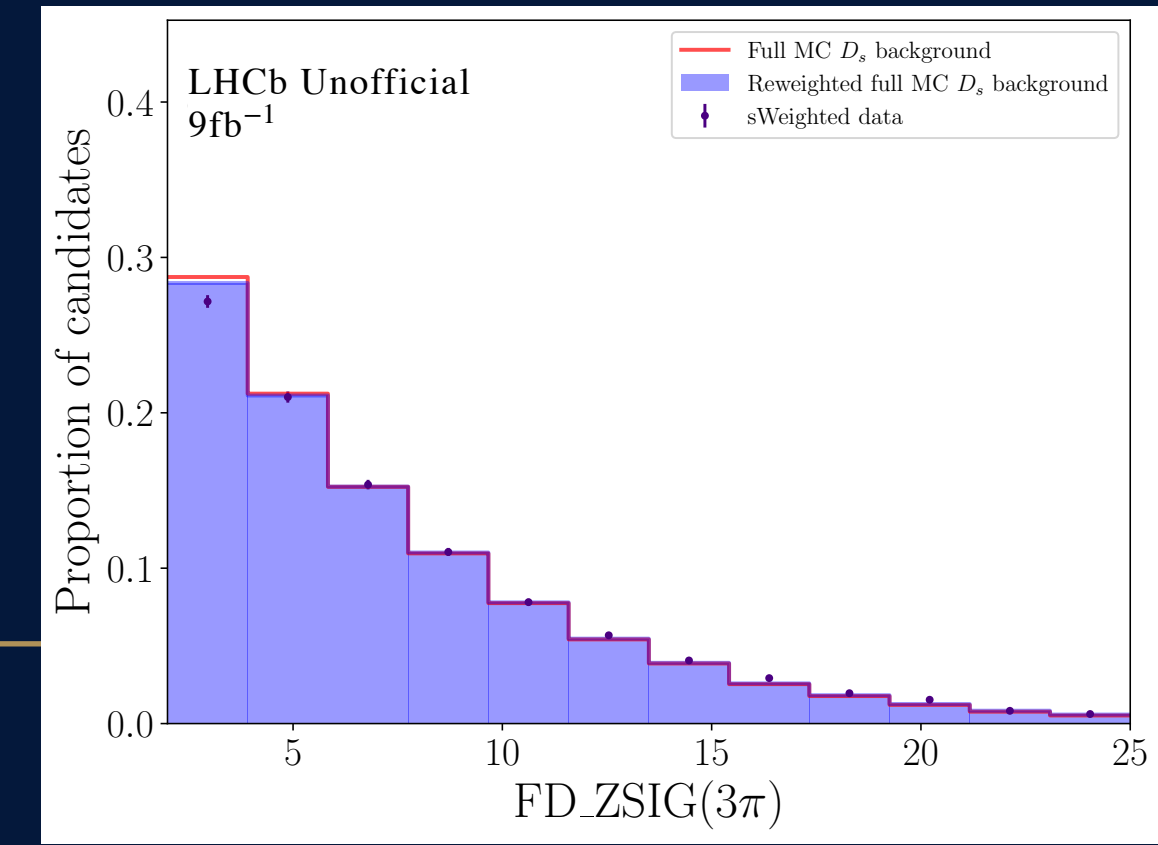
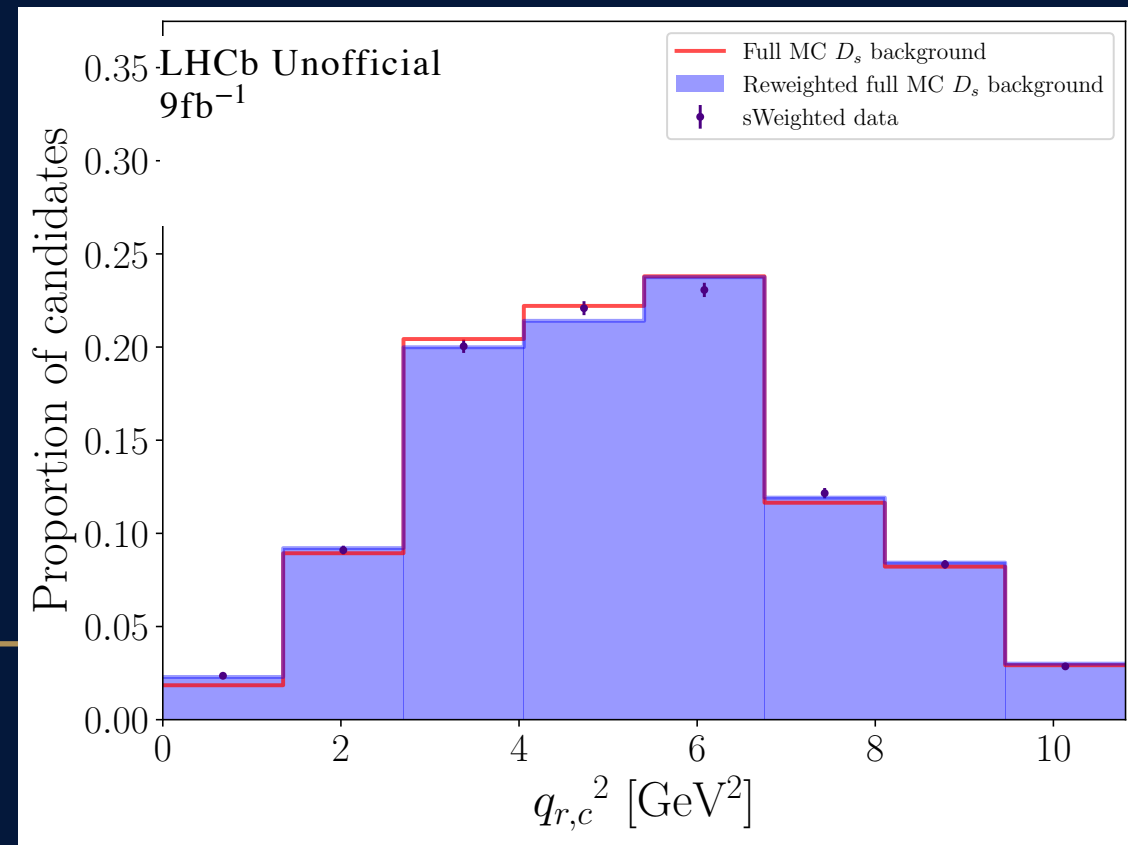
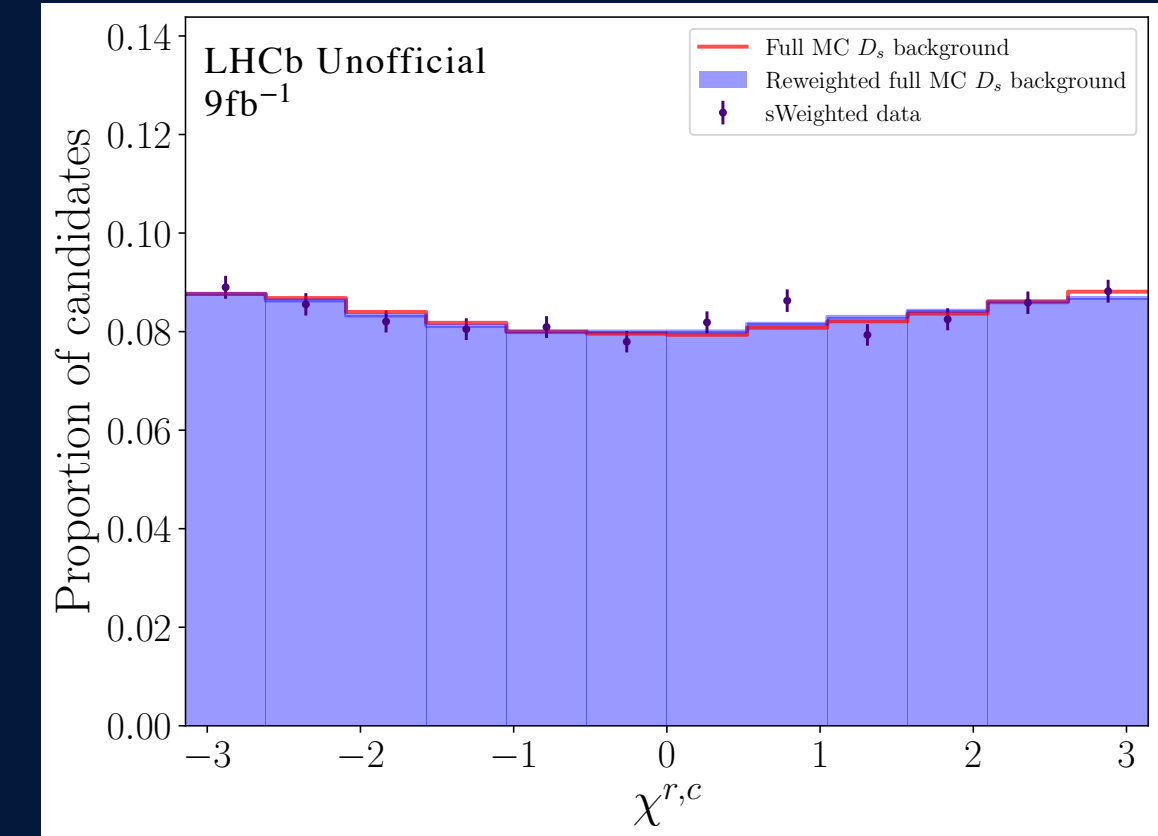
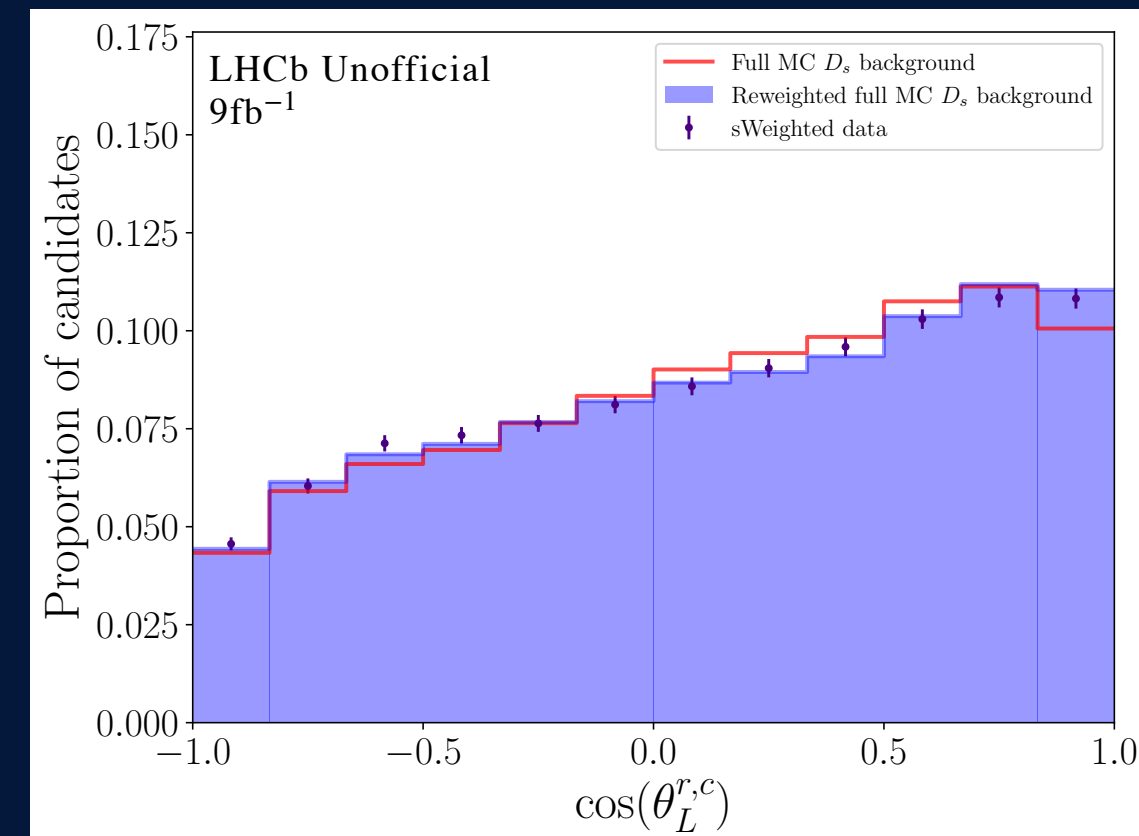
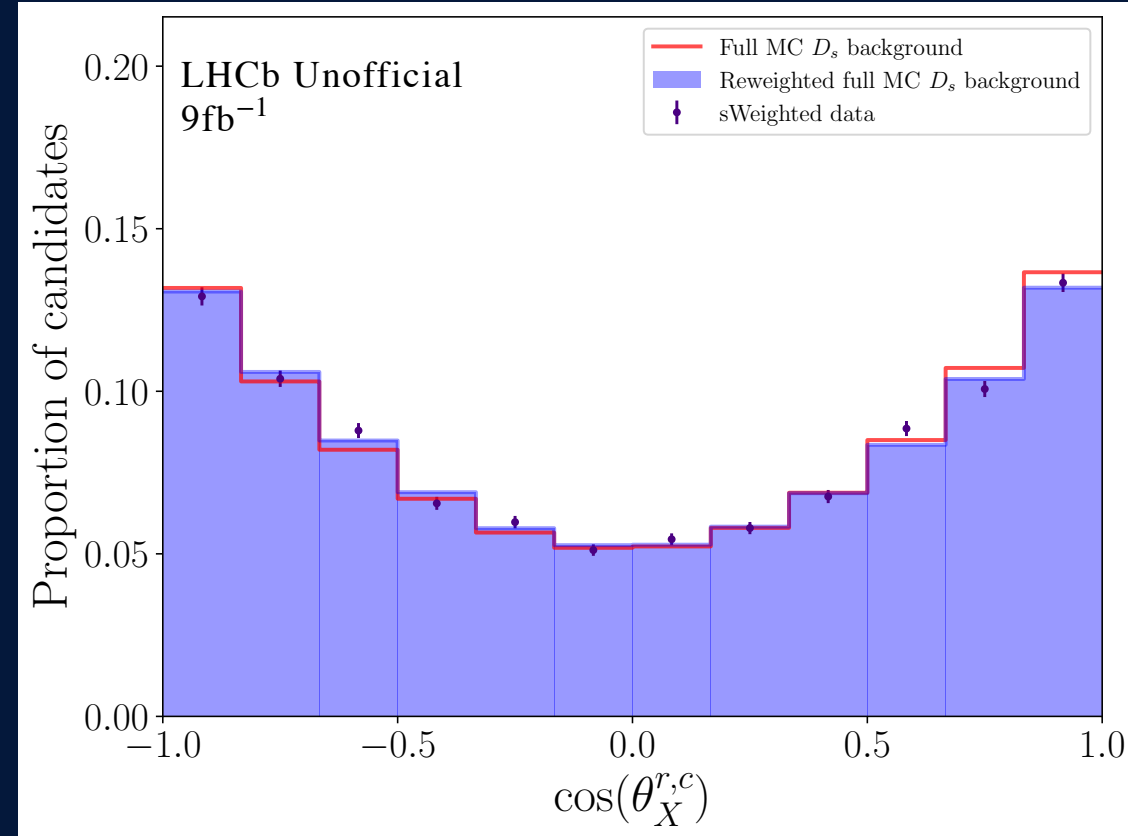
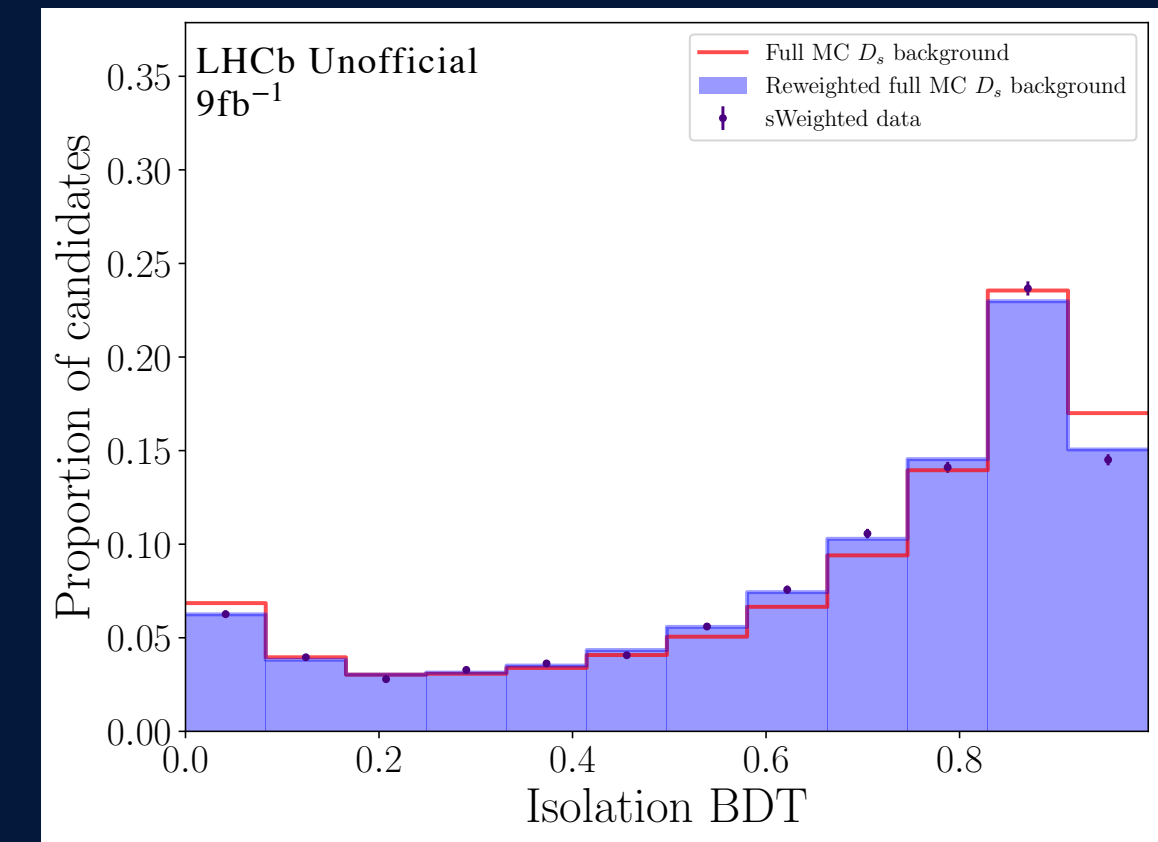
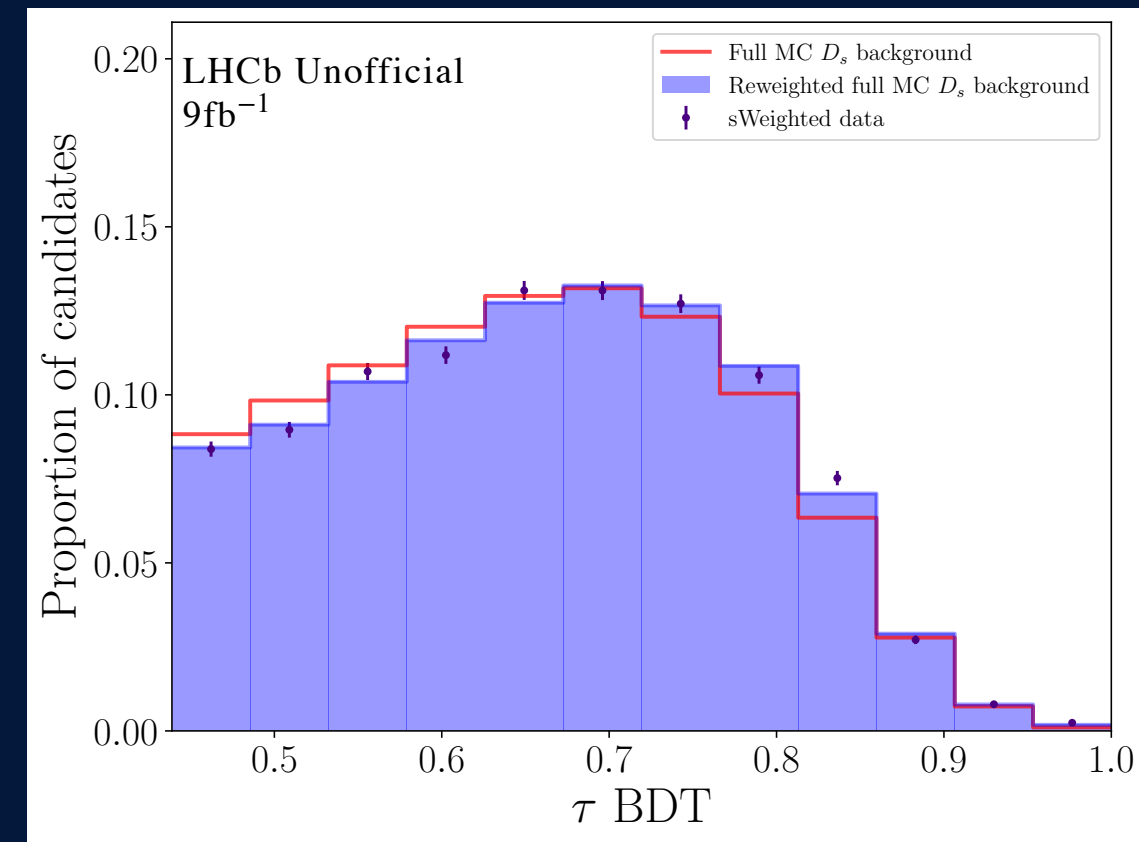
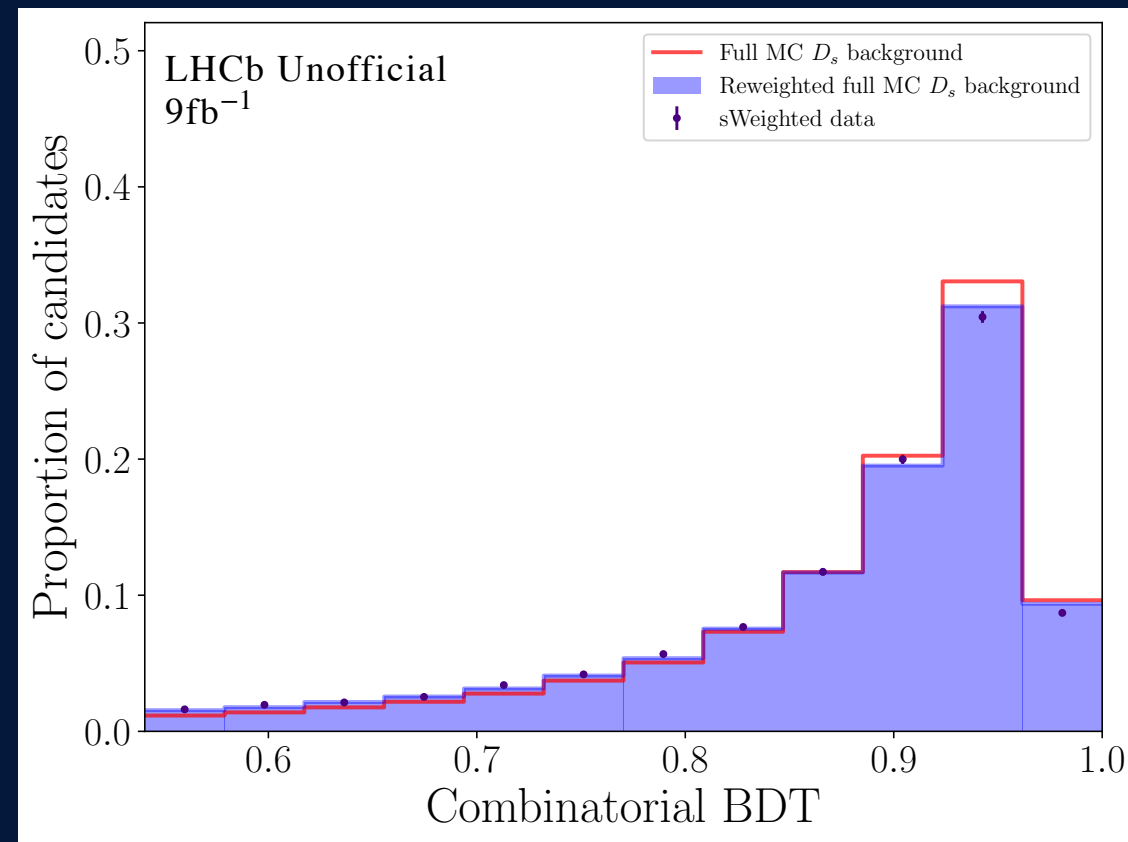
# $B \rightarrow D^* D_s(X)$ CONTROL STUDY - DECAY ANGLES



# $B \rightarrow D^* D_s(X)$ CONTROL STUDY - OTHER VARIABLES



# $B \rightarrow D^* D_s(X)$ VARIABLES AFTER REWEIGHTING



Use spline reweighting to correct residual discrepancies

- ▶ Imperfect knowledge of  $B \rightarrow D^{**} D_s(X)$  modes and their relative proportions



## CONTROL STUDIES

- ▶ Several control studies
  - ▶  $B \rightarrow D^{*-}D^0(X)$  : Weights for data/MC agreement
    - ▶ Isolate  $B \rightarrow D^{*-}D^0(X)$  via  $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$  using  $s$ Weights
  - ▶  $B \rightarrow D^{*-}D^+(X)$  : Weights for data/MC agreement
    - ▶ Isolate  $B \rightarrow D^{*-}D^+(X)$  via  $D^+ \rightarrow K^-\pi^+\pi^+$  using  $s$ Weights
  - ▶  $B \rightarrow D^{*-}D_s(X)$  : Weights for data/MC agreement and for relative decay fractions
    - ▶ Isolate  $D_s \rightarrow \pi^+\pi^-\pi^+$  using  $s$ Weights
    - ▶ Fit  $m(D^{*-}D_s)$  to measure decay fractions
  - ▶  $D_s \rightarrow \pi^+\pi^-\pi^+(X)$  : Weights for relative decay fractions
    - ▶ Simultaneous fit in four variables to measure decay fractions
- ▶ Methodology aligned with the Run 1  $\mathcal{R}(D^*)$  measurement [PRL 120 \(2018\) 171802](#), [PRD 97 \(2018\) 072013](#)

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 $D_s \rightarrow \pi^+ \pi^- \pi^+(X)$  CONTROL STUDY

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- ▶ MC contains certain fractions of  $D_s \rightarrow \pi^+ \pi^- \pi^+(X)$  decays
- ▶ Not necessarily aligned with data
- ▶ Need to perform a fit to measure these fractions in data and correct the MC
- ▶ Simultaneous fit in four variables
  - ▶  $m(\pi^+ \pi^+)$
  - ▶  $\min[m(\pi^+ \pi^-)]$
  - ▶  $\max[m(\pi^+ \pi^-)]$
  - ▶  $m(\pi^+ \pi^- \pi^+)$

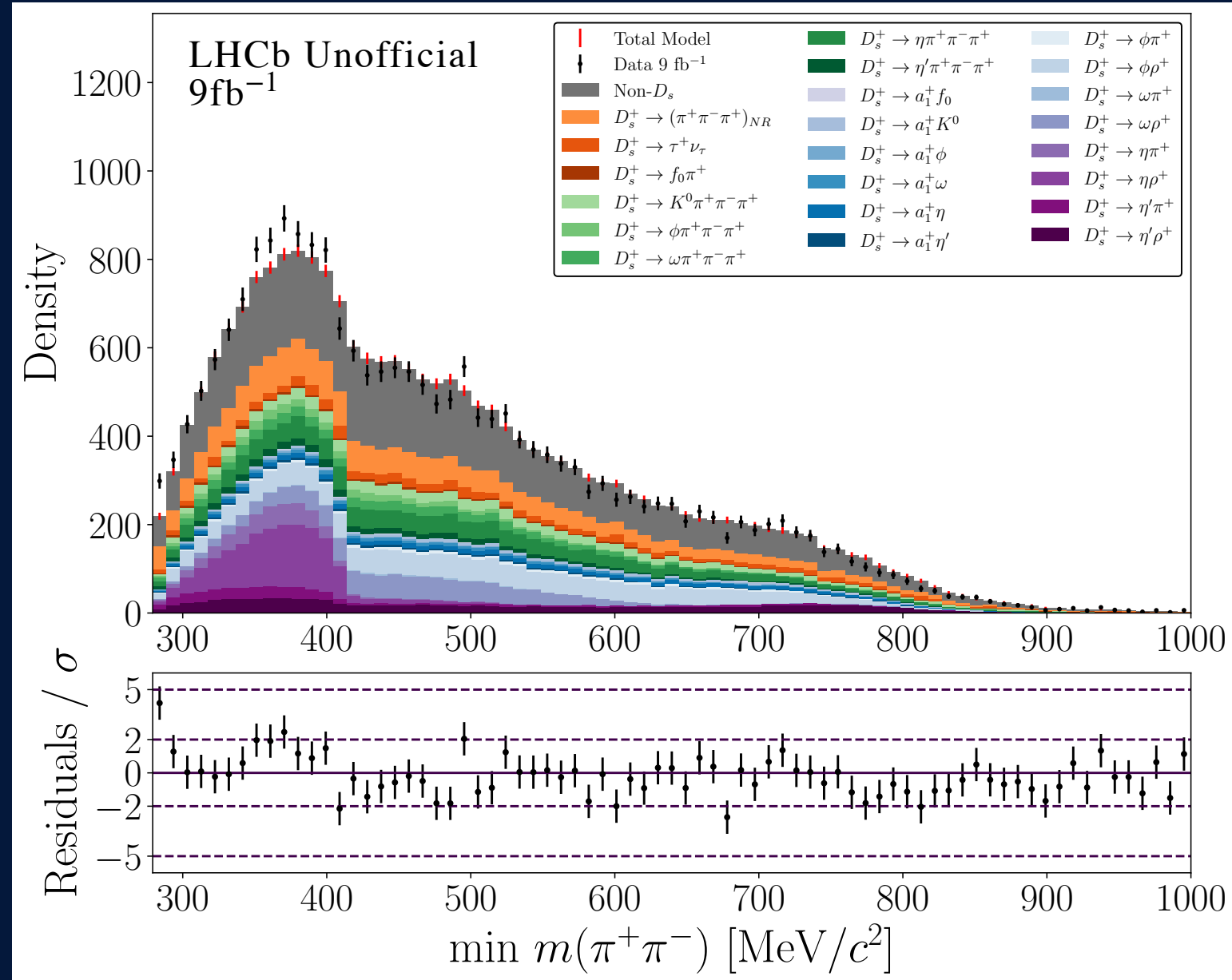
# $D_s \rightarrow \pi^+ \pi^- \pi^+(X)$ SELECTION

Variable	Condition
Trigger	(B0_L0HadronDecision_TOS or B0_L0Global_TIS) and (B0_Hlt1TrackMVADecision_TOS or B0_Hlt1TwoTrackMVADecision_TOS) and (B0_Hlt2Topo2BodyDecision_TOS or B0_Hlt2Topo3BodyDecision_TOS or B0_Hlt2Topo4BodyDecision_TOS)
PV( $\tau^+$ )	= PV( $D^0$ )
$V_z(\tau^+) - V_z(\text{PV})/\text{error}$	> 10.0
$m(D^{*-} \pi^+ \pi^- \pi^+)$	< 5000.0 MeV/ $c^2$
$m(D^* - D^0)$	$\in [140.0, 160.0]$ MeV/ $c^2$
$m(D^0)$	$\in m(D^0)_{\text{PDG}} \pm 40.0$ MeV/ $c^2$
$\tau$ flight distance significance	$\in [4.0, 25.0]$
Combinatorial BDT	> 0.5407
$\tau$ BDT	< 0.4388
Isolation BDT	> 0.8017
$\min[m(\pi^+ \pi^-)]$	$\in [2m(\pi^\pm), 1000]$ MeV/ $c^2$
$\max[m(\pi^+ \pi^-)]$	$\in [300, 1500]$ MeV/ $c^2$
$m(\pi^+ \pi^+)$	$\in [2m(\pi^\pm), 1500]$ MeV/ $c^2$
$m(\pi^+ \pi^- \pi^+)$	$\in [500, 1600]$ MeV/ $c^2$

$D_s \rightarrow \pi^+ \pi^- \pi^+(X)$  PID SELECTION

Variable	Condition
$\pi^+$	PIDK $< 4$
	$p \in [3000, 100,000] \text{ MeV}/c$
	$p_T \in [300, 10,000] \text{ MeV}/c$
$\pi^-$	PIDK $< 1$
	$p \in [3000, 100,000] \text{ MeV}/c$
	$p_T \in [300, 10,000] \text{ MeV}/c$

# $D_s \rightarrow \pi^+ \pi^- \pi^+(X)$ RESULTS - FIT VARIABLES



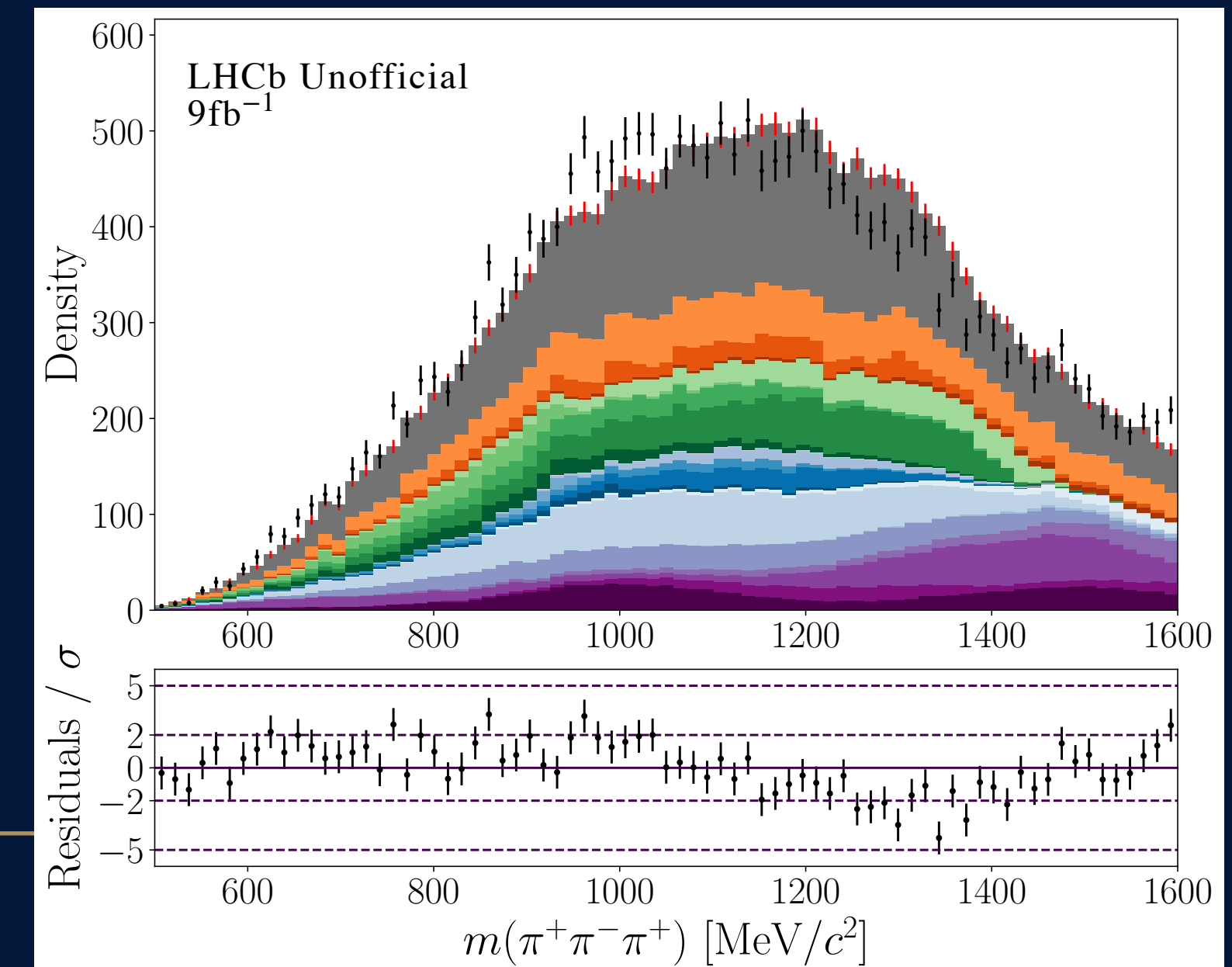
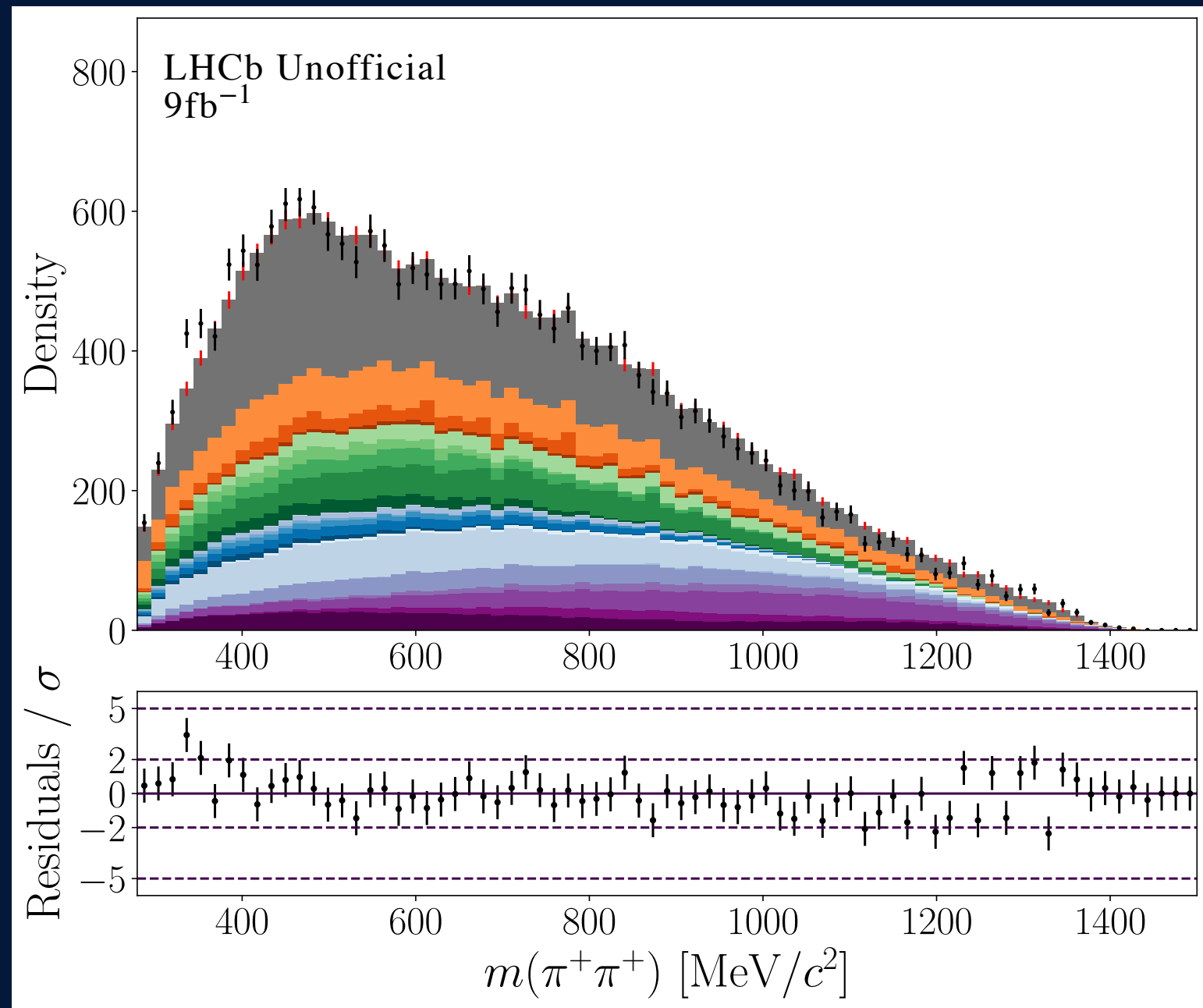
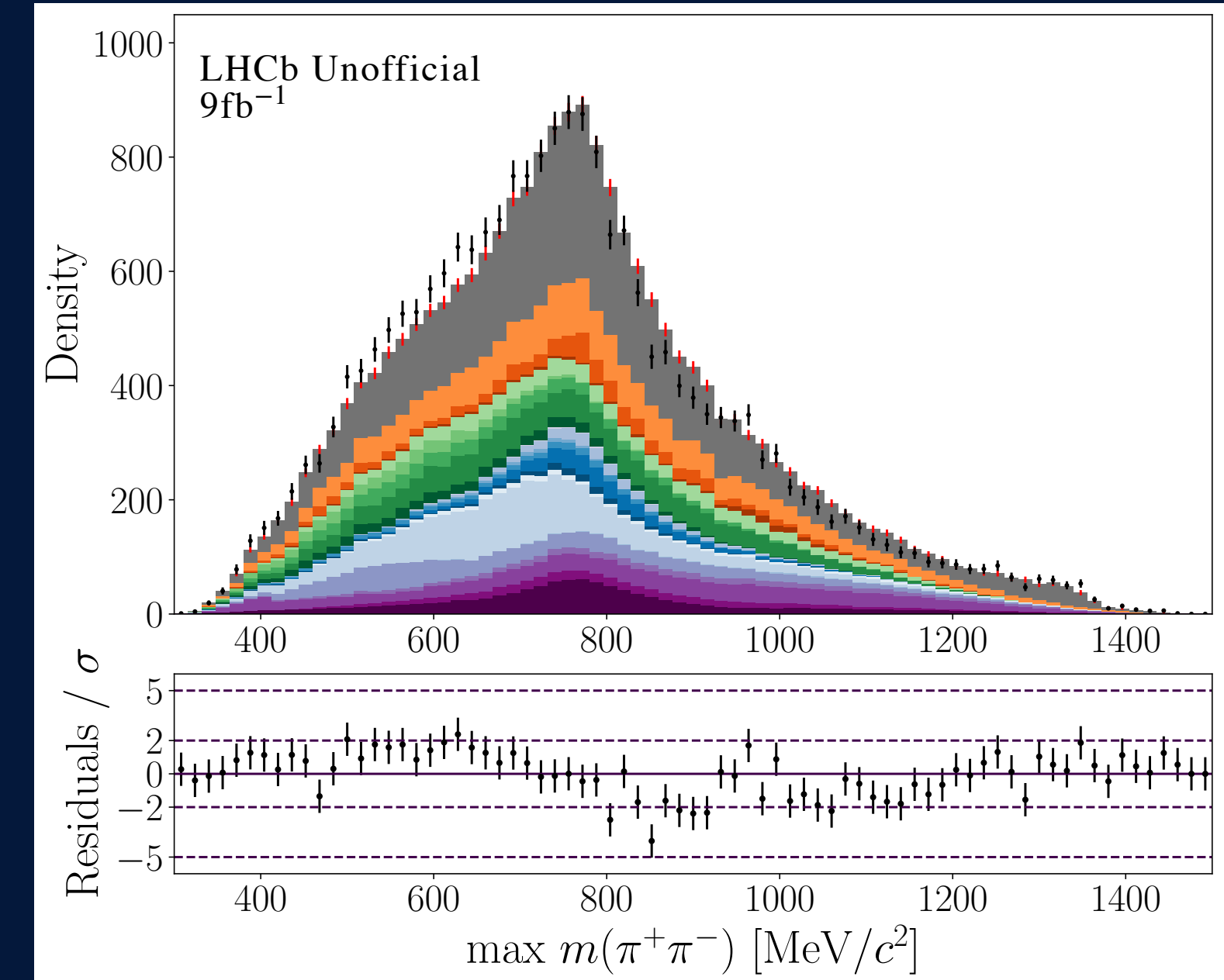
► Simultaneous fit in four variables

►  $m(\pi^+ \pi^+)$

►  $\min[m(\pi^+ \pi^-)]$

►  $\max[m(\pi^+ \pi^-)]$

►  $m(\pi^+ \pi^- \pi^+)$





A Feynman diagram illustrating a signal fit. It shows a particle interaction with several external lines and internal propagators. The diagram is drawn with gold lines on a dark blue background. It features a top vertex with a wavy line, a middle vertex with a wavy line, and a bottom vertex with a wavy line. A dashed line connects the middle and bottom vertices. The bottom vertex is connected to a series of four circles, which are then connected to a series of four more circles. The text "SIGNAL FIT" is centered in the diagram.

# SIGNAL FIT

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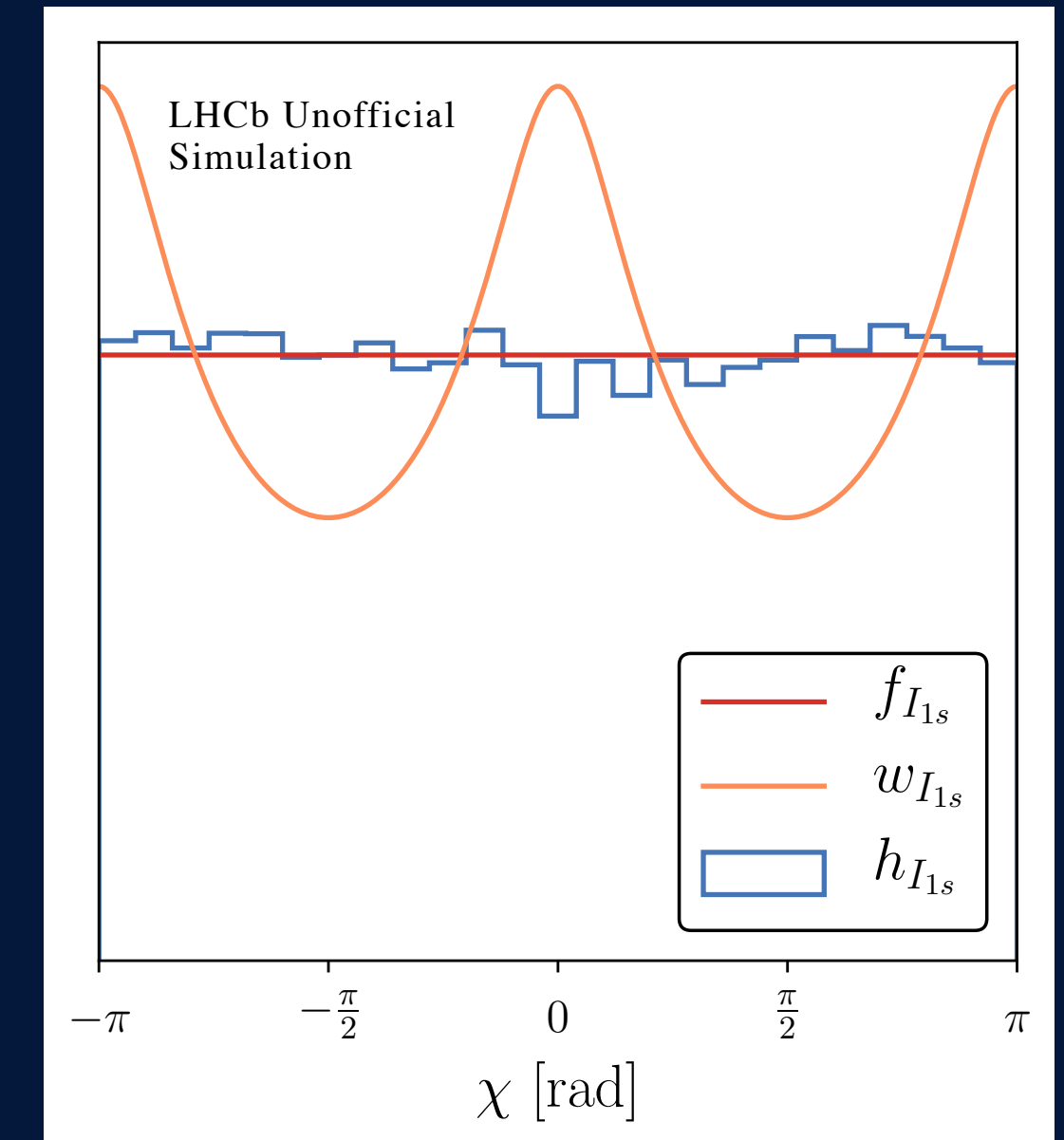
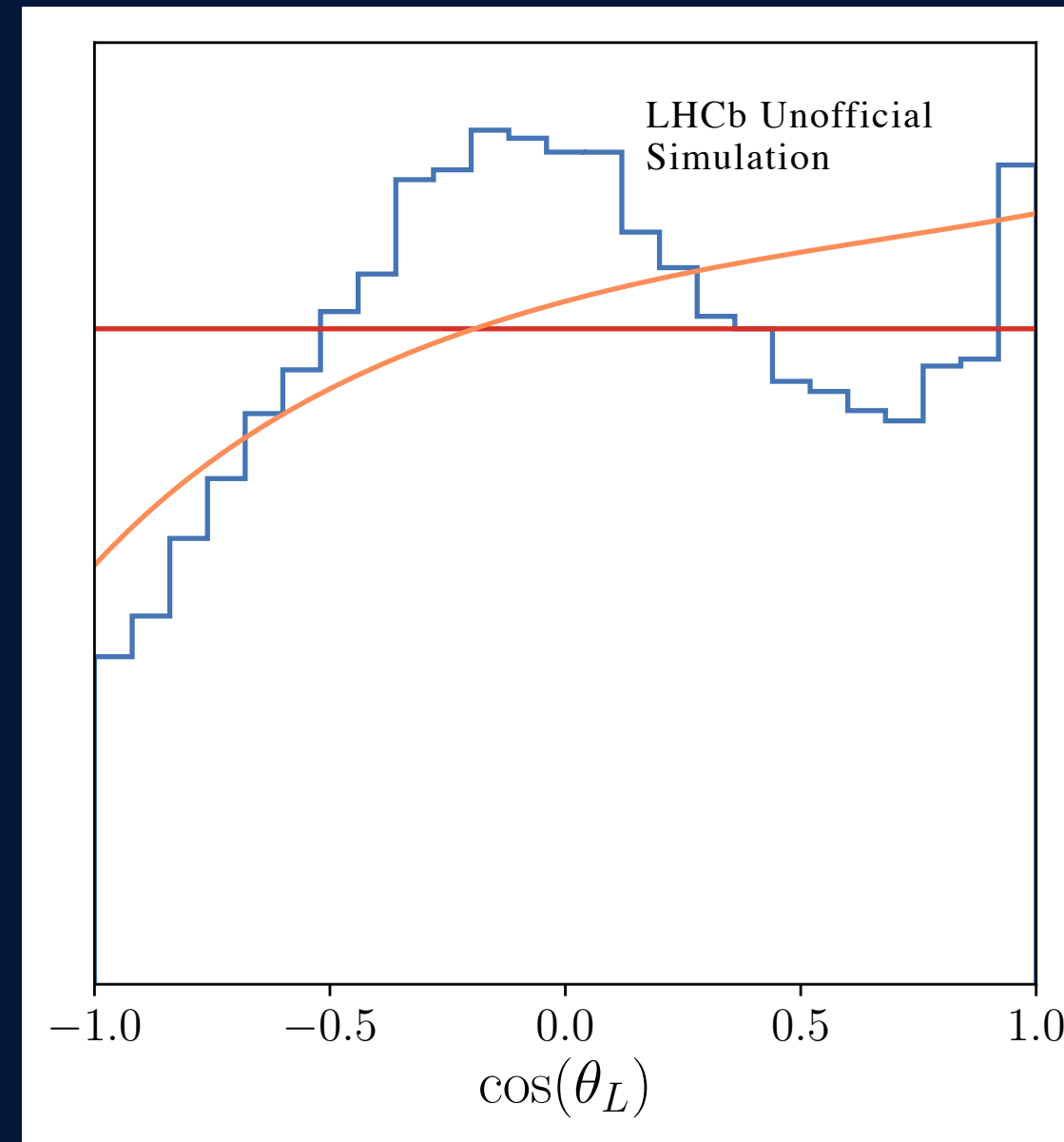
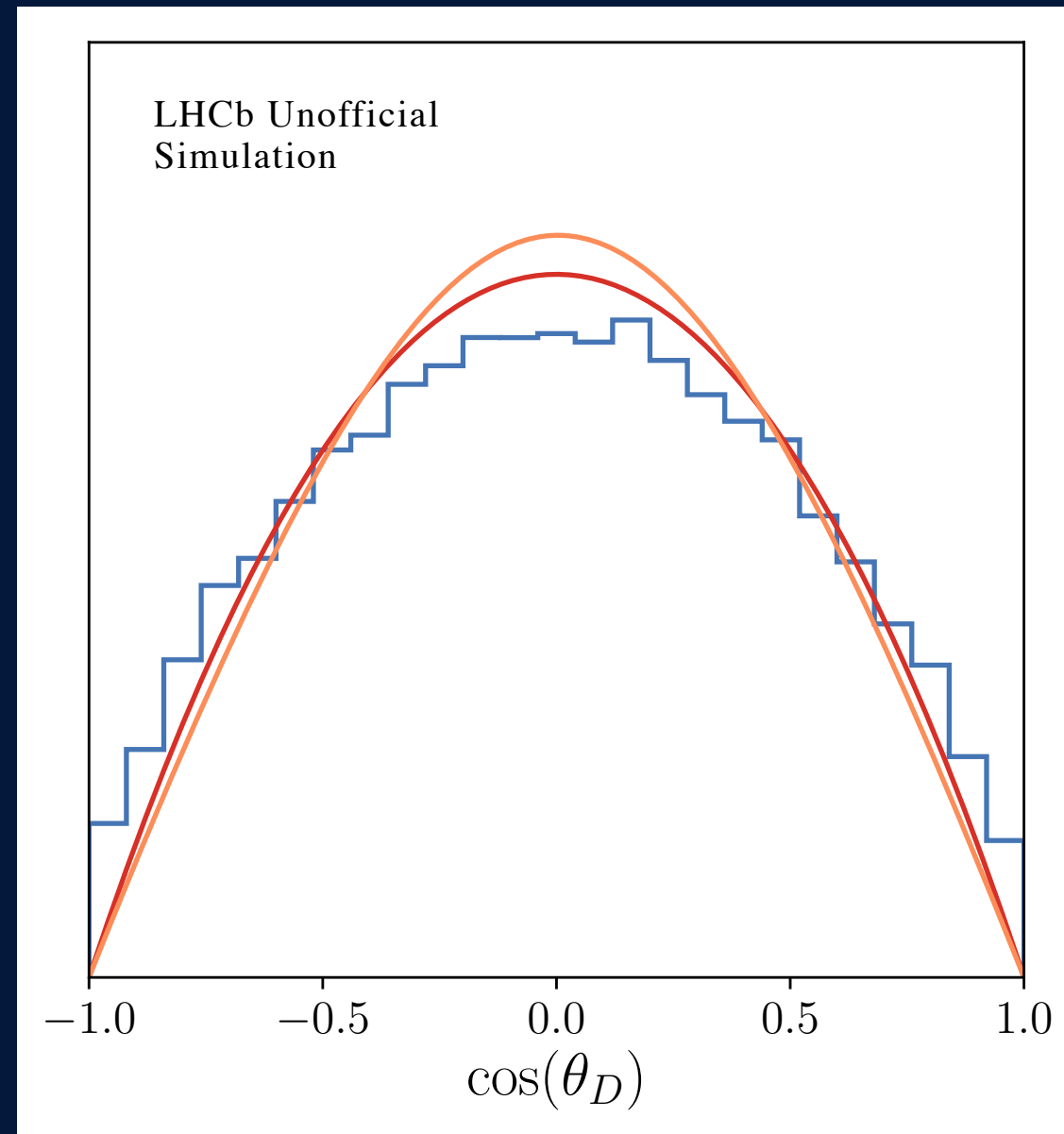
## SIGNAL FIT - SIGNAL PDF

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- ▶ Simultaneous multidimensional template fit
  - ▶ 3D fit in the decay angles
  - ▶ 3D fit in BDT,  $q^2$ ,  $\tau$   $z$  flight distance significance
  
- ▶ In traditional  $\mathcal{R}(D^*)$  analyses, the signal and background PDFs use SM simulation as the templates
  - ▶ Assumes SM and a form factor model
  
- ▶ In this analysis, background templates are still SM shapes taken from simulation
- ▶ The signal simulation is divided into 12 model independent angular templates,  $h_{I_x}$ 
  - ▶ Signal template is the sum of these angular templates
    - ▶ Each  $h_{I_x}$  is normalised by their  $I_x$  coefficient which floats in the fit:

$$P_{D^*\tau\nu} = \left( \frac{1}{3} (4 - 6I_{1s} + I_{2c} + 2I_{2s}) \right) h_{I_{1c}} + \sum_x I_x h_{I_x}$$

# SIGNAL PDF CREATION



- ▶ Take angular function for a particular  $I_x$ ,

$$f_{I_x}: I_{1s} \sin^2 \theta_D$$

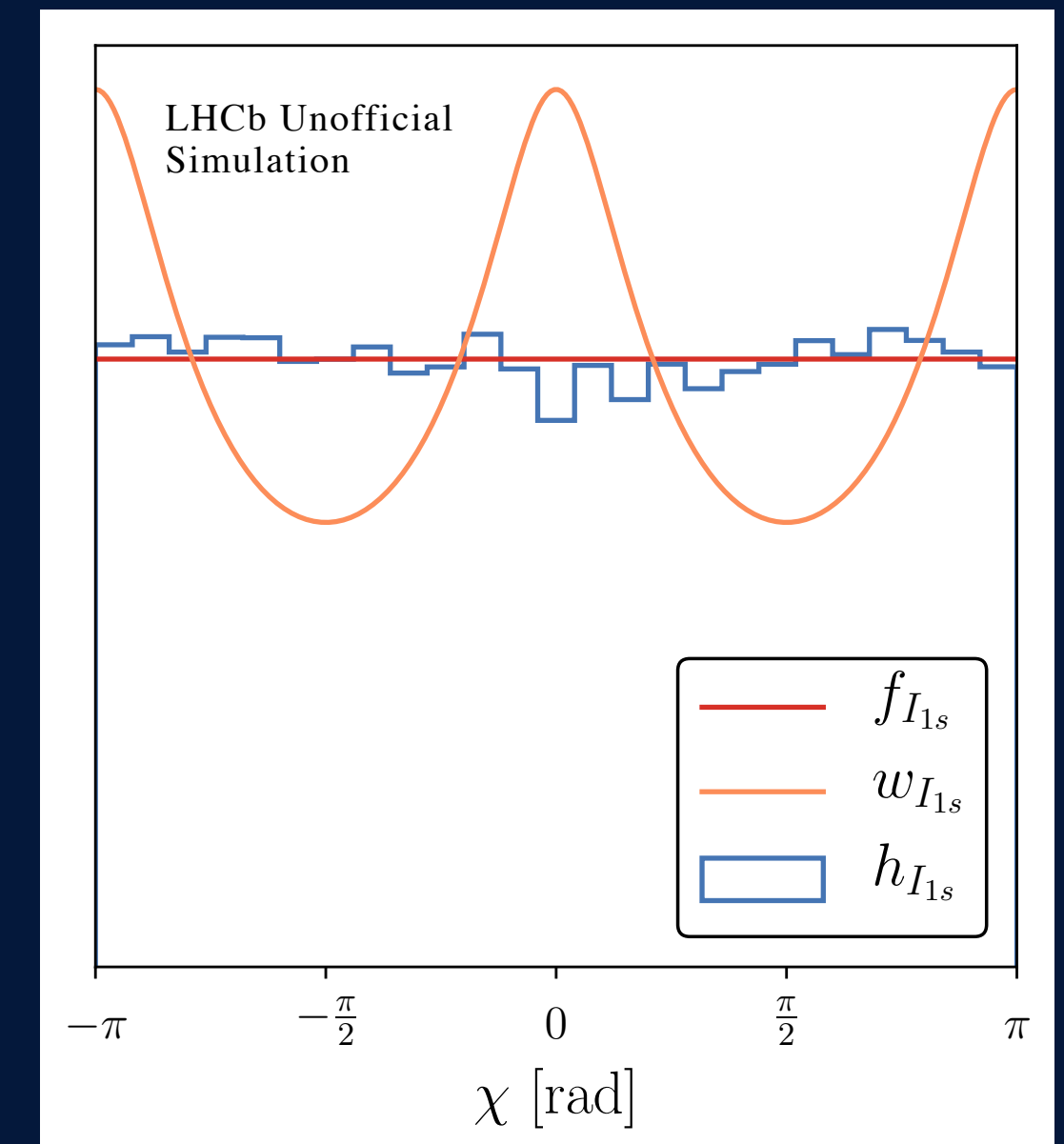
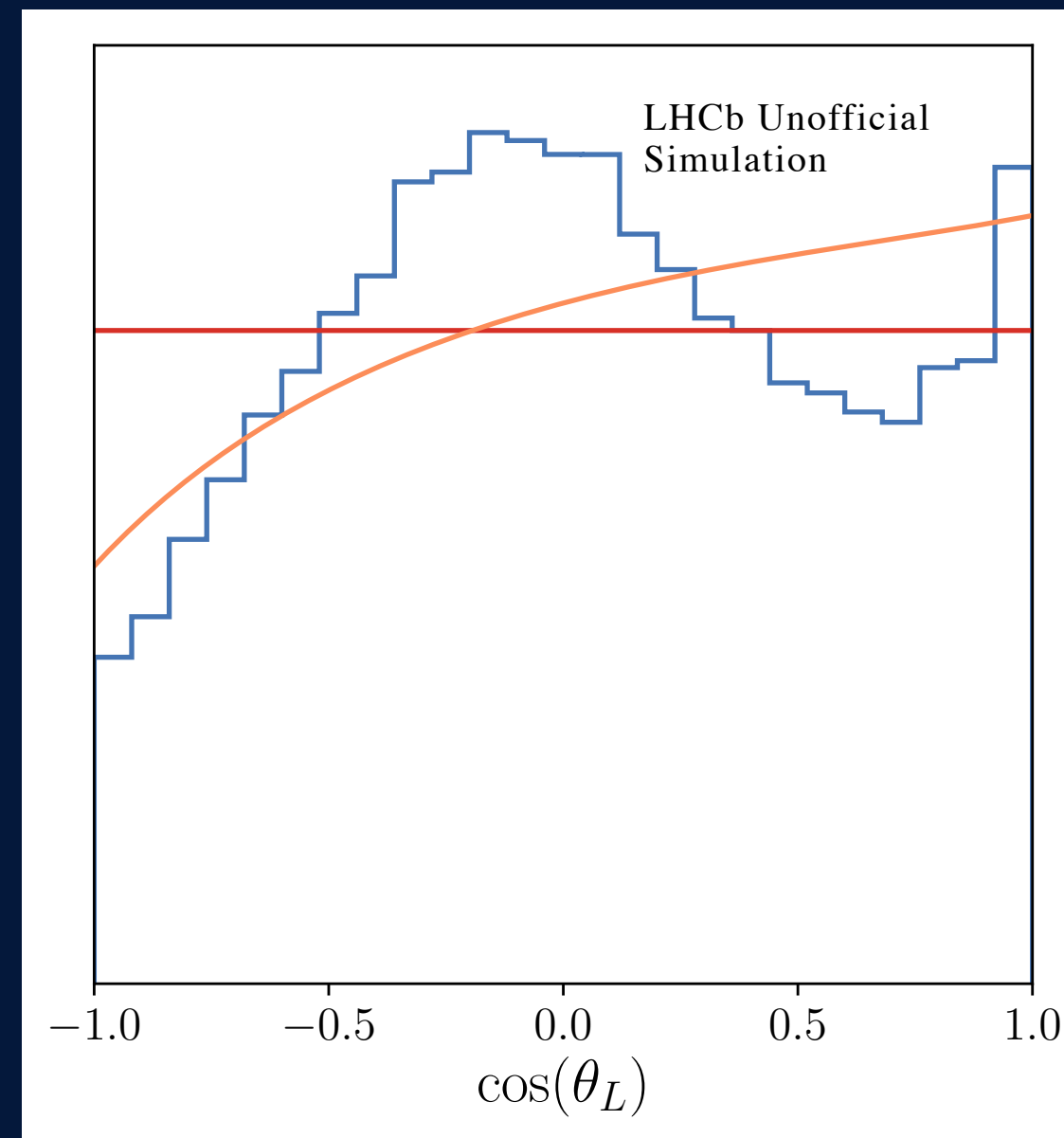
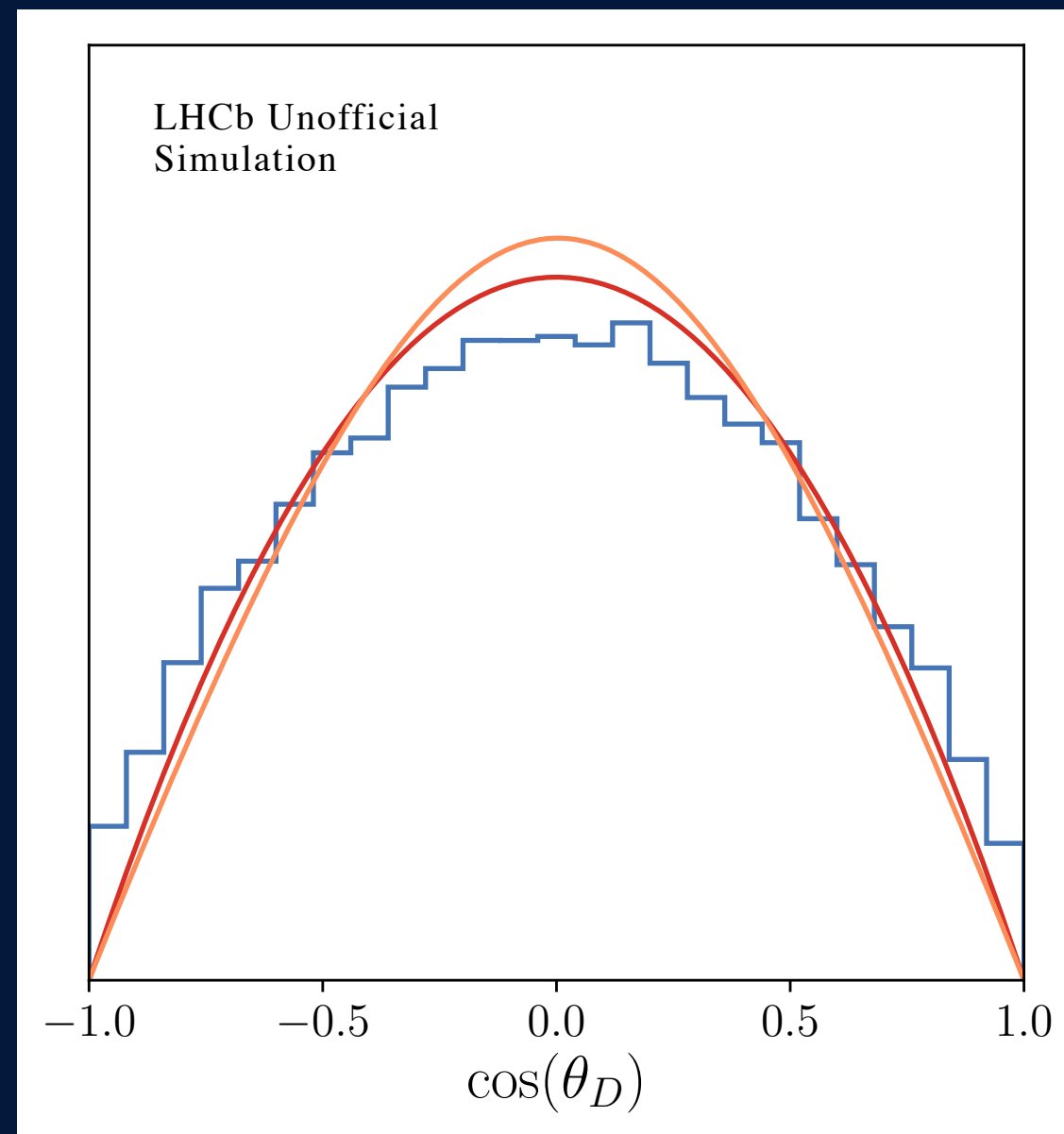
- ▶ Divide by the total model  $M$  to obtain weight

$$\text{function, } w_{I_x} \quad M = \frac{d^4\Gamma}{dq^2 d \cos \theta_D d \cos \theta_L d \chi}$$

- ▶ Calculate the value of the weight function for signal simulation (using truth variables)

$$\begin{aligned} \frac{d^4\Gamma}{dq^2 d \cos \theta_D d \cos \theta_L d \chi} &= \frac{9}{32\pi} \left\{ I_{1c} \cos^2 \theta_D + I_{1s} \sin^2 \theta_D \right. \\ &+ [I_{2c} \cos^2 \theta_D + I_{2s} \sin^2 \theta_D] \cos 2\theta_L \\ &+ [I_{6c} \cos^2 \theta_D + I_{6s} \sin^2 \theta_D] \cos \theta_L \\ &+ [I_3 \cos 2\chi + I_9 \sin 2\chi] \sin^2 \theta_L \sin^2 \theta_D \\ &+ [I_4 \cos \chi + I_8 \sin \chi] \sin 2\theta_L \sin 2\theta_D \\ &\left. + [I_5 \cos \chi + I_7 \sin \chi] \sin \theta_L \sin 2\theta_D \right\} \end{aligned}$$

# SIGNAL PDF CREATION



- ▶ Take angular function for a particular  $I_x$ ,

$$f_{I_x}: I_{1s} \sin^2 \theta_D$$

- ▶ Divide by the total model  $M$  to obtain weight

$$\text{function, } w_{I_x} \quad M = \frac{d^4\Gamma}{dq^2 d \cos \theta_D d \cos \theta_L d \chi}$$

- ▶ Calculate the value of the weight function for signal simulation (using truth variables)

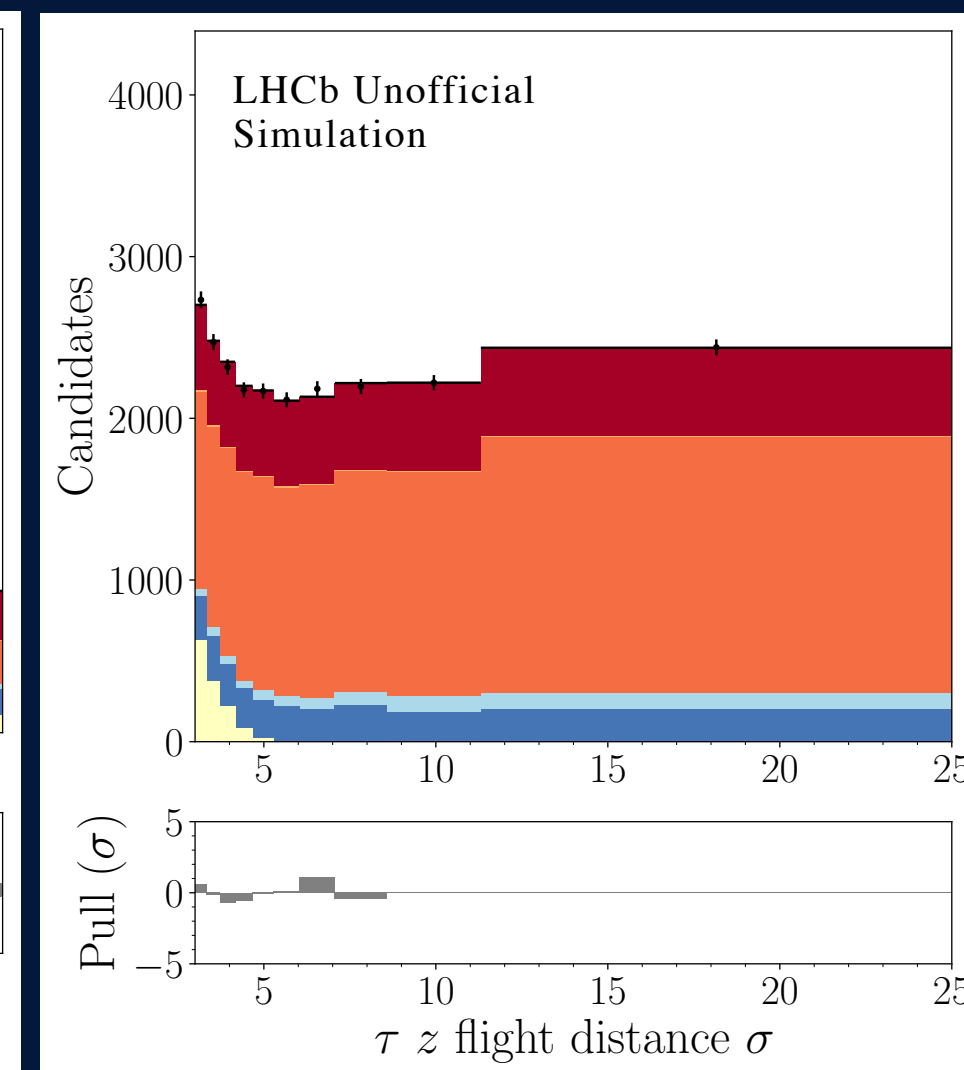
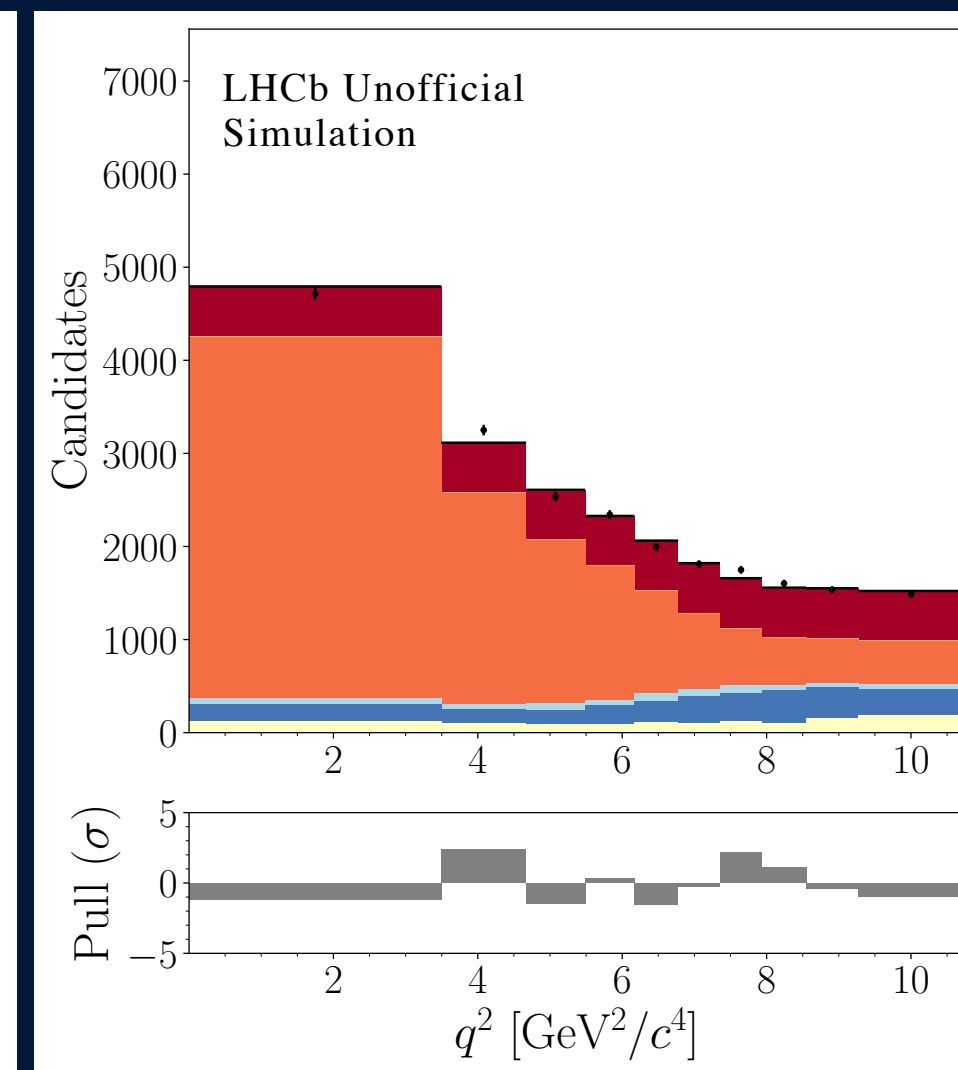
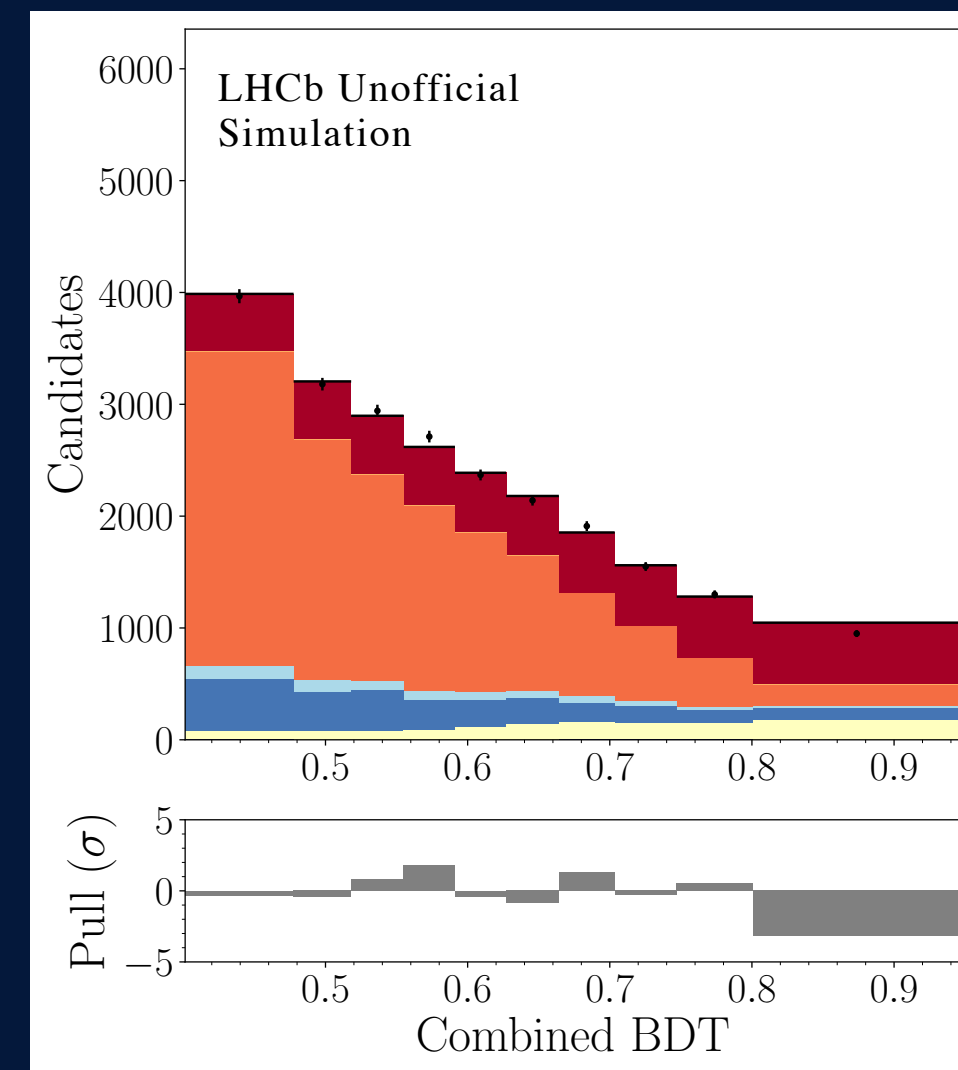
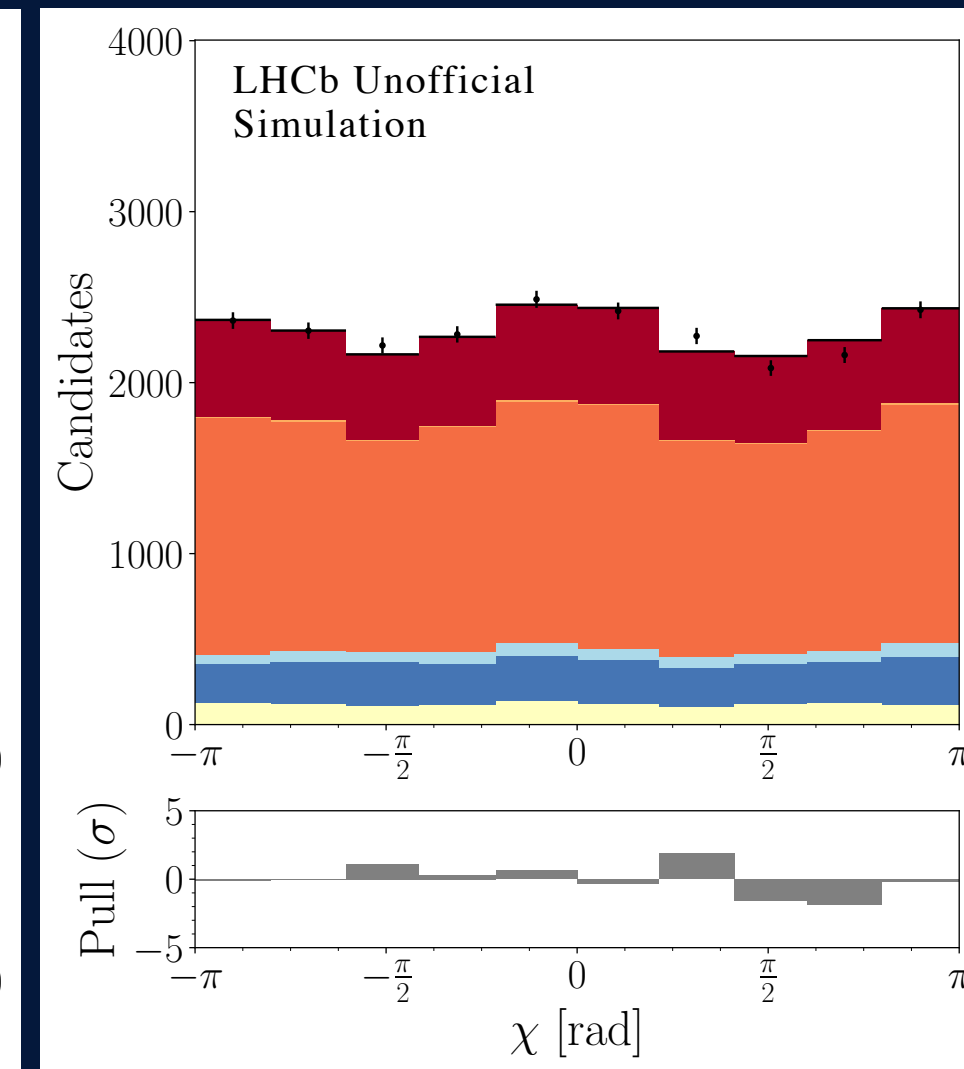
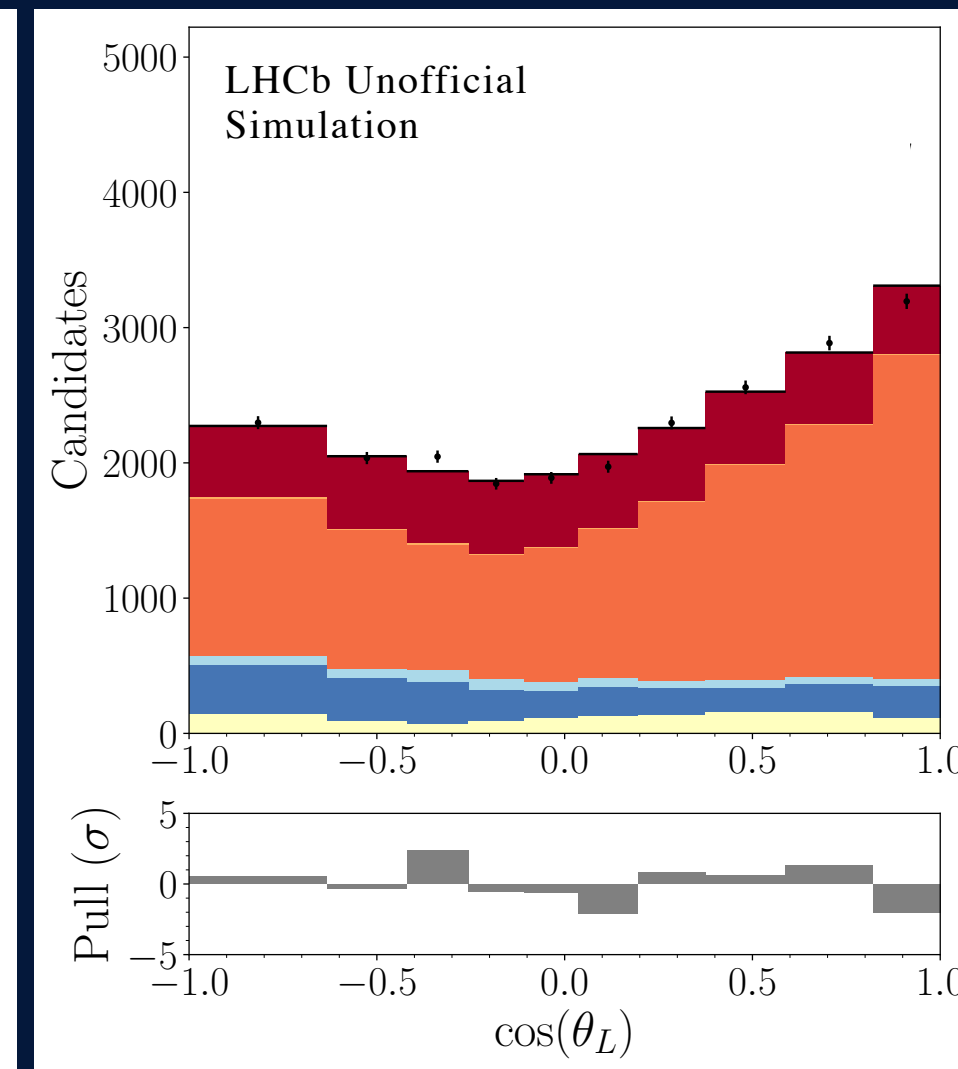
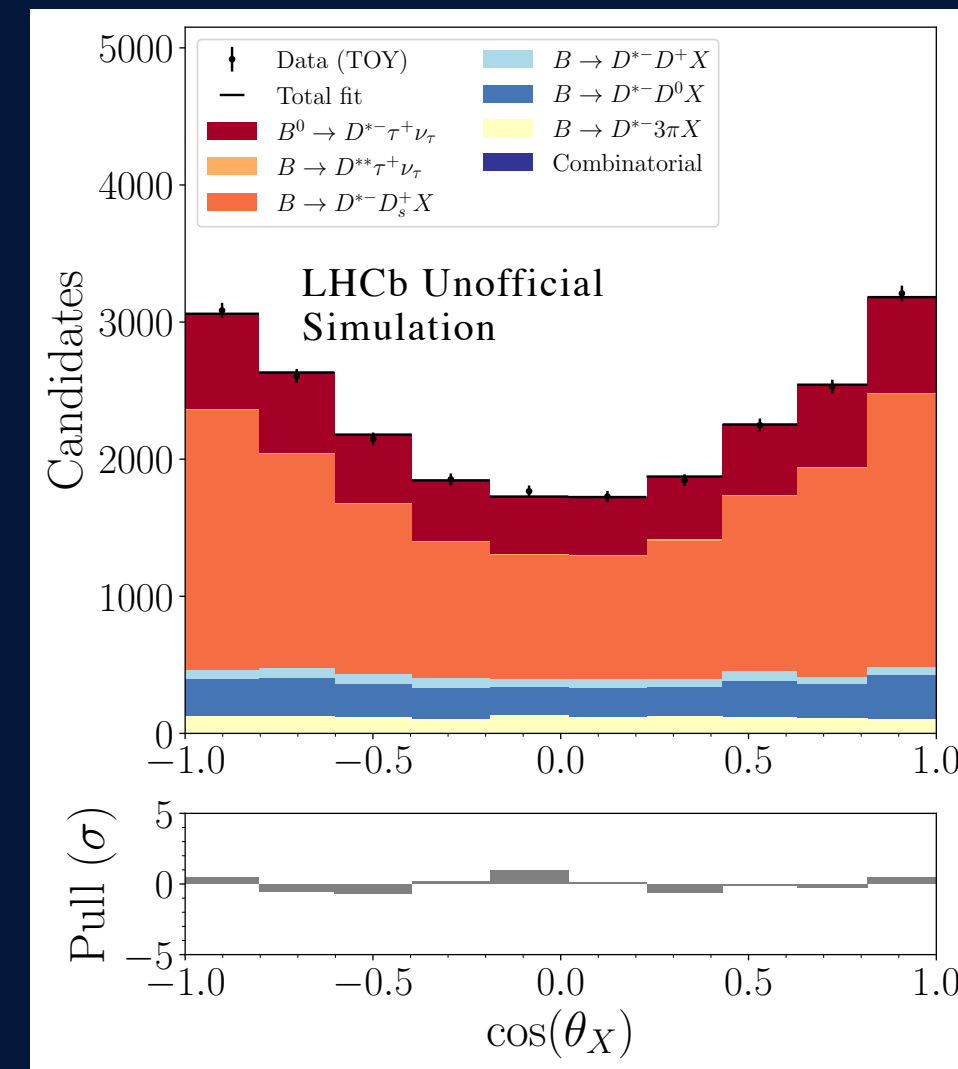
- ▶ Apply weights to signal simulation to create  $I_x$  template,  $h_{I_x}$  (in reconstructed space)

- ▶  $h_{I_x}$  and  $f_{I_x}$  deviate due

- ▶ Selection effects
- ▶ Missing  $\nu$
- ▶ Angular resolution

# ANGULAR FIT - TOY

- ▶ Toy fit based on expected statistics in data
- ▶ Signal toy generated with  $I_x$  according to <https://arxiv.org/abs/1912.09335>
- ▶ Expected precision of 7-8% on  $\mathcal{R}(D^*)$  (no systematics included)
  - ▶ Similar precision to Run 1 result  
[PRL 120 \(2018\) 171802](#), [PRD 97 \(2018\) 072013](#)
  - ▶ BDT has less separation due to model independent restrictions on input variables
  - ▶ Additional freedom in signal PDF due to 12 angular templates
- ▶  $I_x$  measured in fit with signal template





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 ANGULAR FIT - TOY COMPONENTS
 

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Data (TOY)

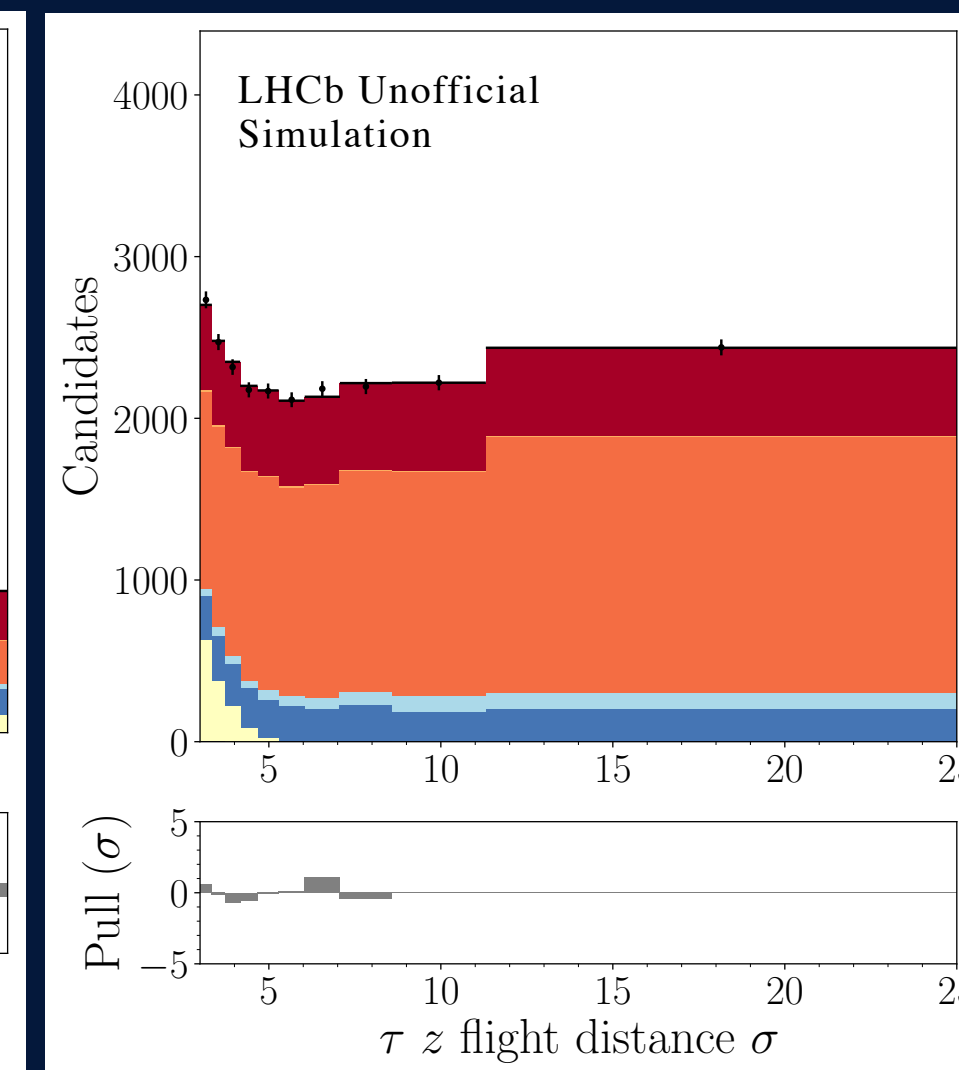
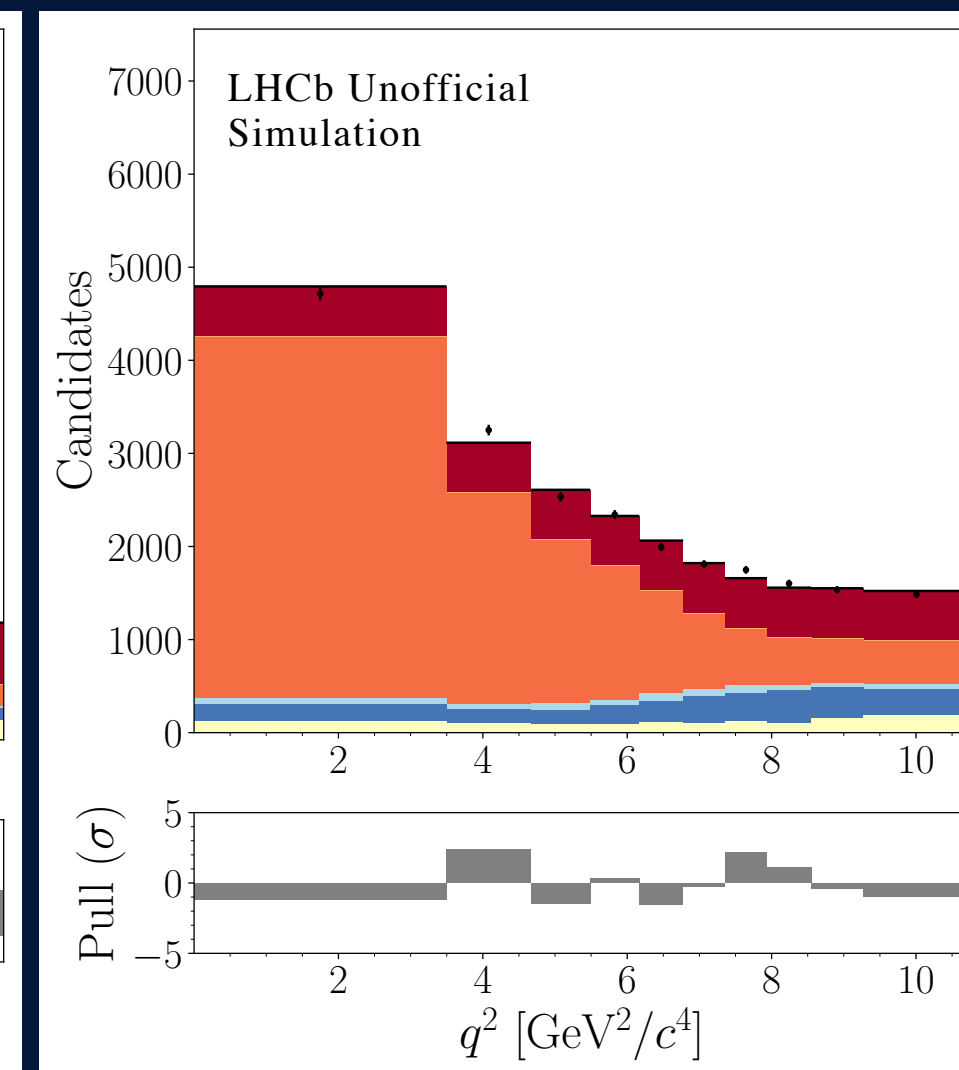
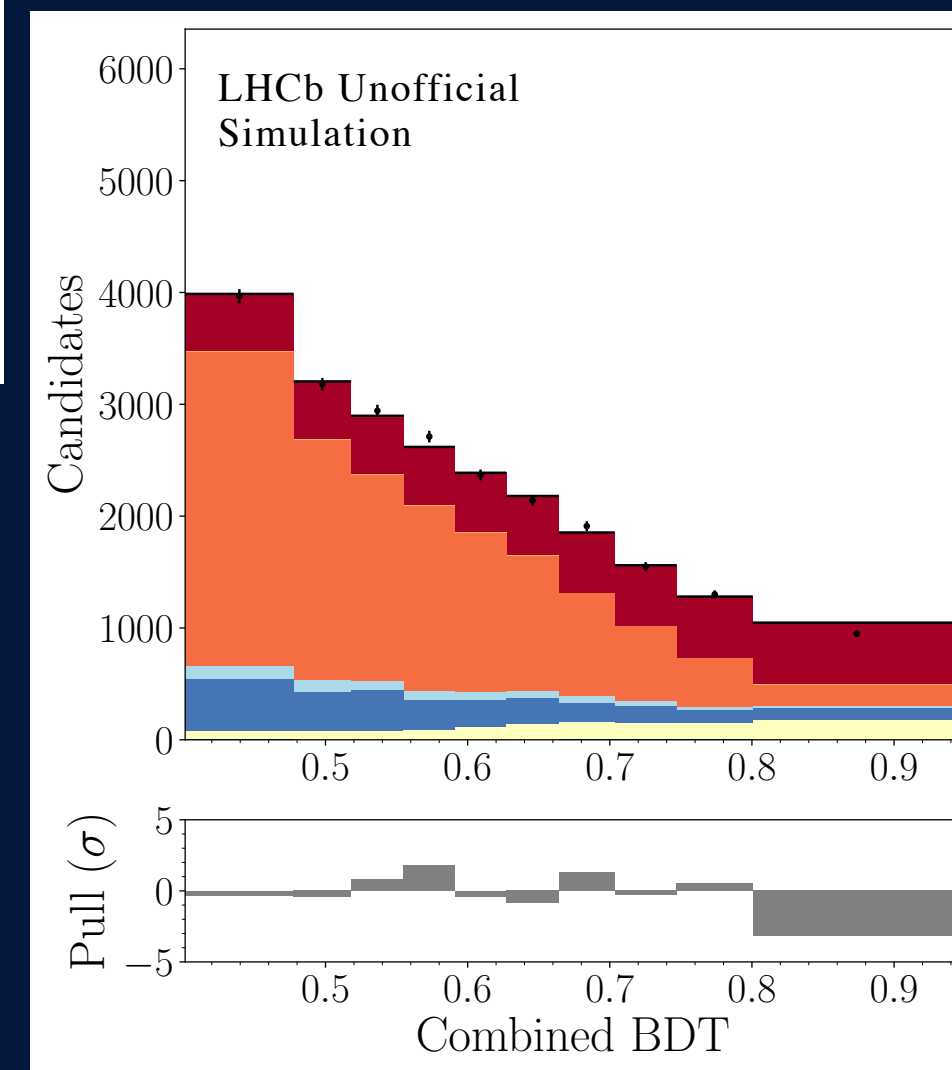
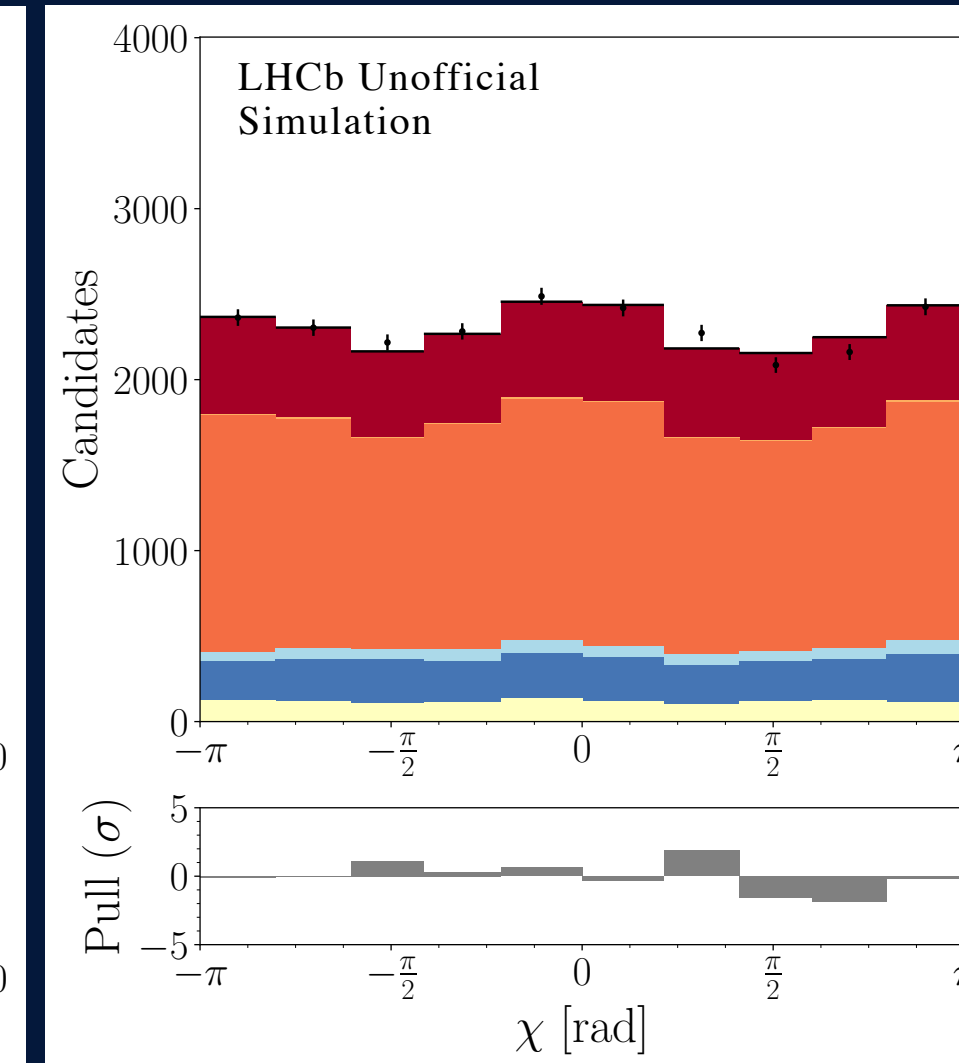
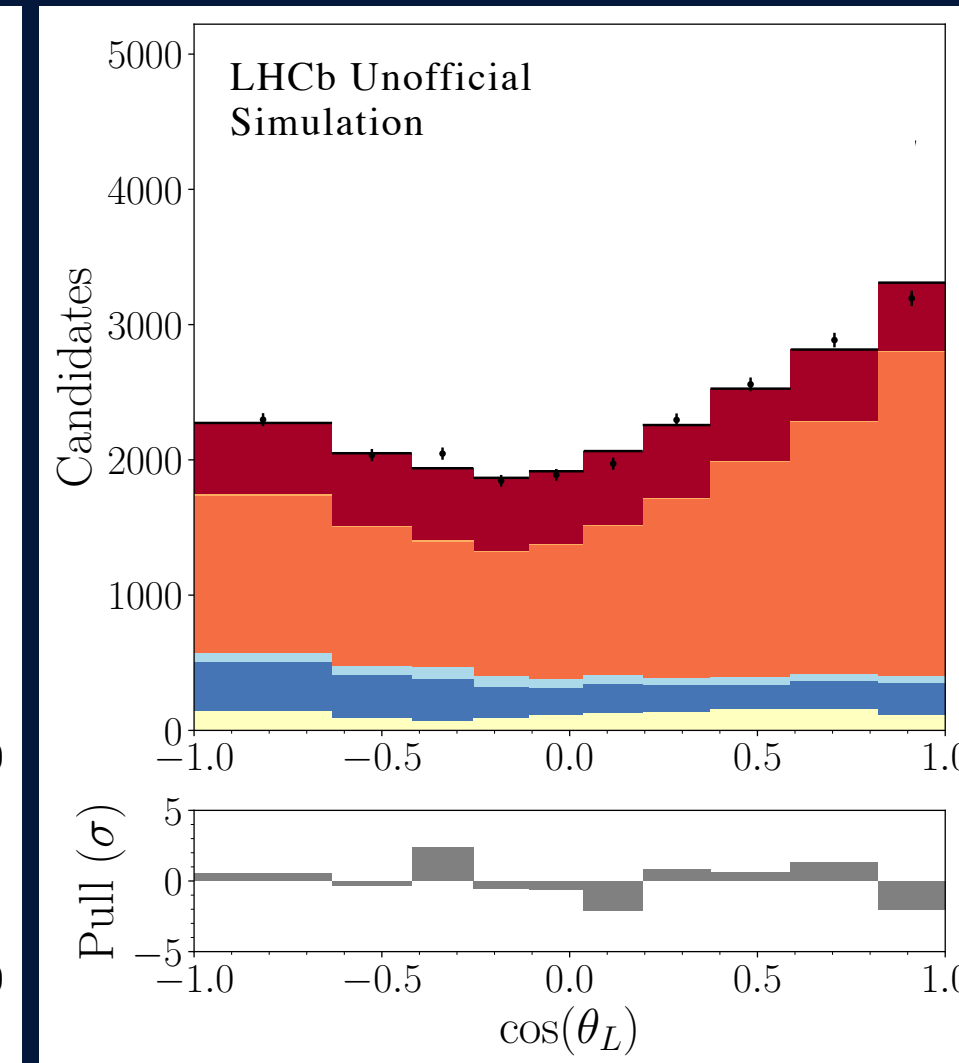
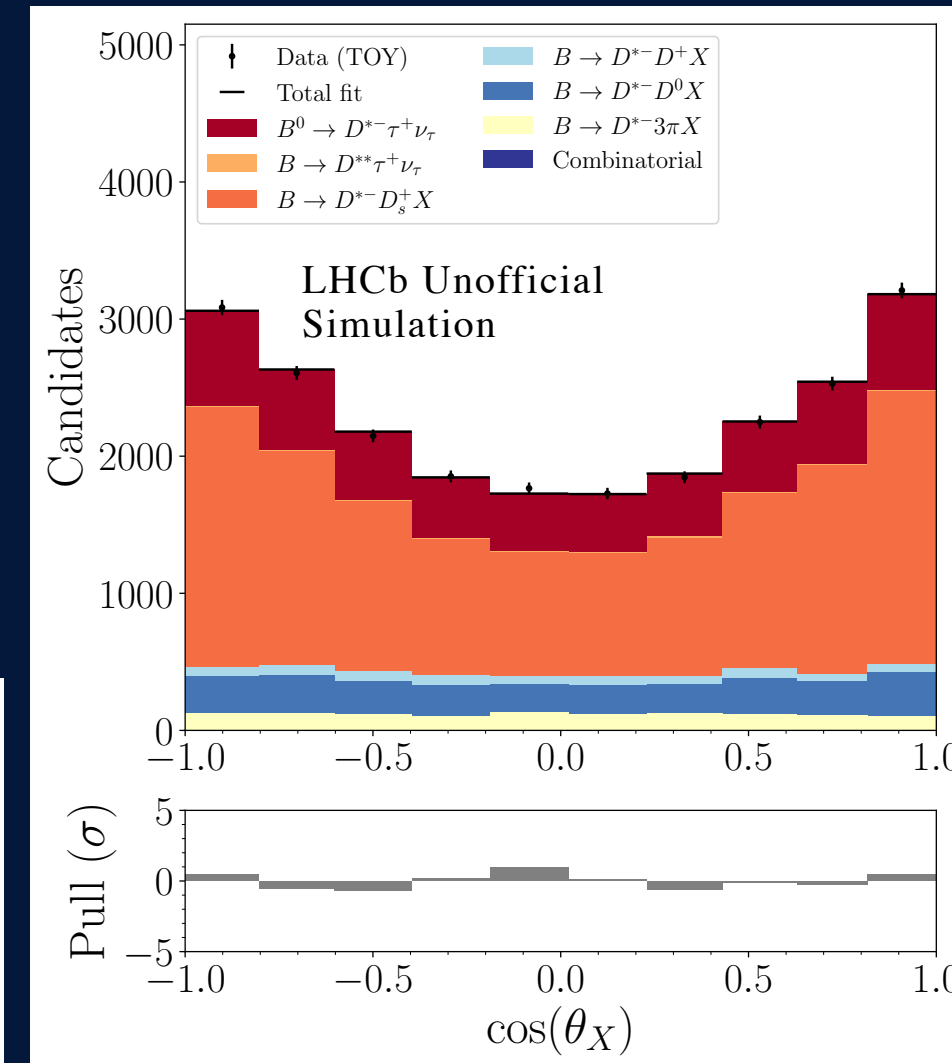
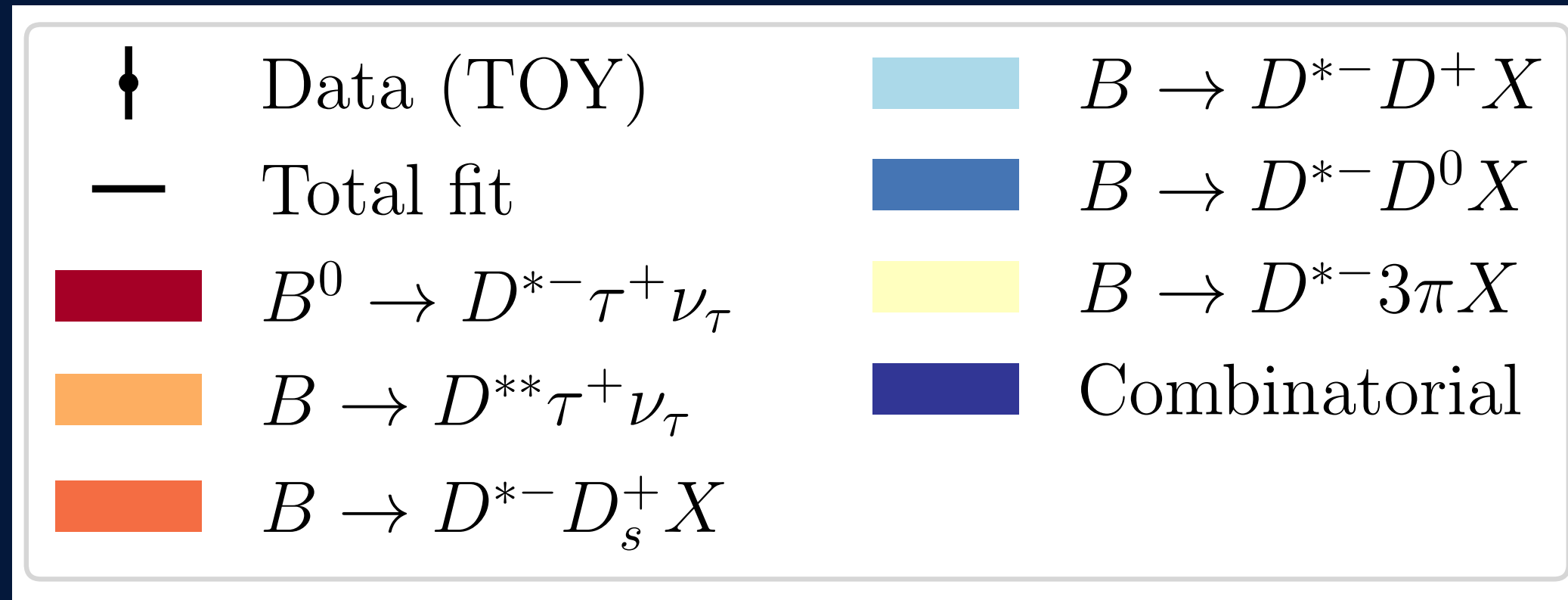


Total fit

 $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$  $B \rightarrow D^{**} \tau^+ \nu_\tau$  $B \rightarrow D^{*-} D_s^+ X$  $B \rightarrow D^{*-} D^+ X$  $B \rightarrow D^{*-} D^0 X$  $B \rightarrow D^{*-} 3\pi X$ 

Combinatorial

# ANGULAR FIT - TOY



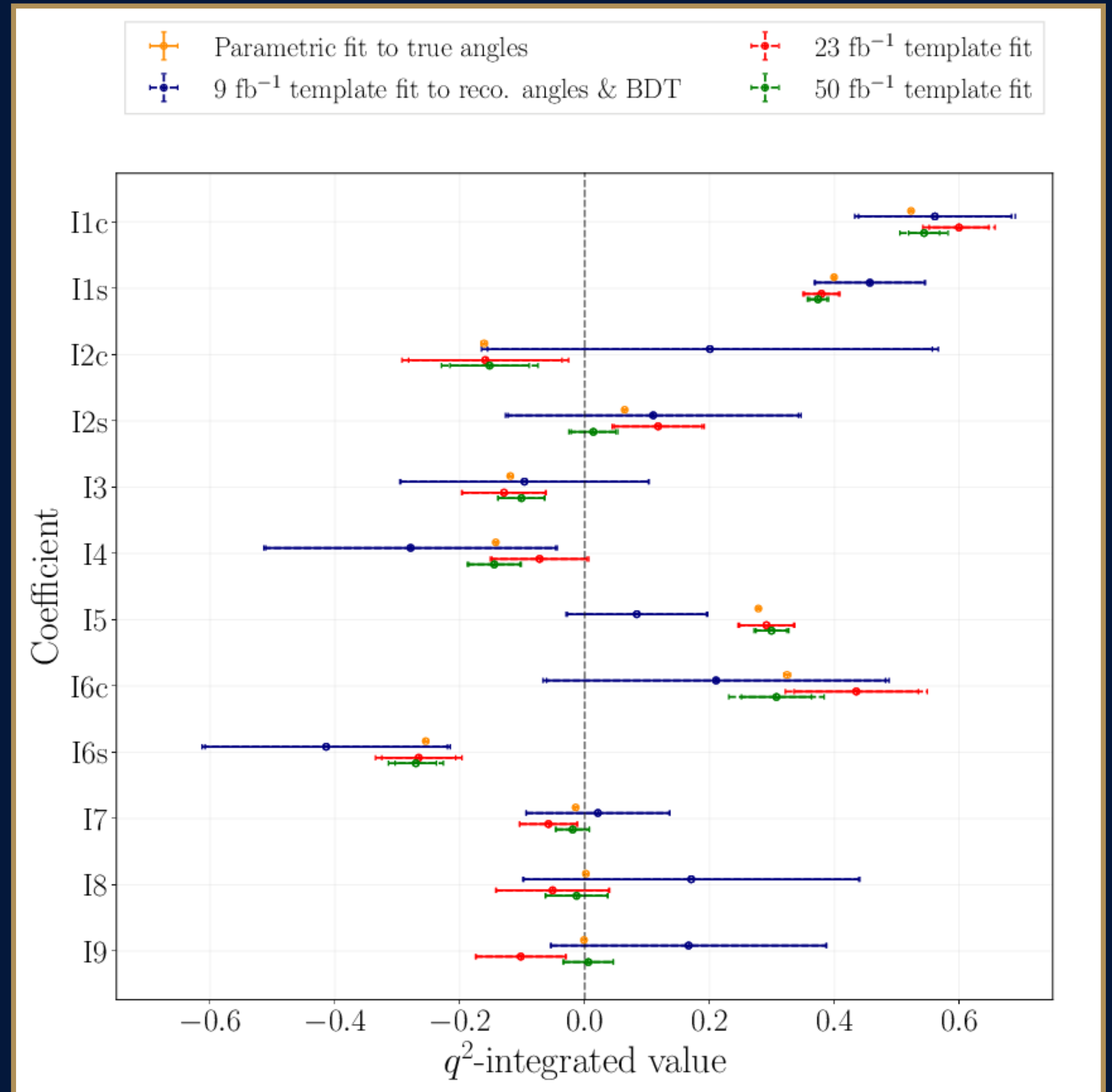
# ANGULAR ANALYSIS: ANGULAR COEFFICIENTS

▶ Expected performance of angular coefficient measurements for different dataset sizes:

▶  $9\text{fb}^{-1}$ : Run 1 + 2 (blue)

▶  $23\text{fb}^{-1}$ : Run 1 + 2 + 3 (red)

▶  $50\text{fb}^{-1}$ : Run 1 + 2 + 3 + 4 (green)



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