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

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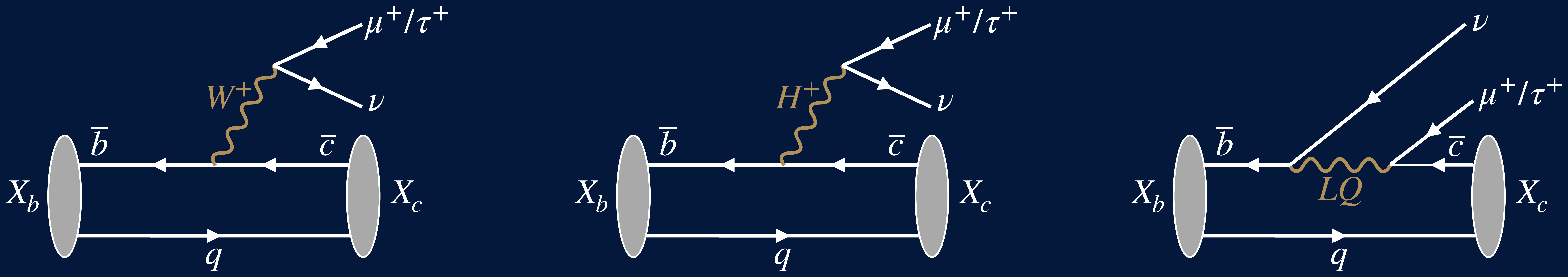
INTRODUCTION - LEPTON FLAVOUR UNIVERSALITY

- 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:

$$\mathcal{R}(X_c) \equiv \frac{\mathcal{B}\left(X_b \to X_c\, \tau^+ \nu_\tau\right)}{\mathcal{B}\left(X_b \to X_c\, \mu^+ \nu_\mu\right)}$$

X_b : b-hadron, X_c : c-hadron

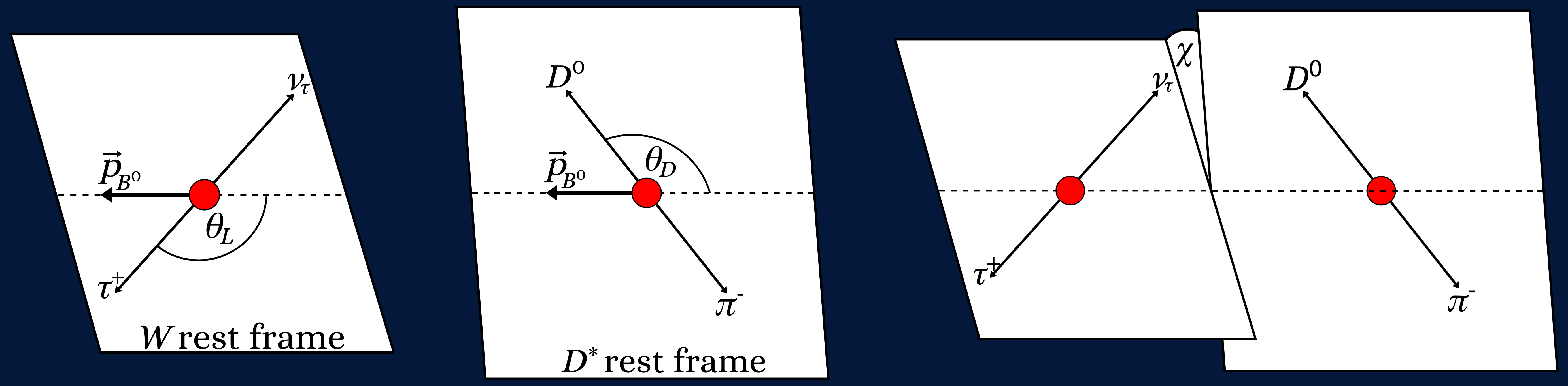
- Current measurements from B-factories and LHCb show discrepancy with SM, but not $> 5\sigma$
- LFUV would be a clear sign of New Physics (NP)



INTRODUCTION - ANGULAR ANALYSIS

- Measure the 12 $B^0 \to D^{*-}\tau^+\nu_\tau$ angular coefficients and $\mathscr{R}(D^*)$
  - 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 $\mathscr{R}(D^*)$ is compatible with SM
- Full Run 1 + 2 LHCb data set and simulation samples: 9fb^{-1}

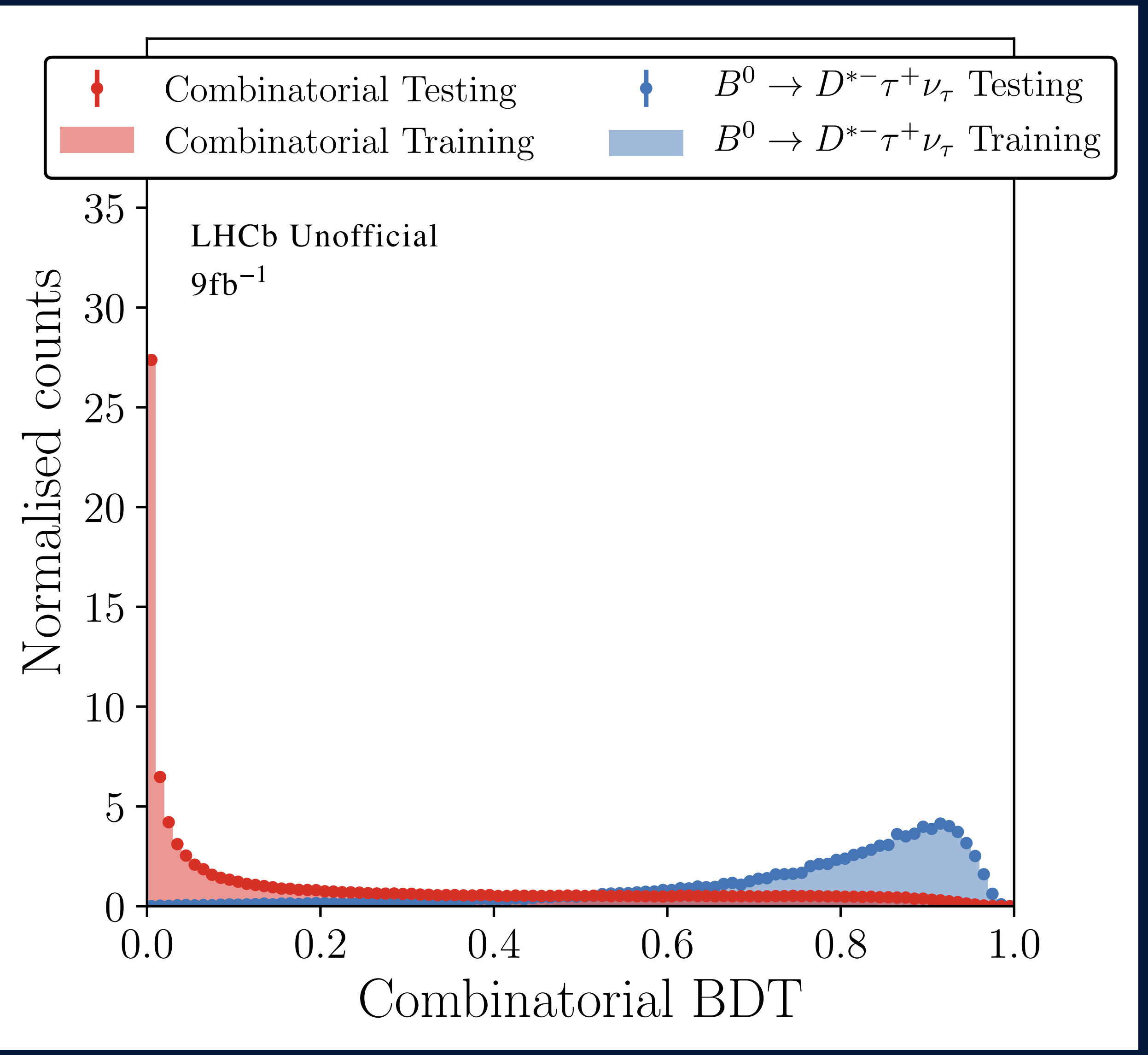
$$\frac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_L d\chi} = \frac{9}{32\pi}\{I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D + [I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D]\cos 2\theta_L + [I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D]\cos\theta_L + [I_3\cos 2\chi + I_9\sin 2\chi]\sin^2\theta_L\sin^2\theta_D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

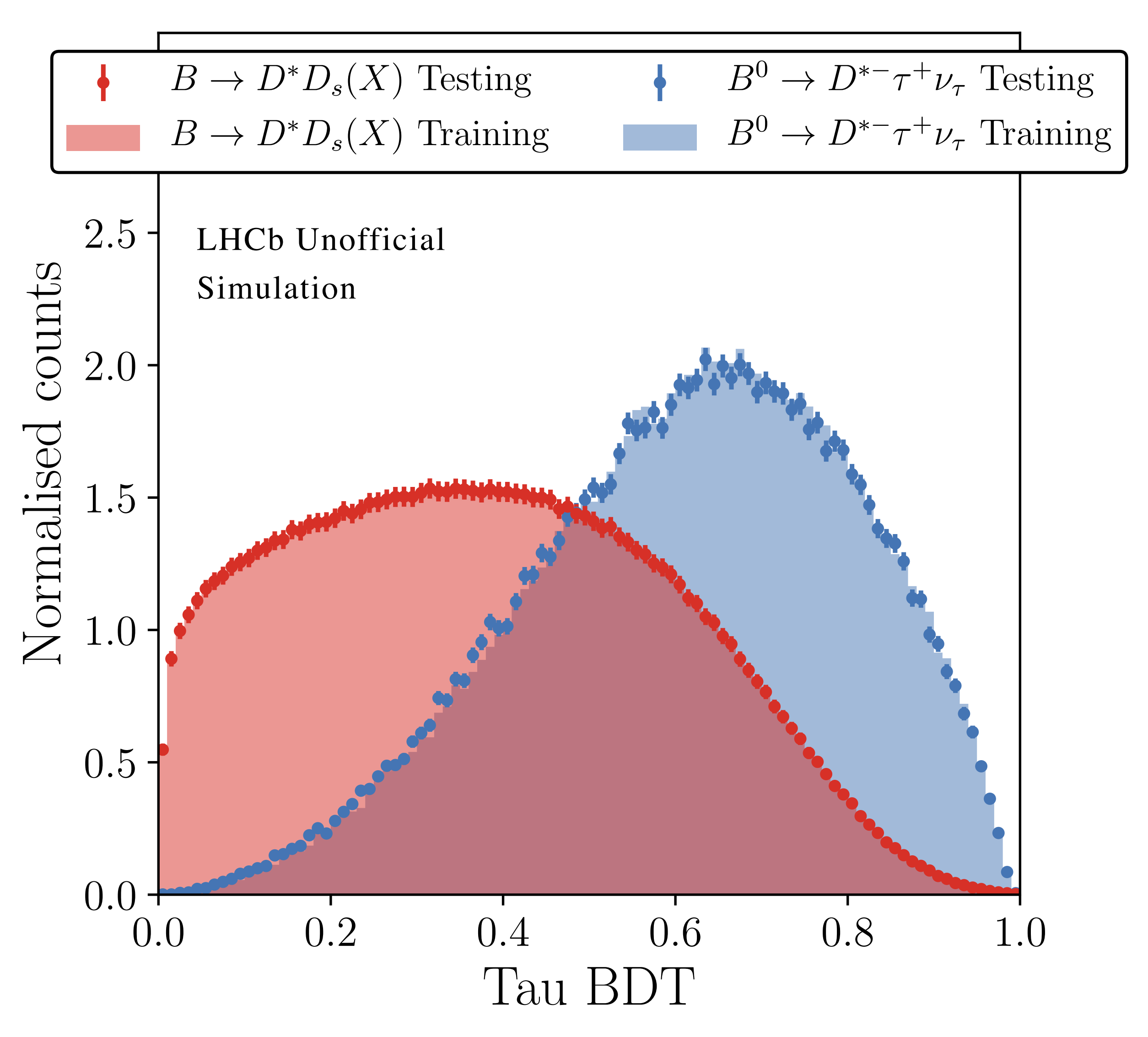


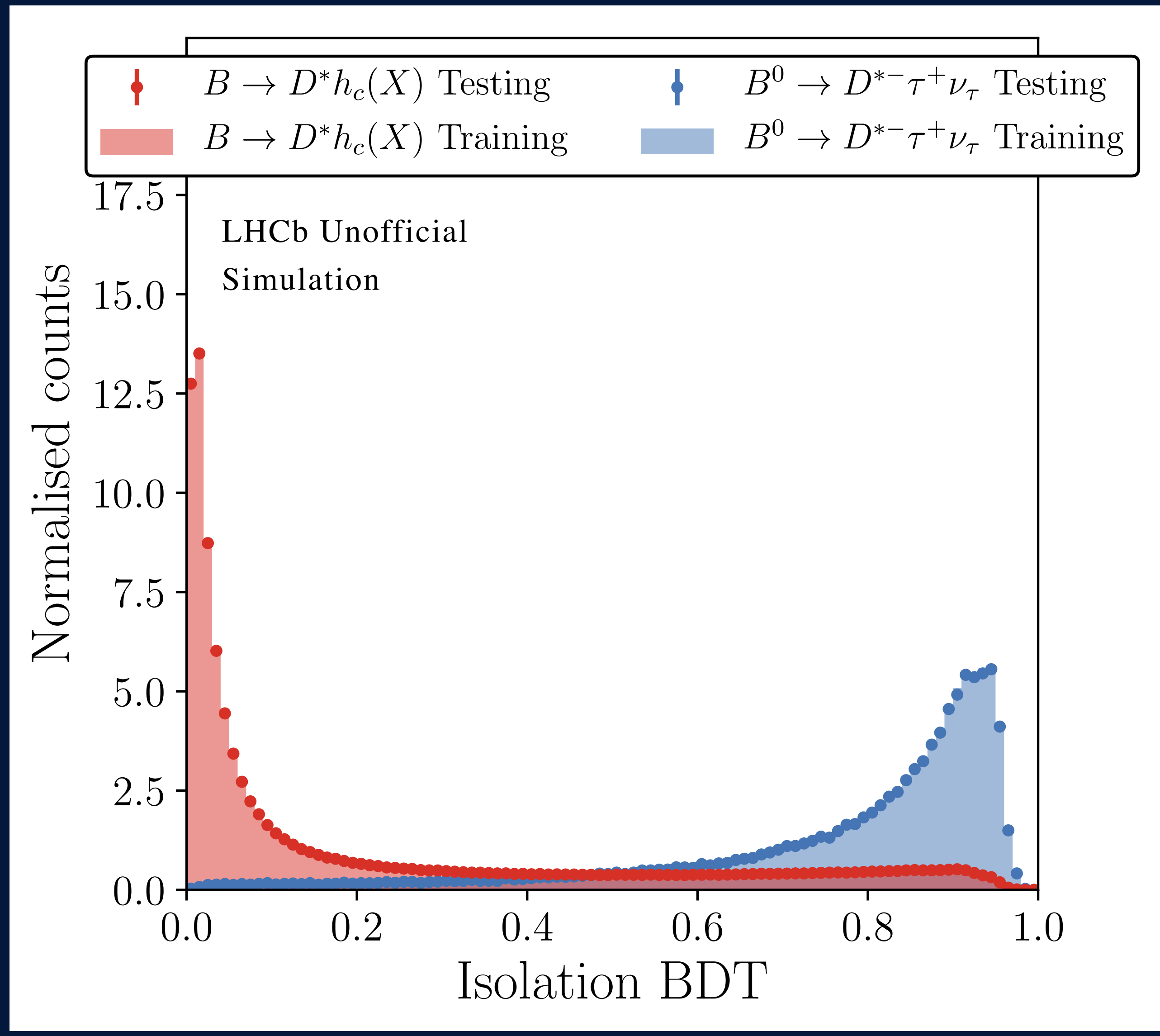
SELECTION OPTIMISATION AND NORMALISATION FITS

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 $B \to D^*D_s(X)$ MC
  - Variables: $\tau \to \pi^+\pi^-\pi^+$ information, B^0 information
- Isolation BDT
  - Signal MC vs $B \to D^*D_s(X)$ MC
  - Variables: charged and neutral isolation variables







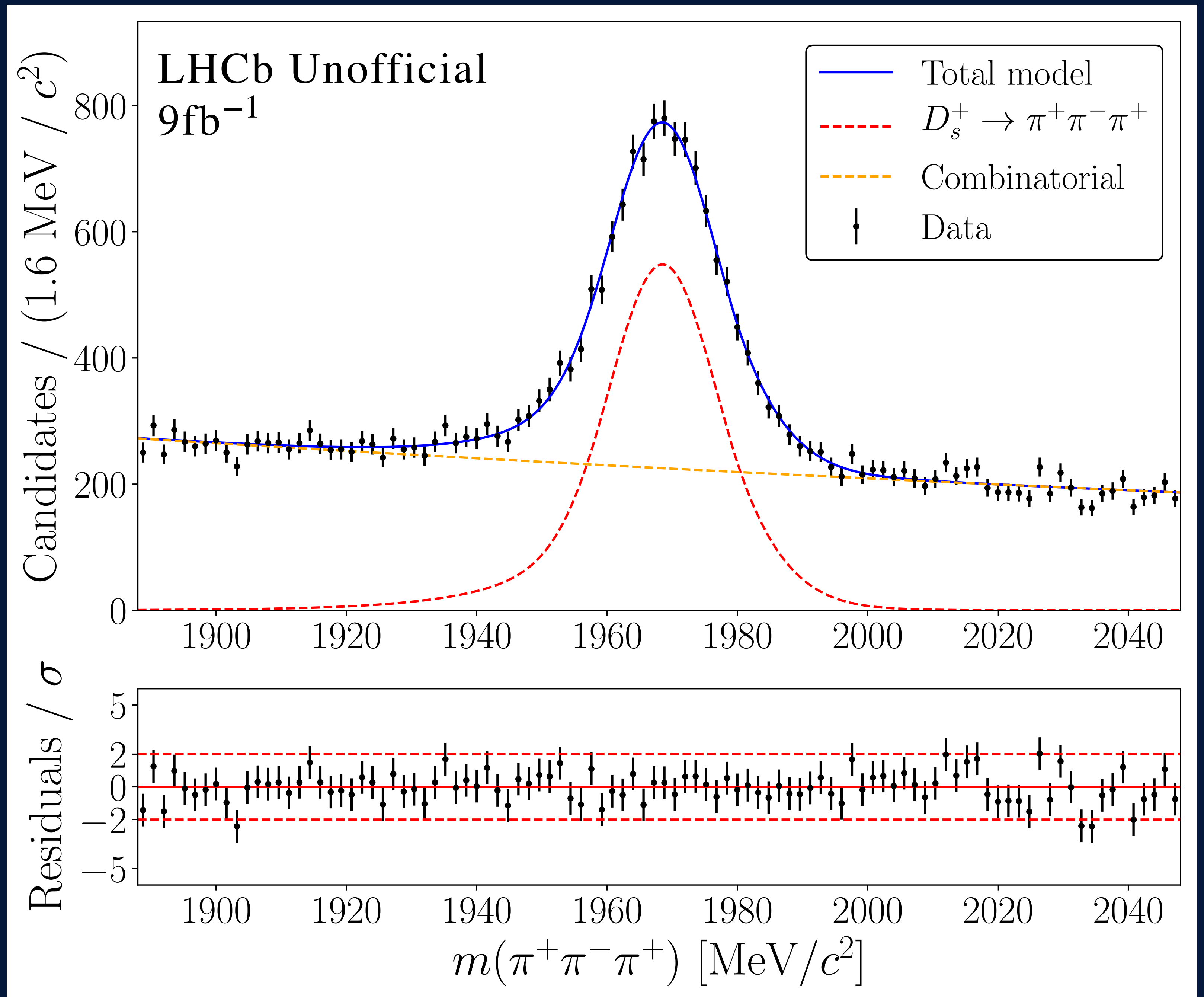
MVA SELECTION OPTIMISATION

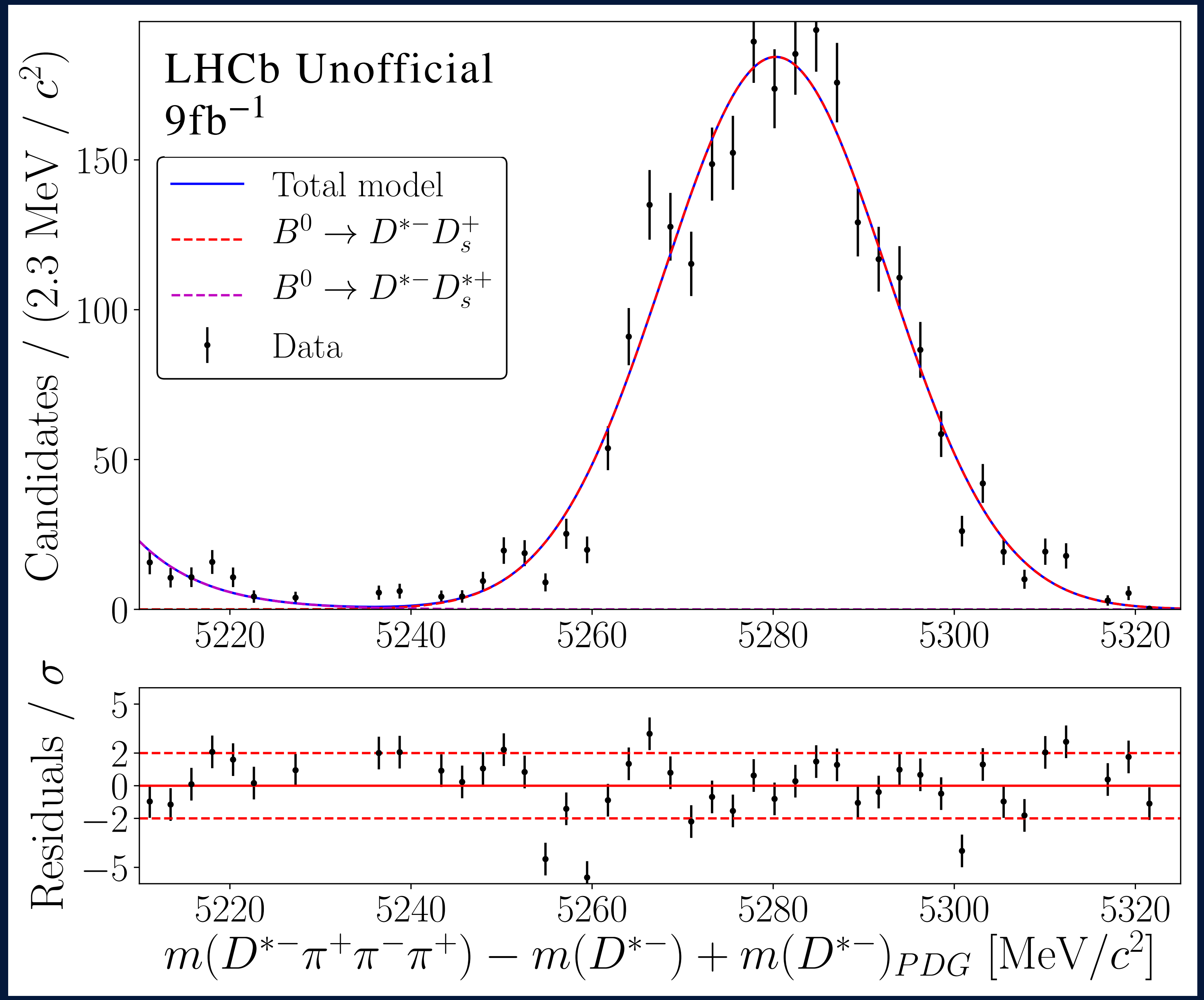
- In order to obtain control and signal samples, need to have a selection in place
- Selection involved several rectangular cuts, as well as 3 BDT cuts
- BDT cuts are optimised simultaneously using numerical method
- Cuts are optimised to maximise signal purity while maintaining a particular signal yield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

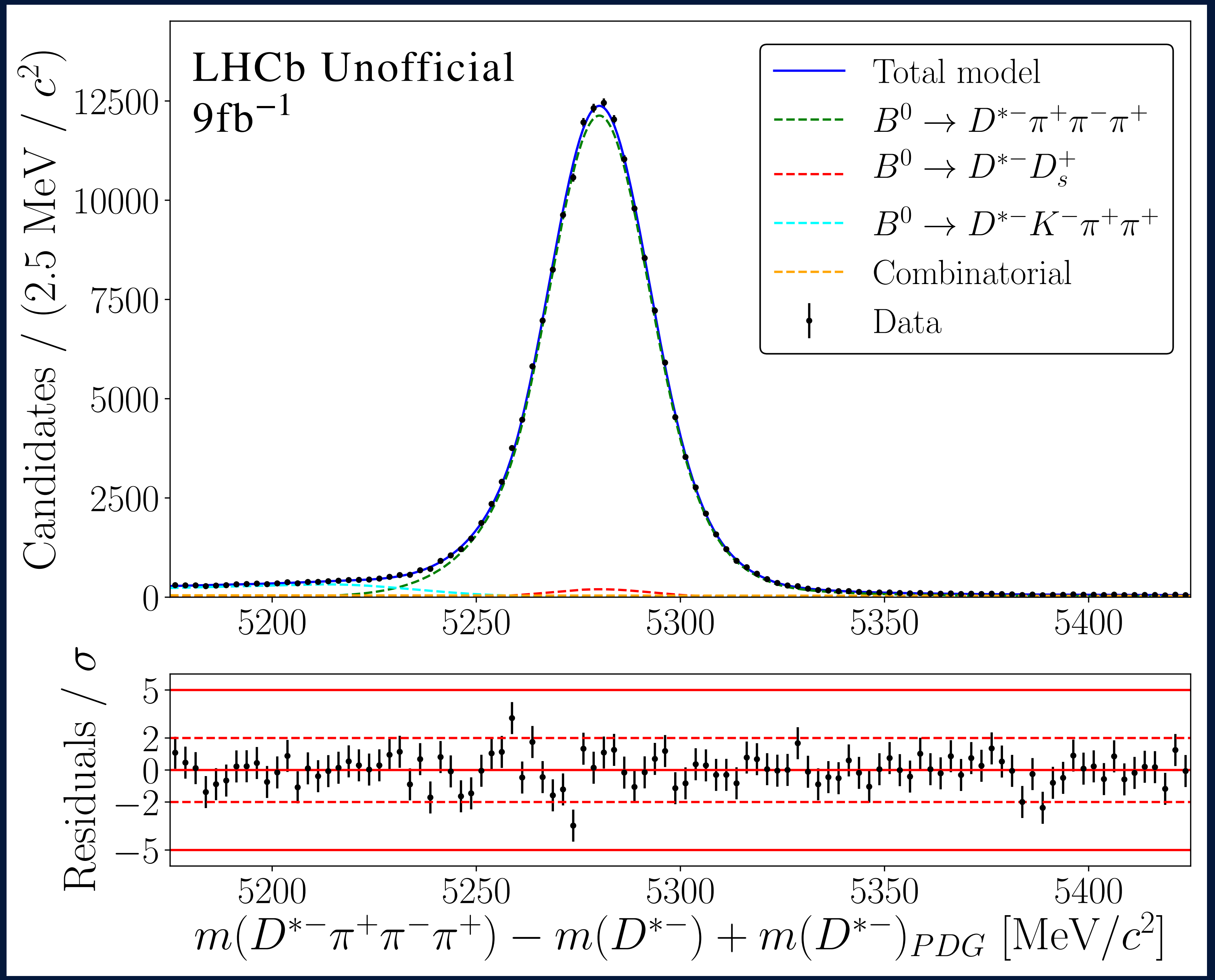
$$N_{sig} = N_{norm} * \frac{\epsilon_{sig}}{\epsilon_{norm}} * \frac{\mathscr{B}(B^0 \to D^{*-}\tau^+\nu_\tau) \cdot (\mathscr{B}(\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau) + \mathscr{B}(\tau^+ \to \pi^+\pi^-\pi^+\pi^0\overline{\nu}_\tau))}{\mathscr{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}$$

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

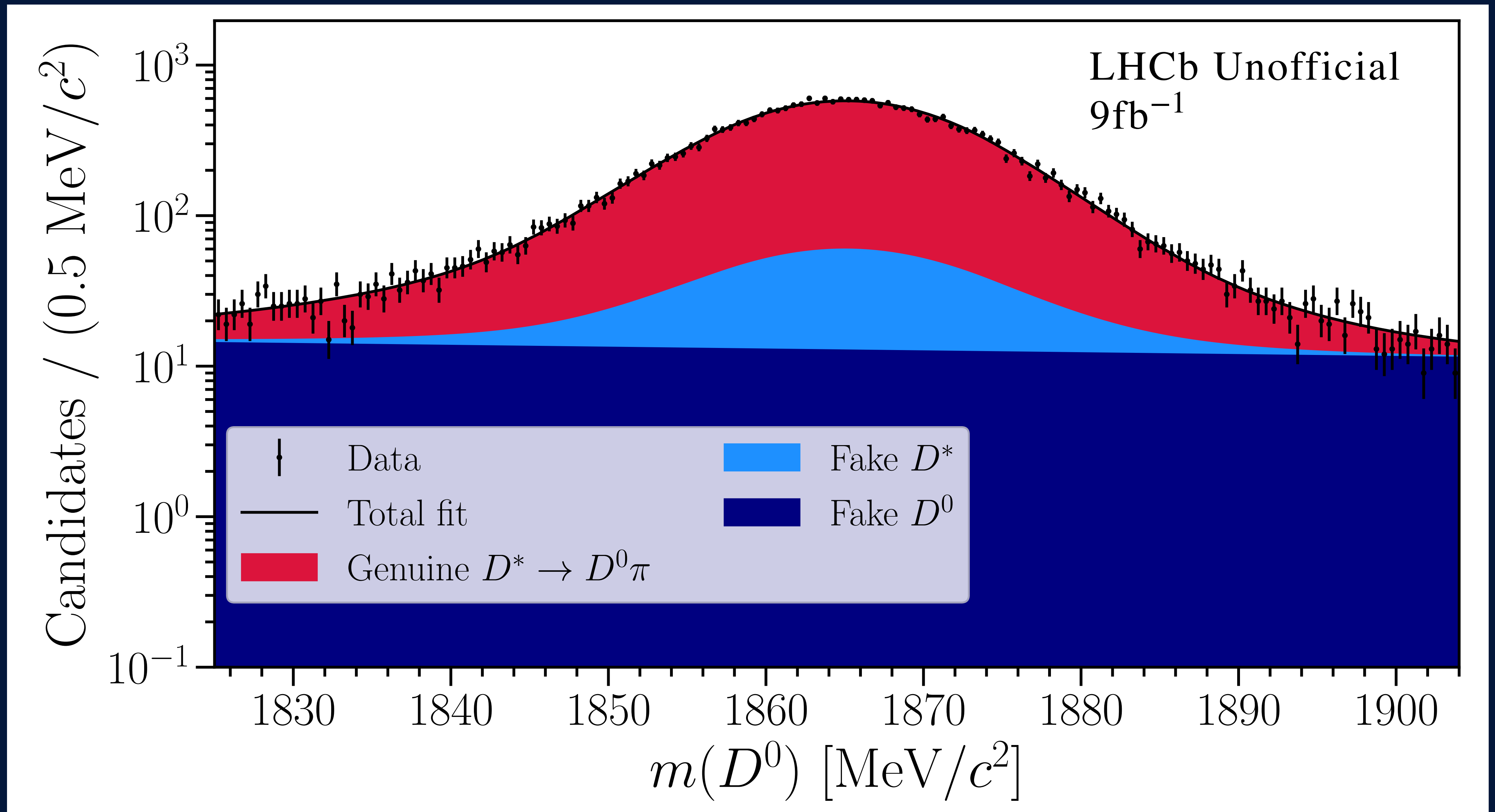
REMOVING FAKE D^*

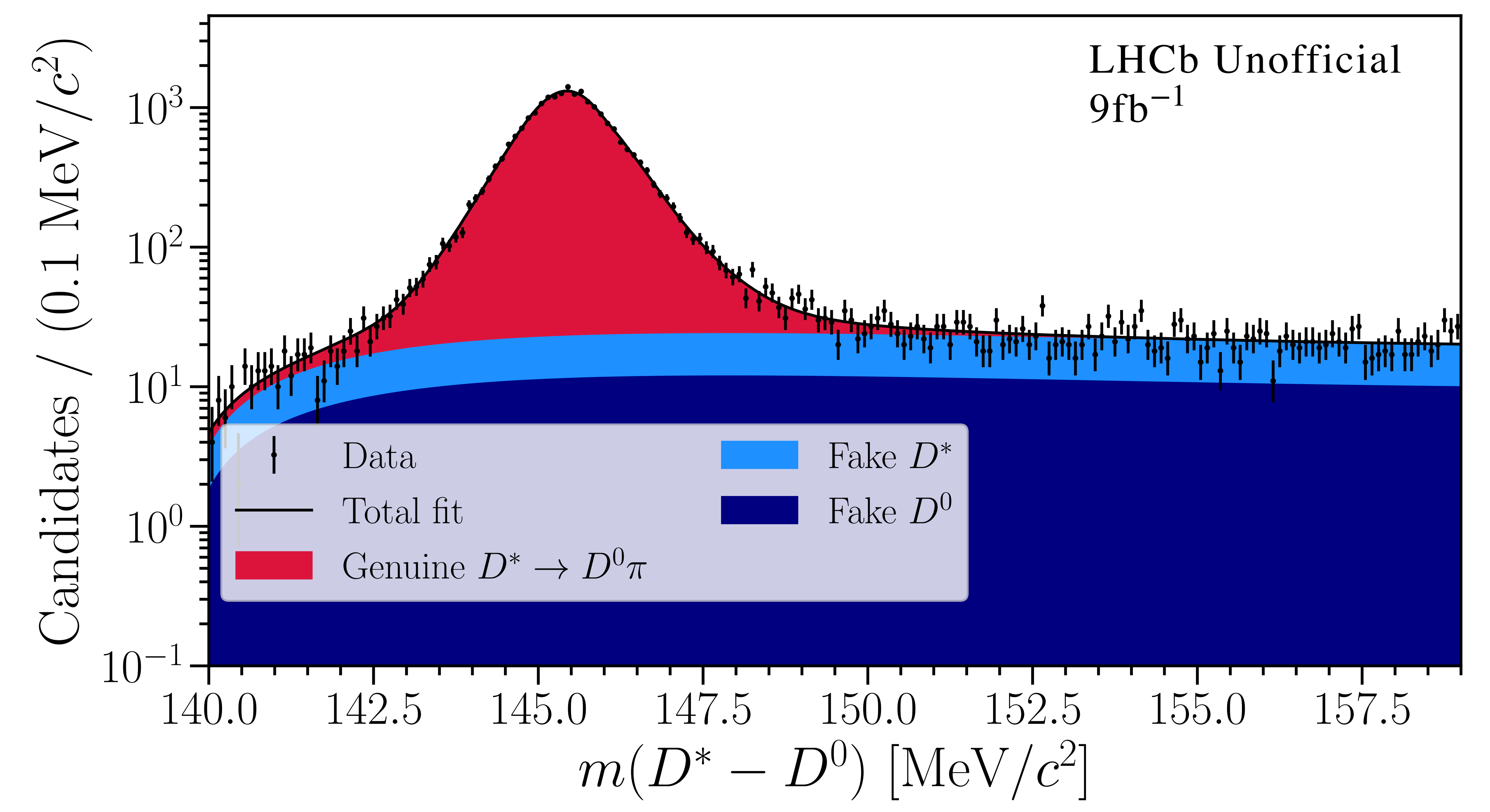
MEASURING FAKE D^* RATE - DATA FIT

- 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 3π combinatorial - modelled with inclusive MC
  - B1B2 background - modelled with WS data after sWeight fit is performed on WS data

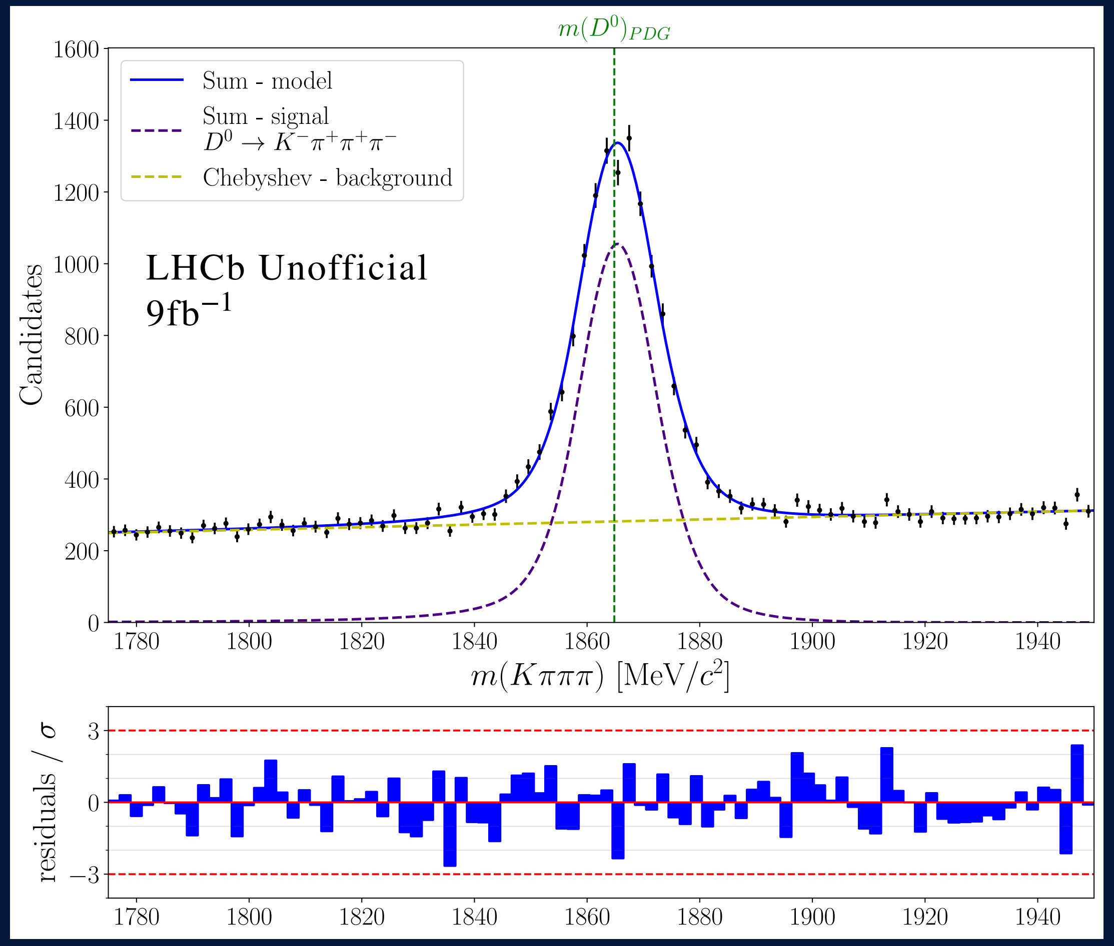




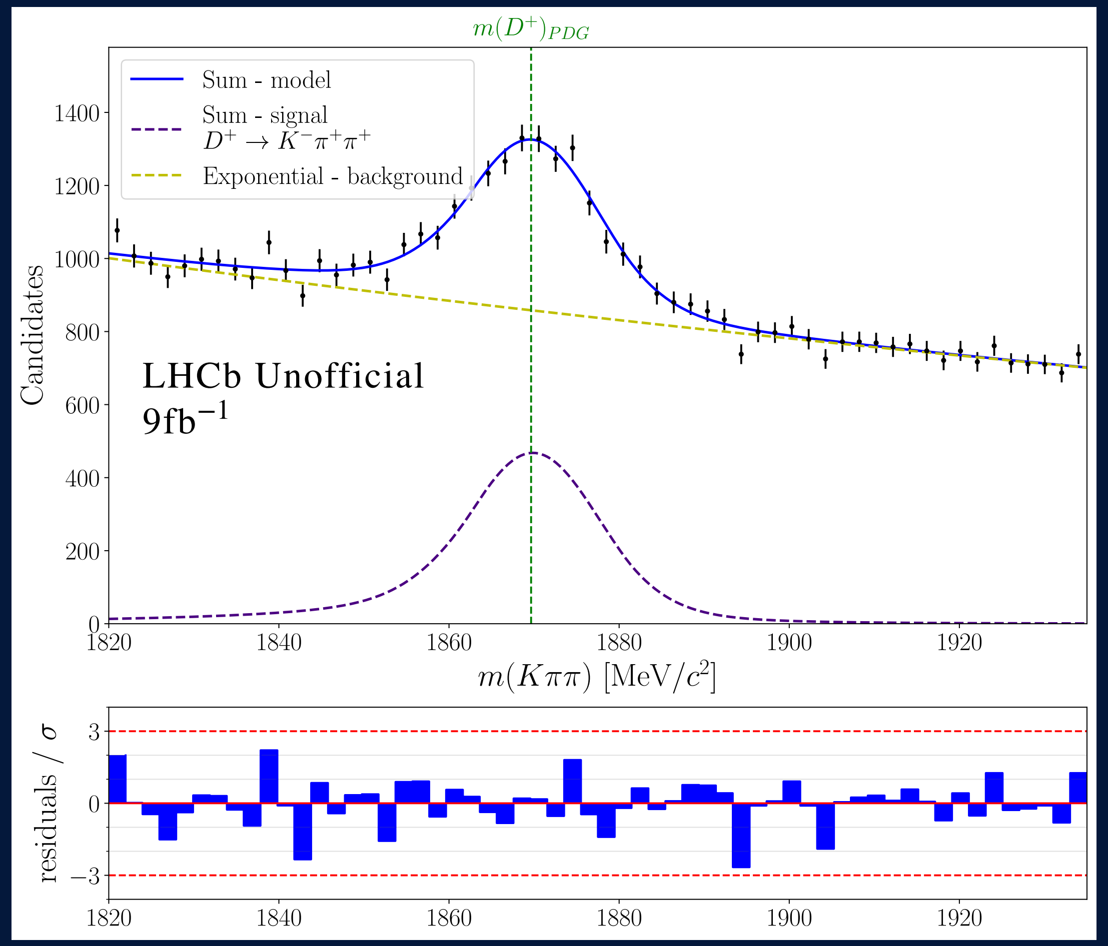
CONTROL STUDIES

CONTROL STUDIES

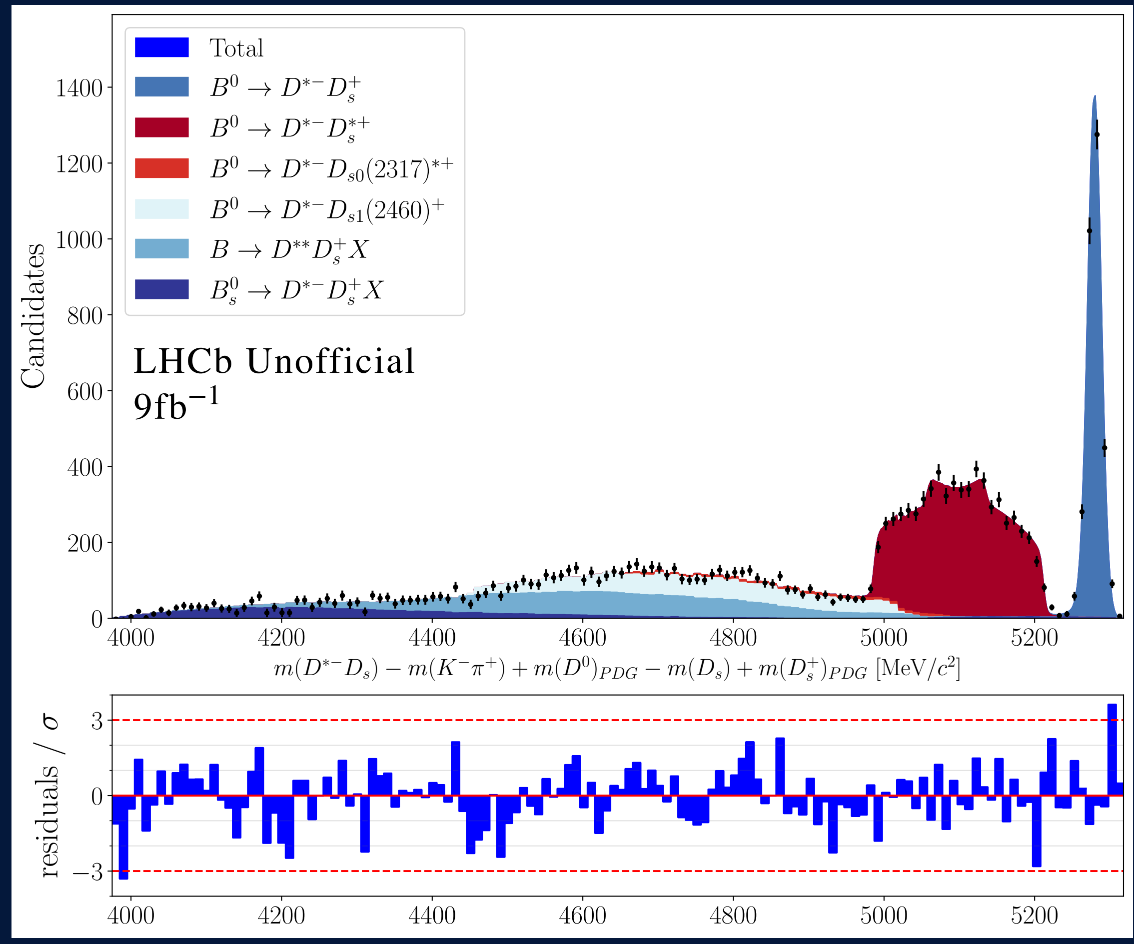
$B \to D^{*-}D^0(X)$



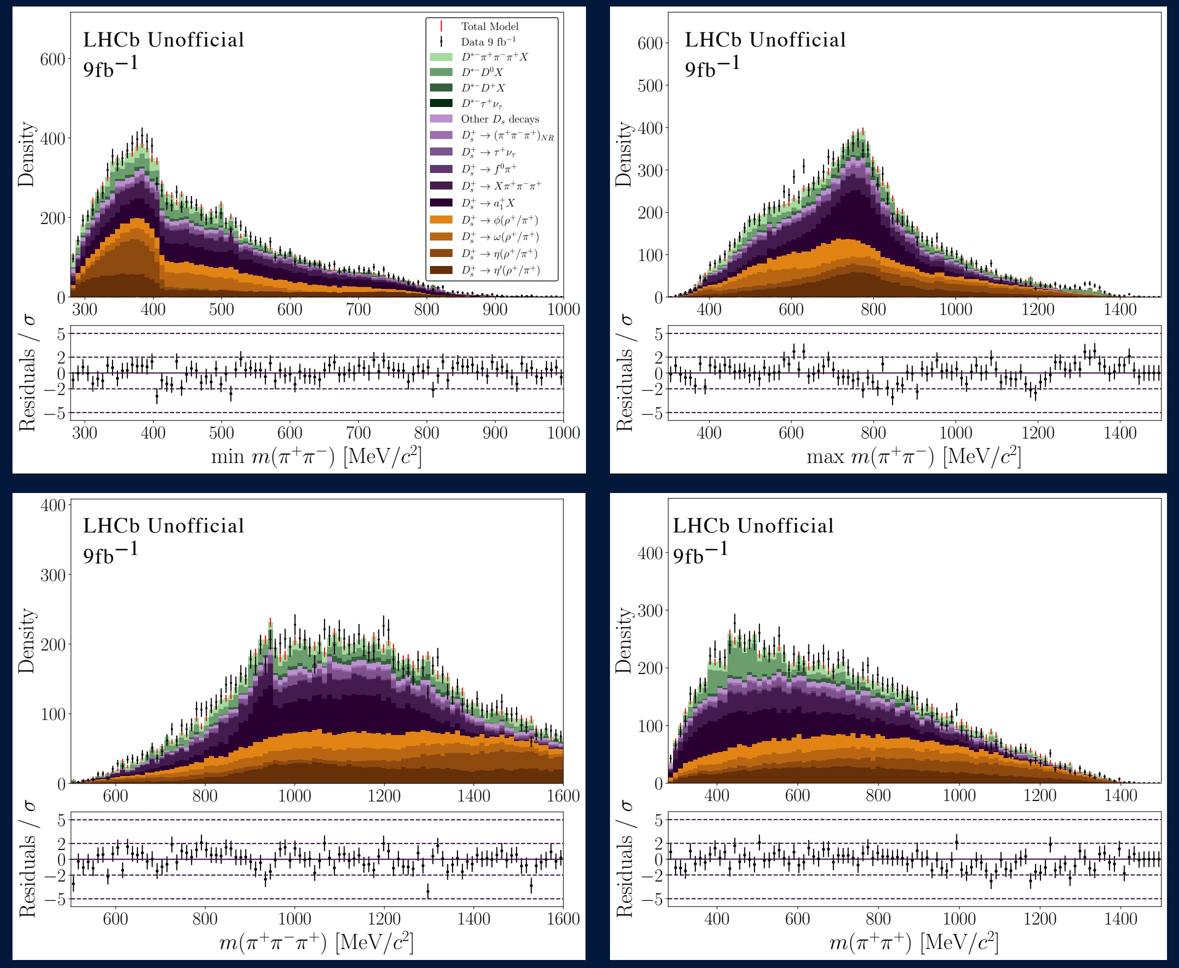
$B \to D^{*-}D^+(X)$



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



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



- 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 $\mathscr{R}(D^*)$ measurement PRL 120 (2018) 171802, PRD 97 (2018) 072013

SIGNAL FIT

SIGNAL FIT - SIGNAL PDF

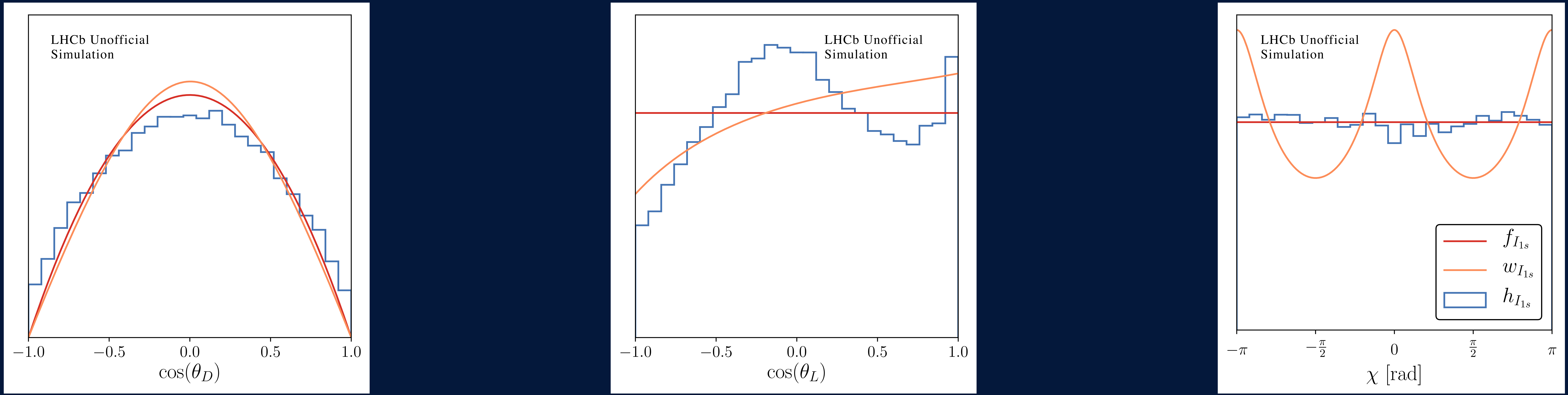
- Simultaneous multidimensional template fit
  - 3D fit in the decay angles
  - 3D fit in BDT, q^2, τ z flight distance significance

- In traditional $\mathscr{R}(D^*)$ 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:

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

SIGNAL PDF CREATION



- Take angular function for a particular I_x ,

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

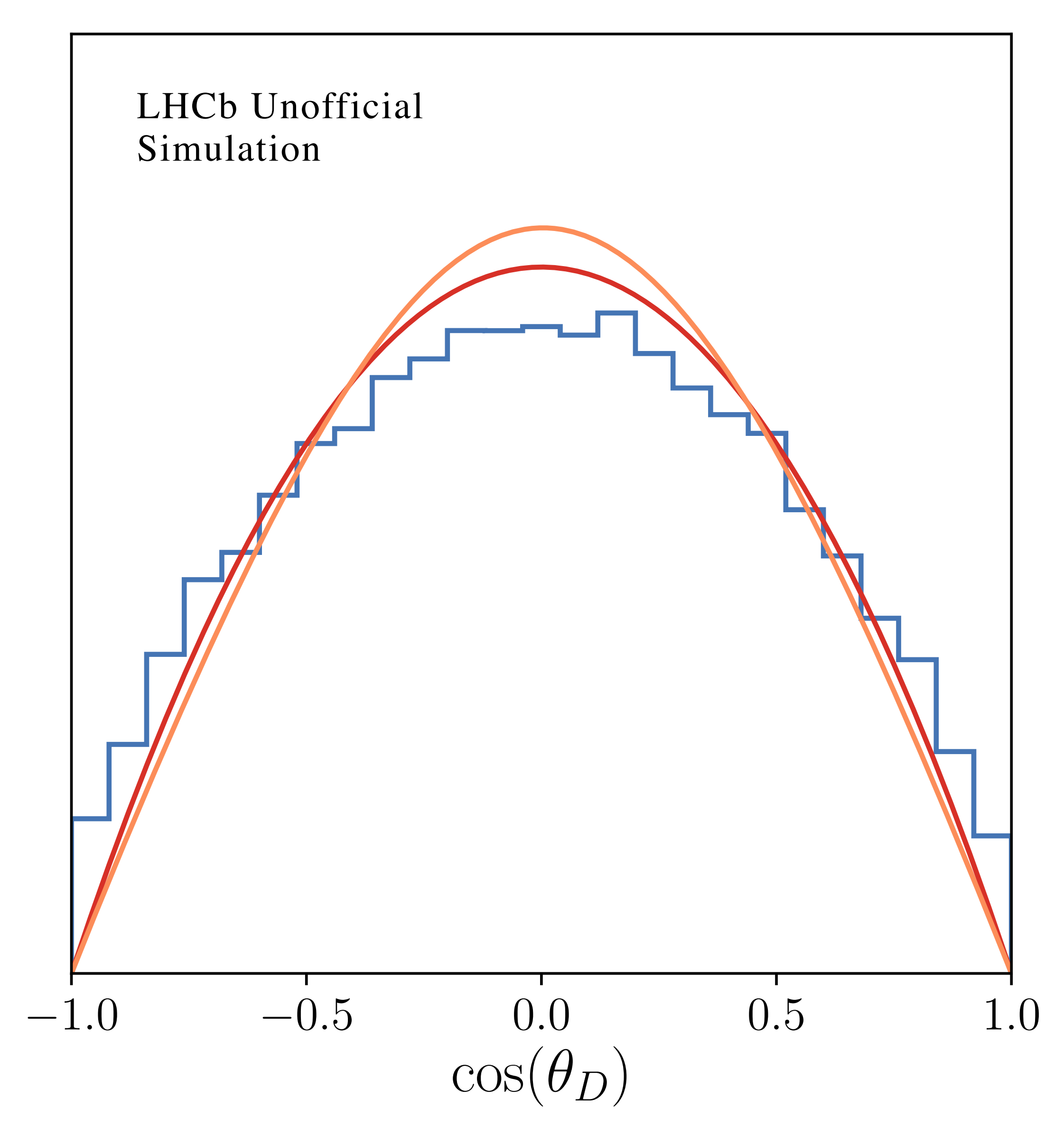
- Divide by the total model M to obtain weight function, w_{I_x}

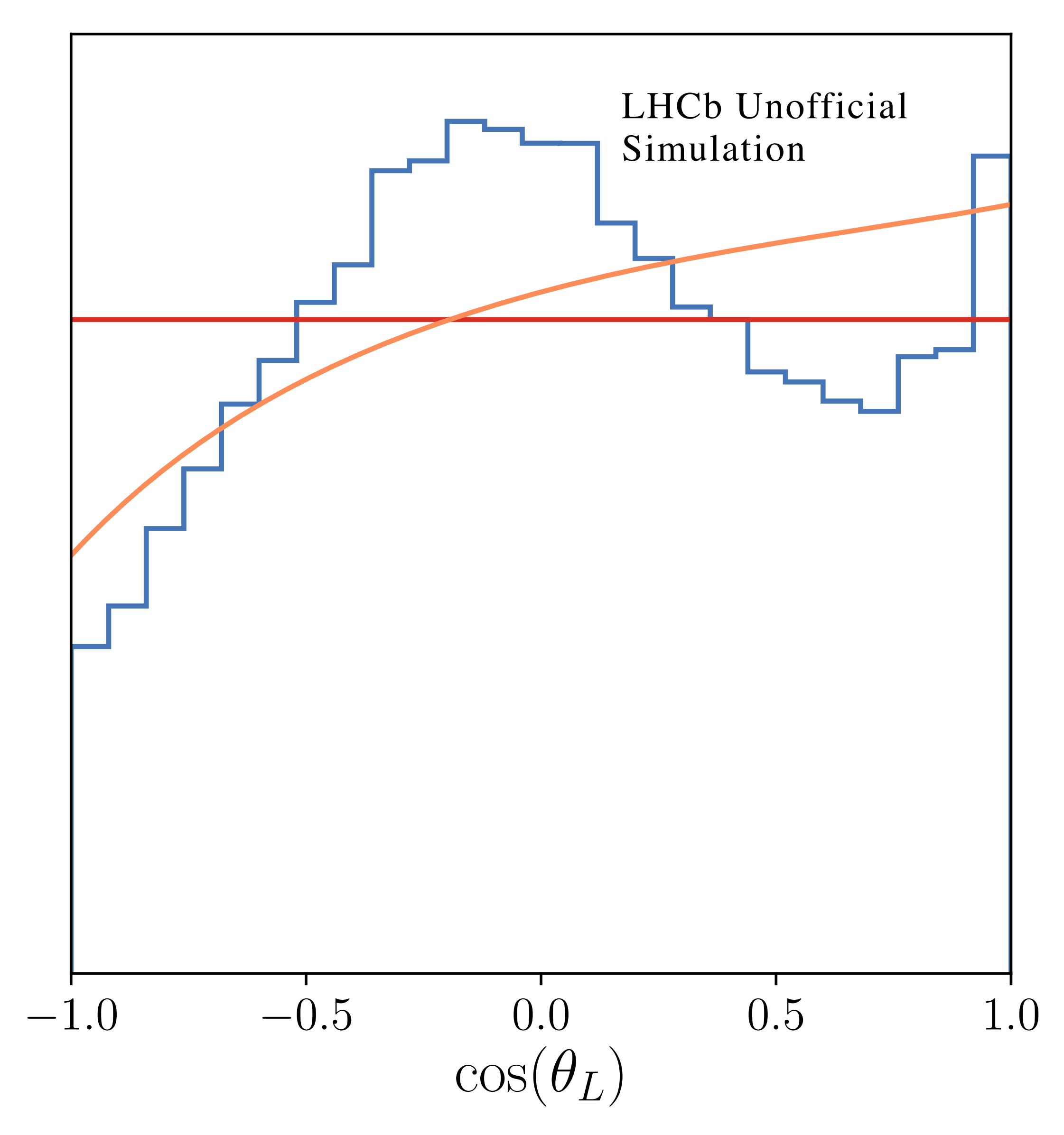
$$M = \frac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_L d\chi}$$

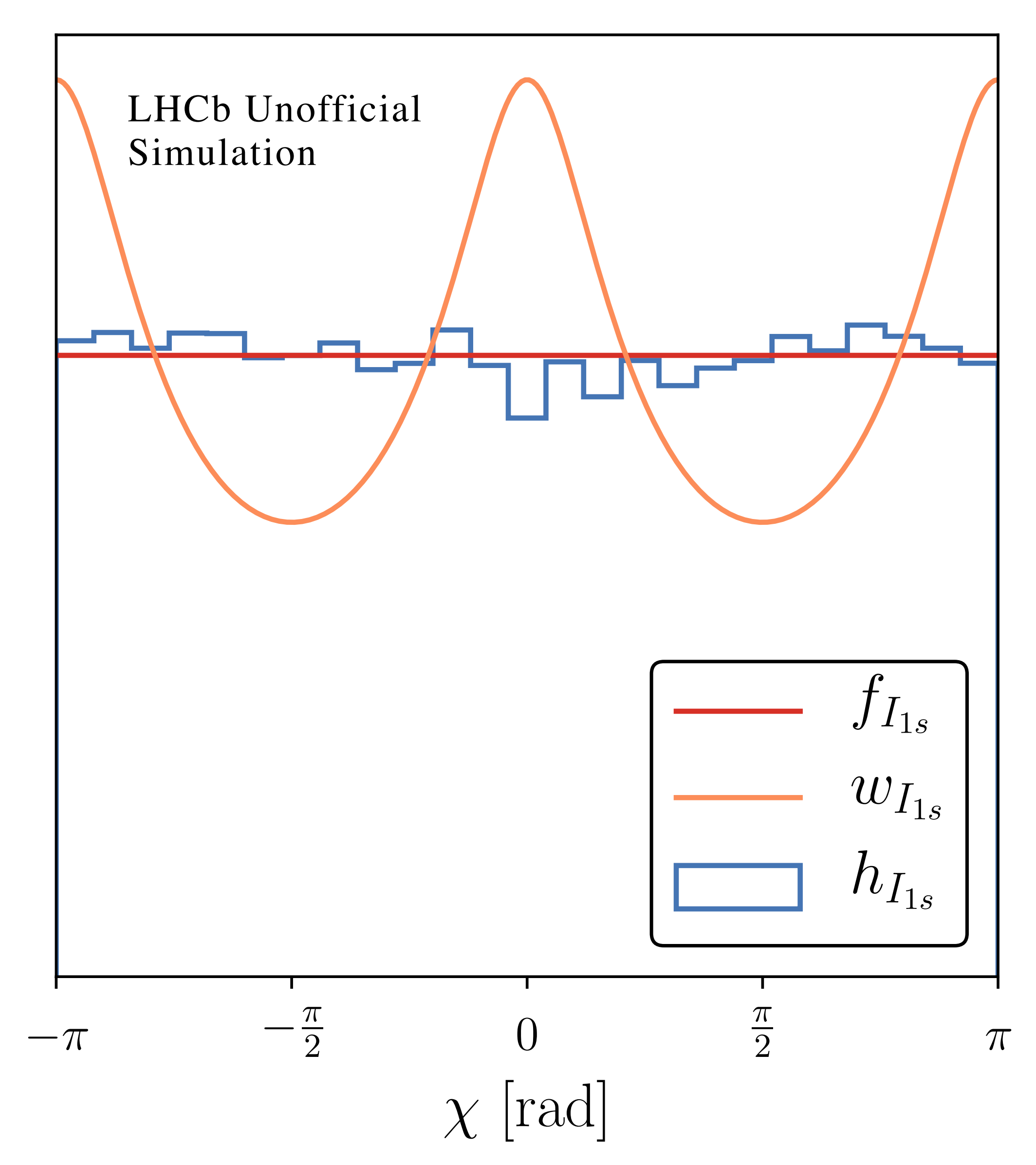
- Calculate the value of the weight function for signal simulation (using truth variables)

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

SIGNAL PDF CREATION





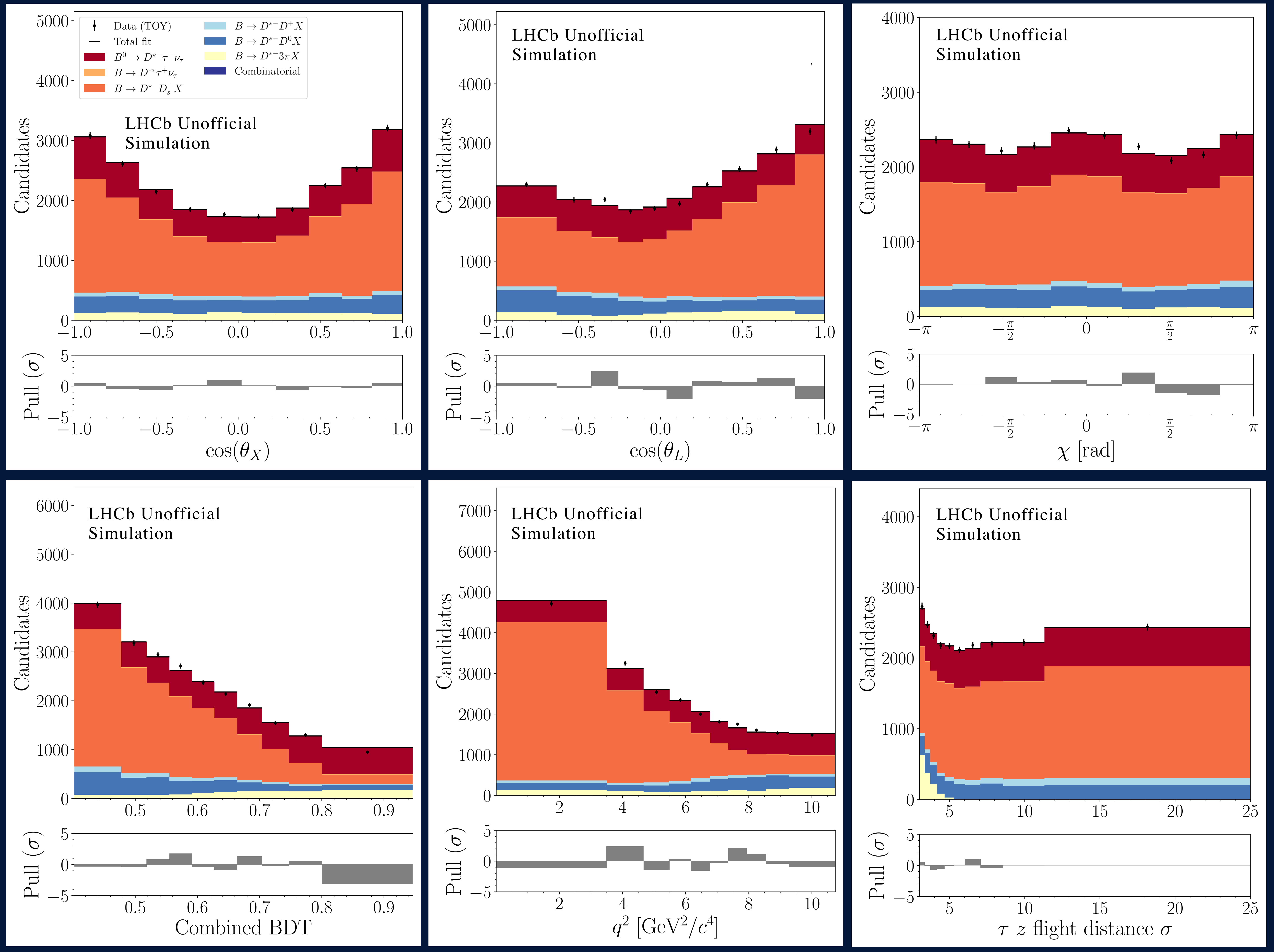


- Take angular function for a particular I_x ,

  f_{I_x}: $I_{1s} \sin^2 \theta_D$
- Divide by the total model M to obtain weight function, w_{I_x} $\quad M = \dfrac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_L d\chi}$
- 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 ν
  - 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 $\mathscr{R}(D^*)$ (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



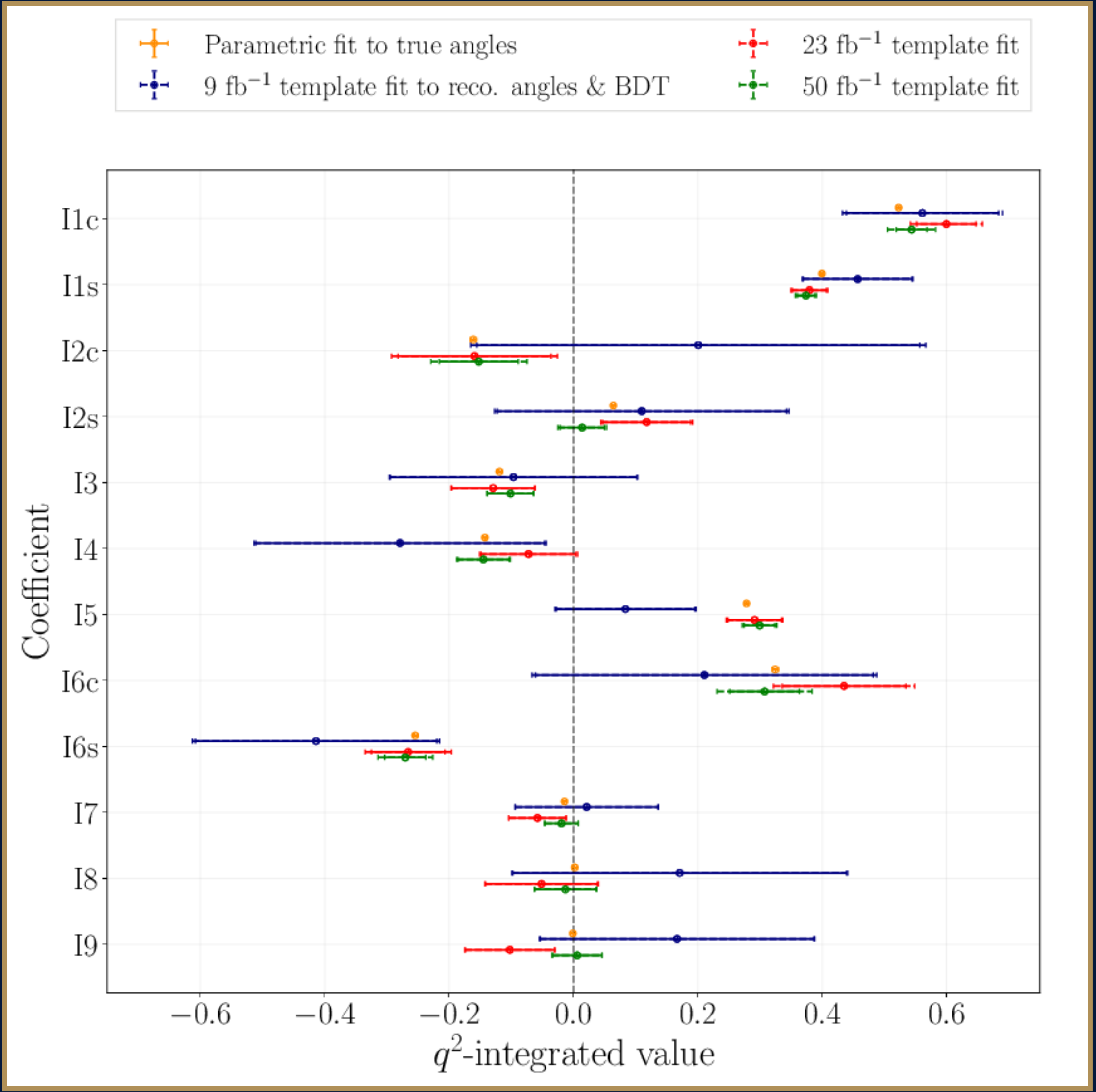
ANGULAR ANALYSIS: ANGULAR COEFFICIENTS

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

- 9fb^{-1}: Run 1 + 2 (blue)

- 23fb^{-1}: Run 1 + 2 + 3 (red)

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



JHEP 11, (2019) 133

SUMMARY

- Measuring the 12 $B^0 \to D^{*-}\tau^+\nu_\tau$ angular coefficients and $\mathscr{R}(D^*)$
  - Expected precision of 7-8% on $\mathscr{R}(D^*)$ (no systematics included)
  - First measurement of angular coefficients for $B^0 \to D^{*-}\tau^+\nu_\tau$

- 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
  - $B \to D^{*-}D^0(X)$
  - $B \to D^{*-}D^+(X)$
  - $B \to D^{*-}D_s^+(X)$
  - $D_s^+ \to \pi^+\pi^-\pi^+(X)$

- Signal fit requires 12 angular templates for signal PDF
  - 3D + 3D fit in decay angles + discriminating variables

BACK UP SLIDES

BDT TRAINING

USING BDTS TO REDUCE BACKGROUND

- 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.

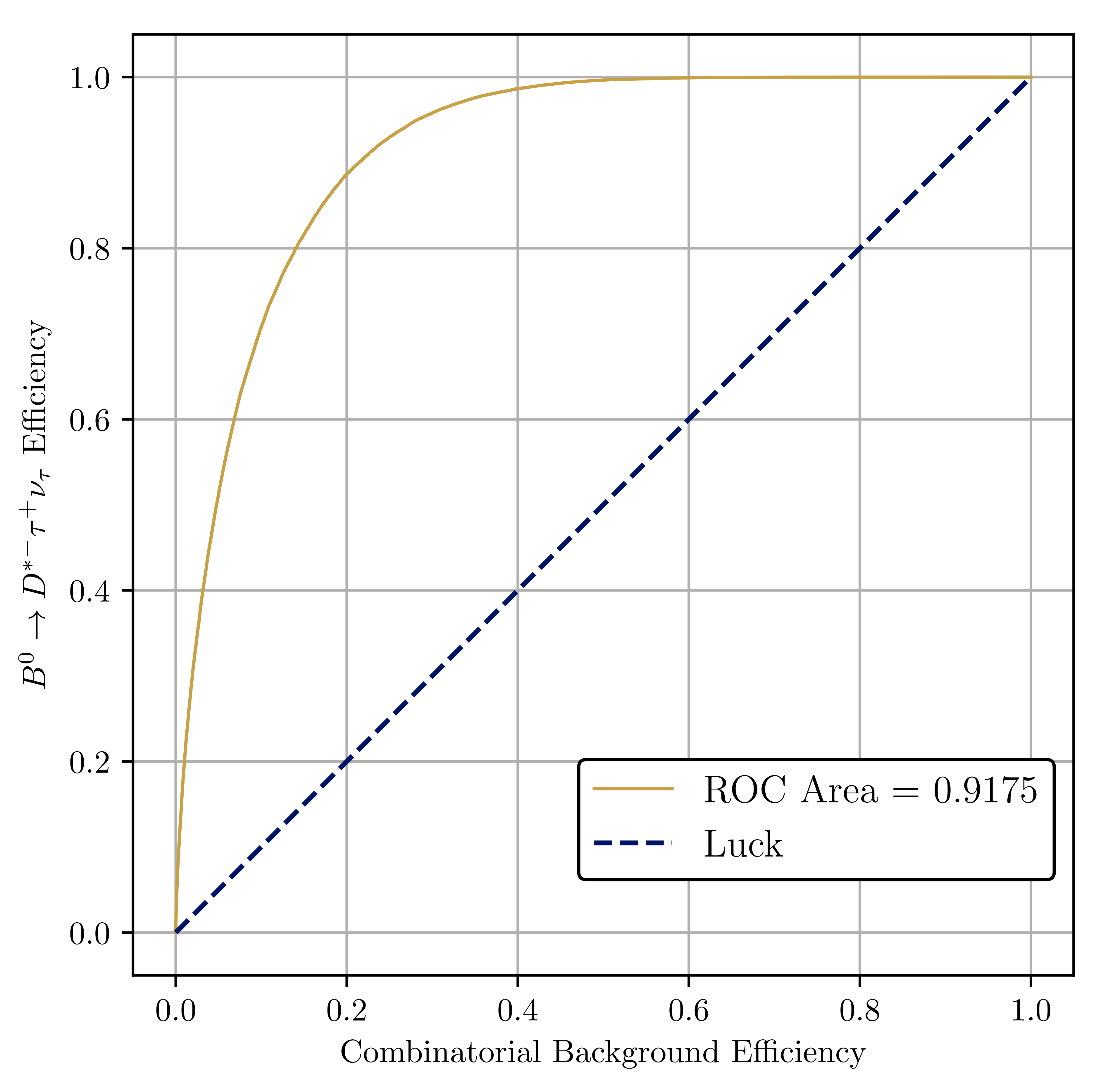
- Tau BDT
  - Signal MC - truth matched + preselection
  - $B \to D^* D_s(X)$ MC - truth matched + preselection
  - Variables: $\tau \to \pi^+\pi^-\pi^+$ information, B^0 information

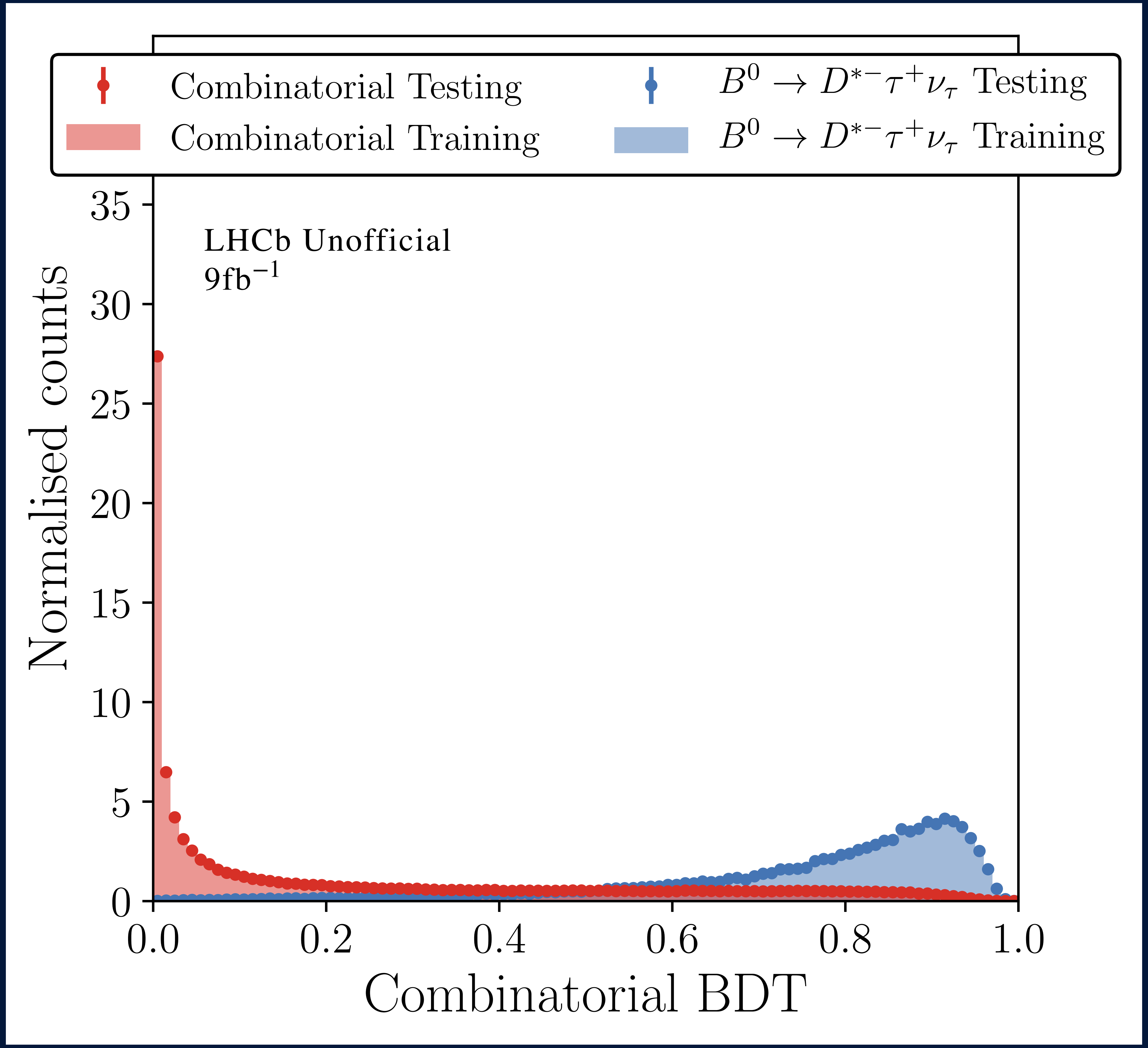
- Isolation BDT
  - Signal MC - truth matched + preselection
  - $B \to D^* D_s(X)$ MC - truth matched + preselection
  - Variables: charged and neutral isolation variables

SIGNAL SELECTION

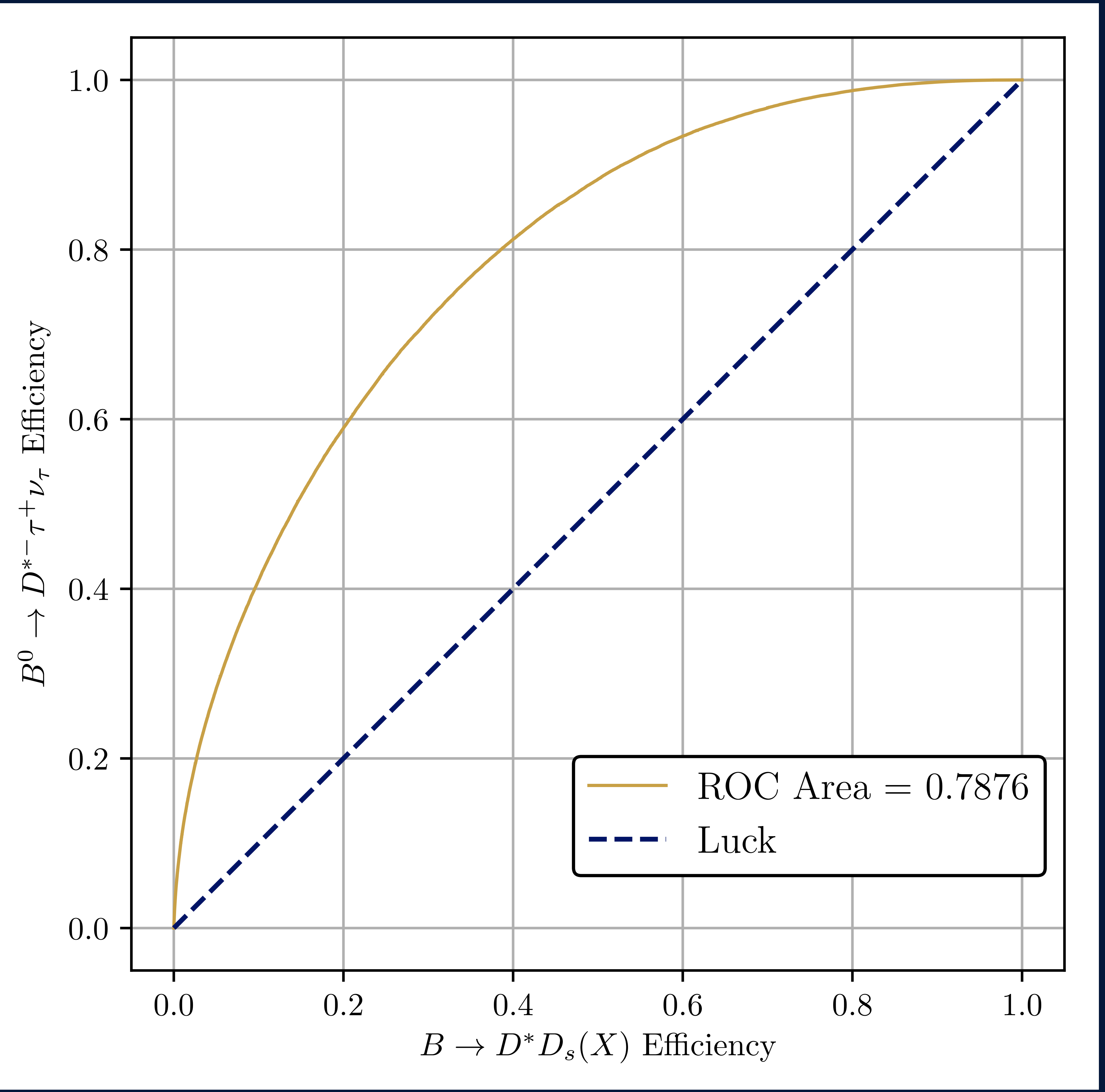
Variable	Condition
Trigger	`(B0_L0HadronDecision_TOS or B0_L0Global_TIS) and (B0_Hlt1TrackMVADecision_TOS or B0_Hlt1TwoTrackMVADecision_TOS) and (B0_Hlt2Topo2BodyDecision_TOS or B0_Hlt2Topo3BodyDecision_TOS or B0_Hlt2Topo4BodyDecision_TOS)`
$\mathrm{PV}(\tau^+)$	$= \mathrm{PV}(D^0)$
$\mathrm{V}_z(\tau^+)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

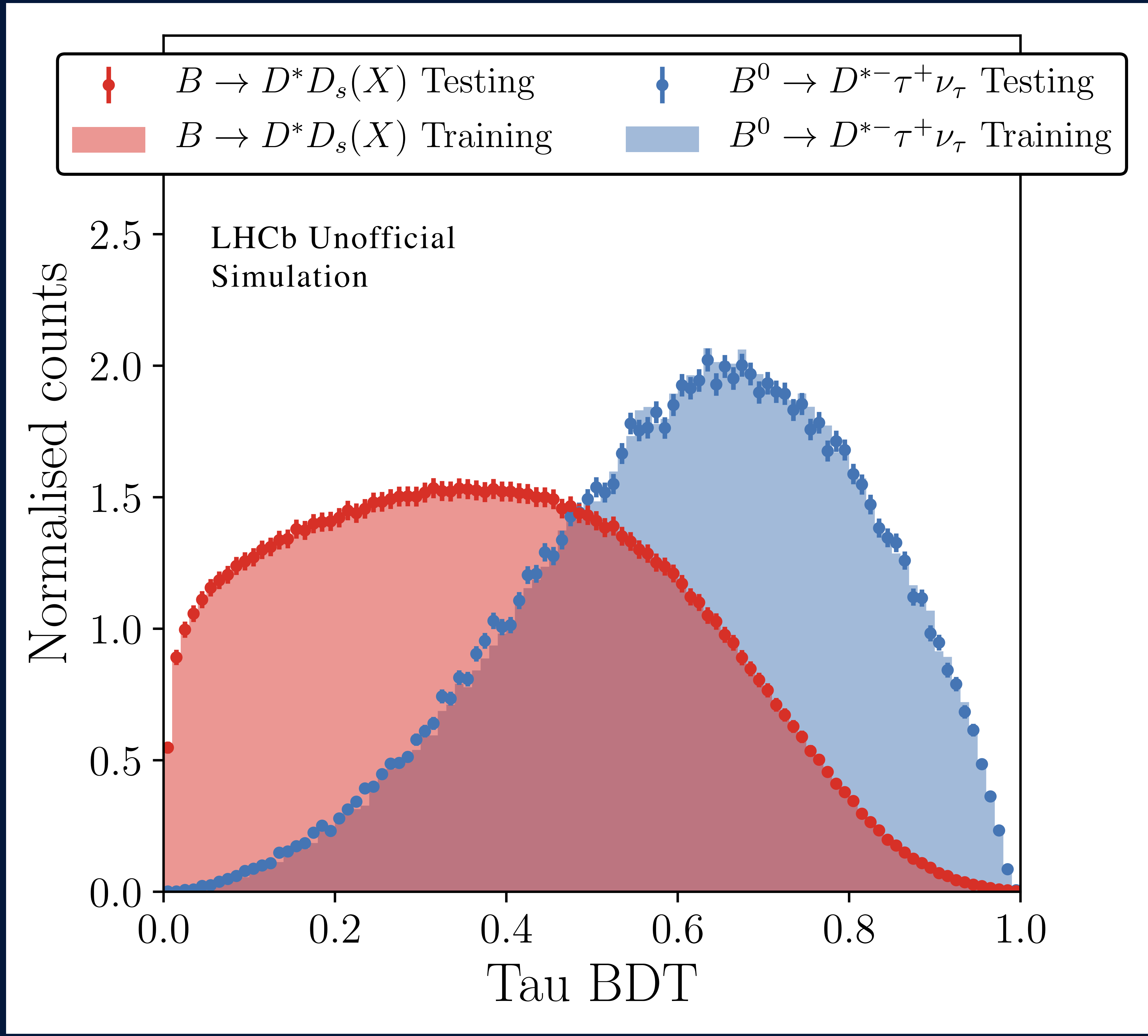
COMBINATORIAL BDT - TRAINING



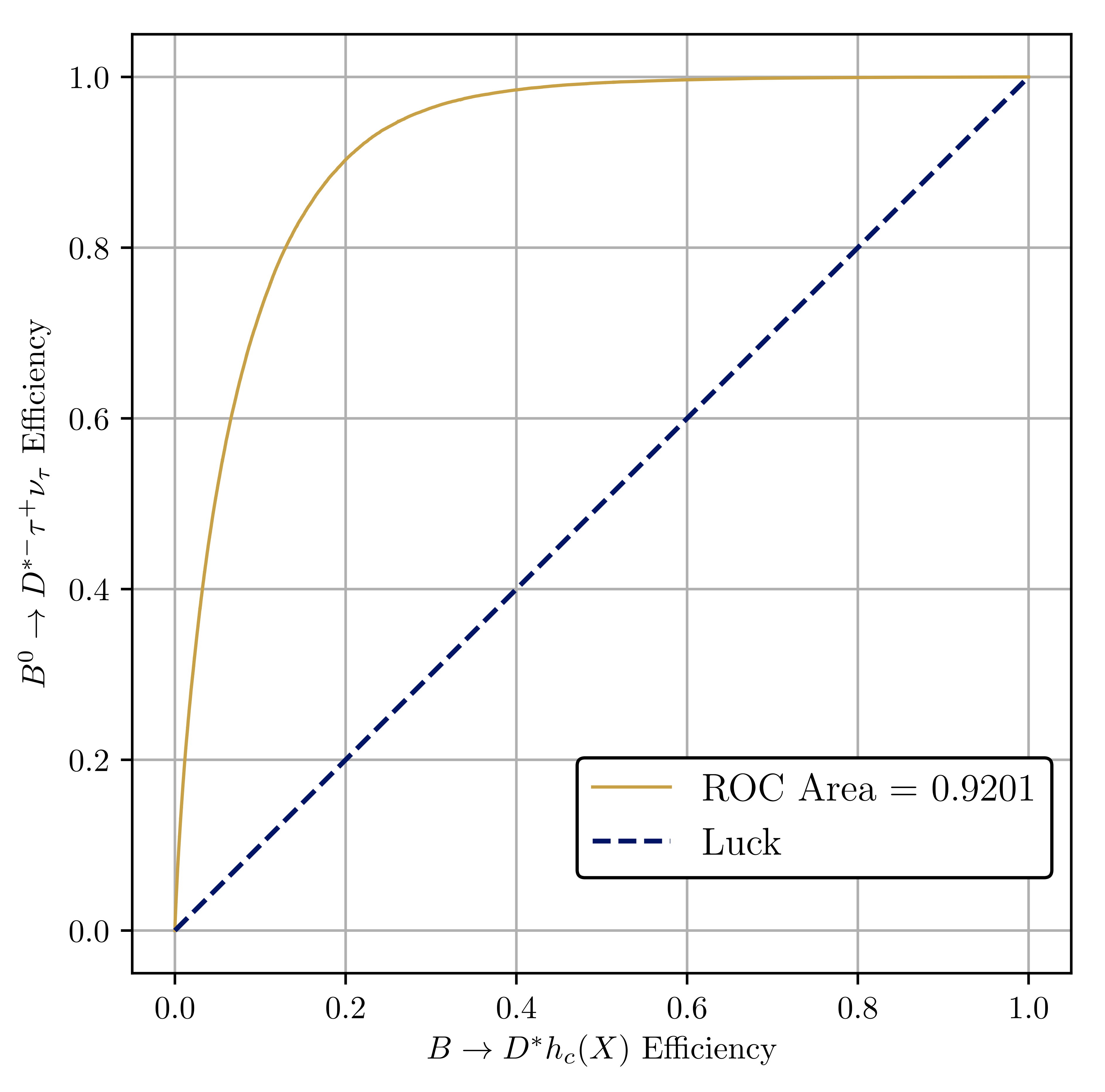


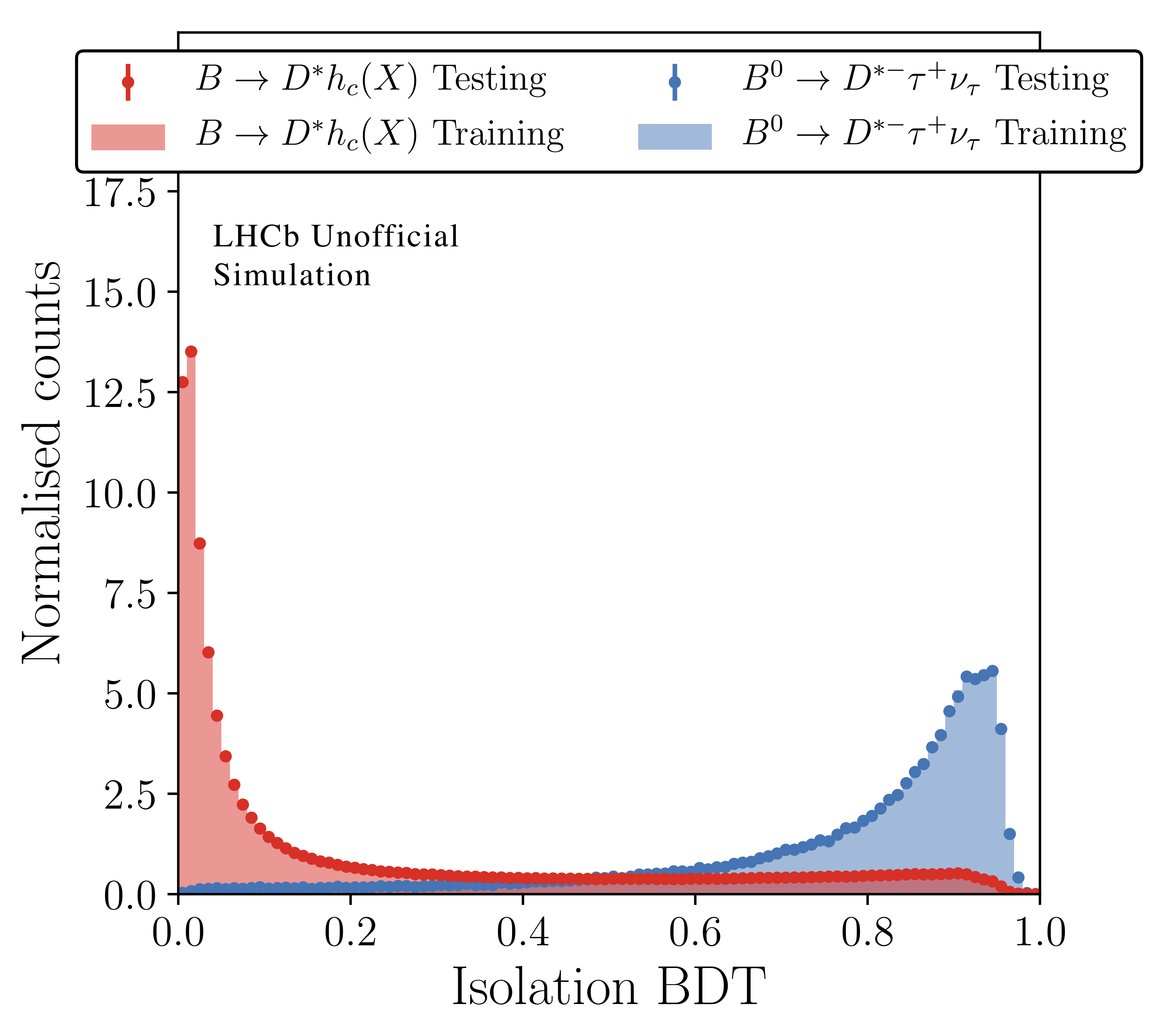
TAU BDT - TRAINING





ISOLATION BDT - TRAINING





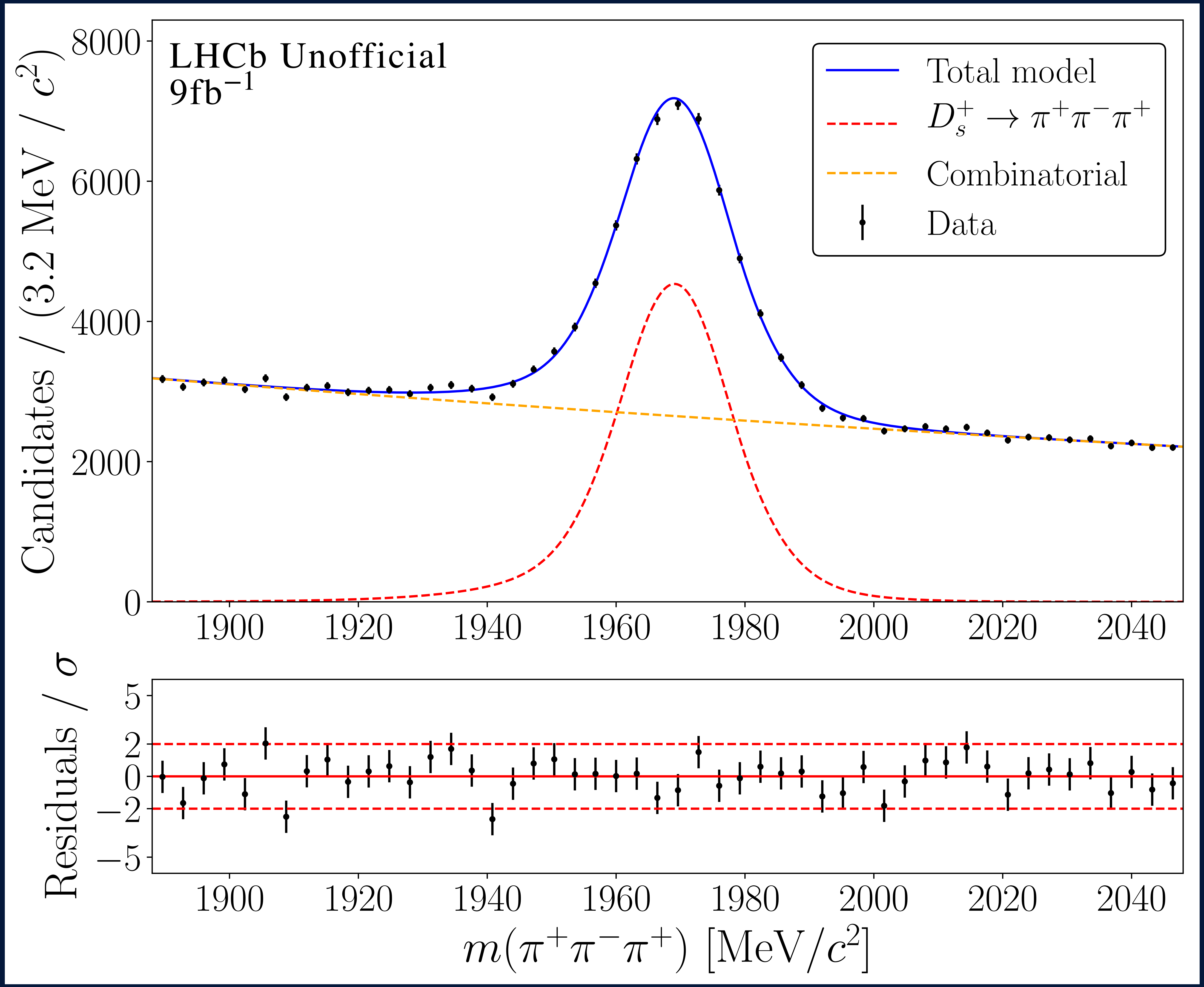
SELECTION OPTIMISATION AND NORMALISATION FITS

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

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

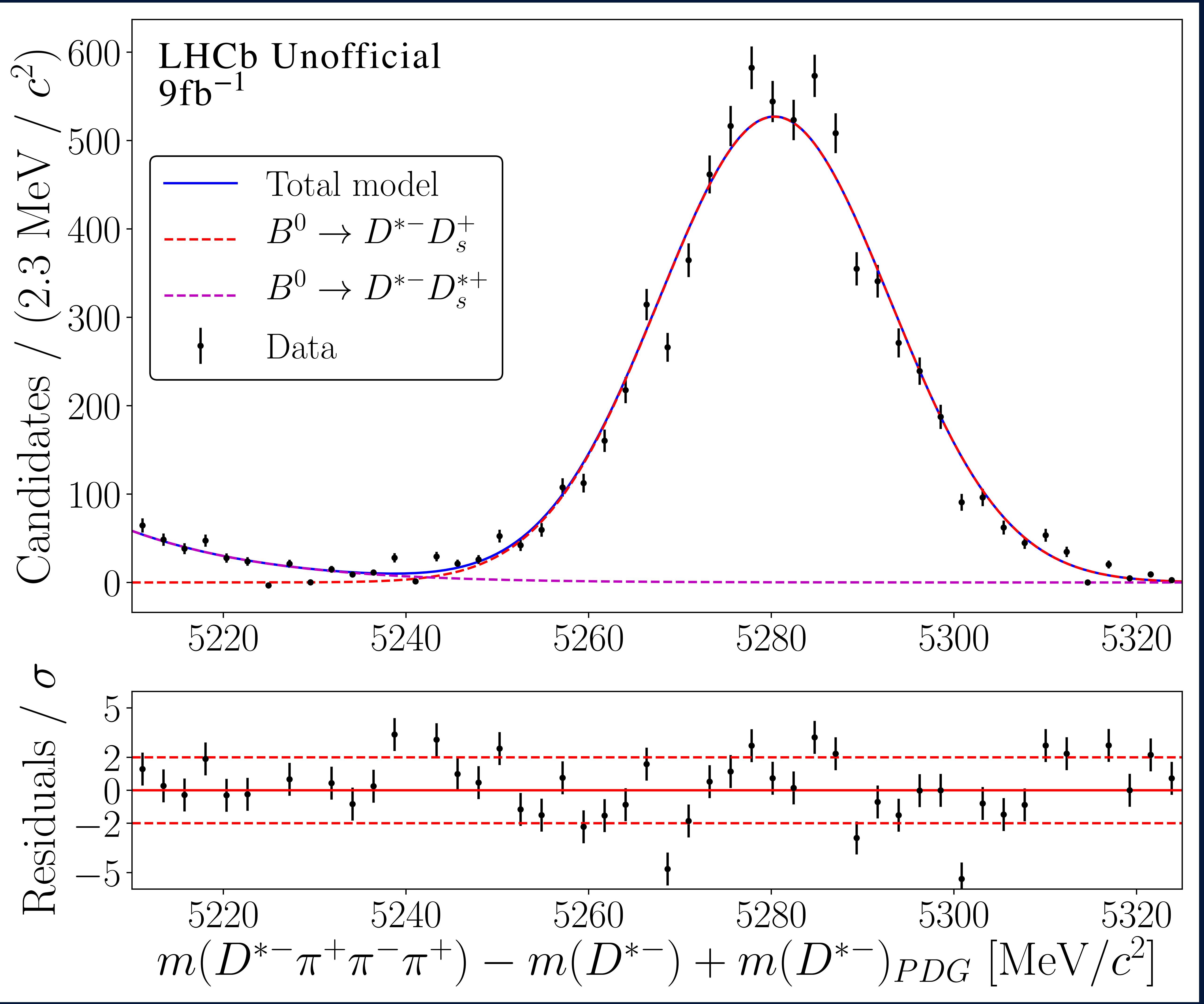
$m(\pi^+\pi^-\pi^+)$ FIT

- Fit $m(\pi^+\pi^-\pi^+)$ around mass of D_s
  - Measure $D_s^+ \to \pi^+\pi^-\pi^+$ 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 $B^0 \to D^{*-}D_s^+(X)$
- Measure pure $B^0 \to D^{*-}D_s^+$ yield



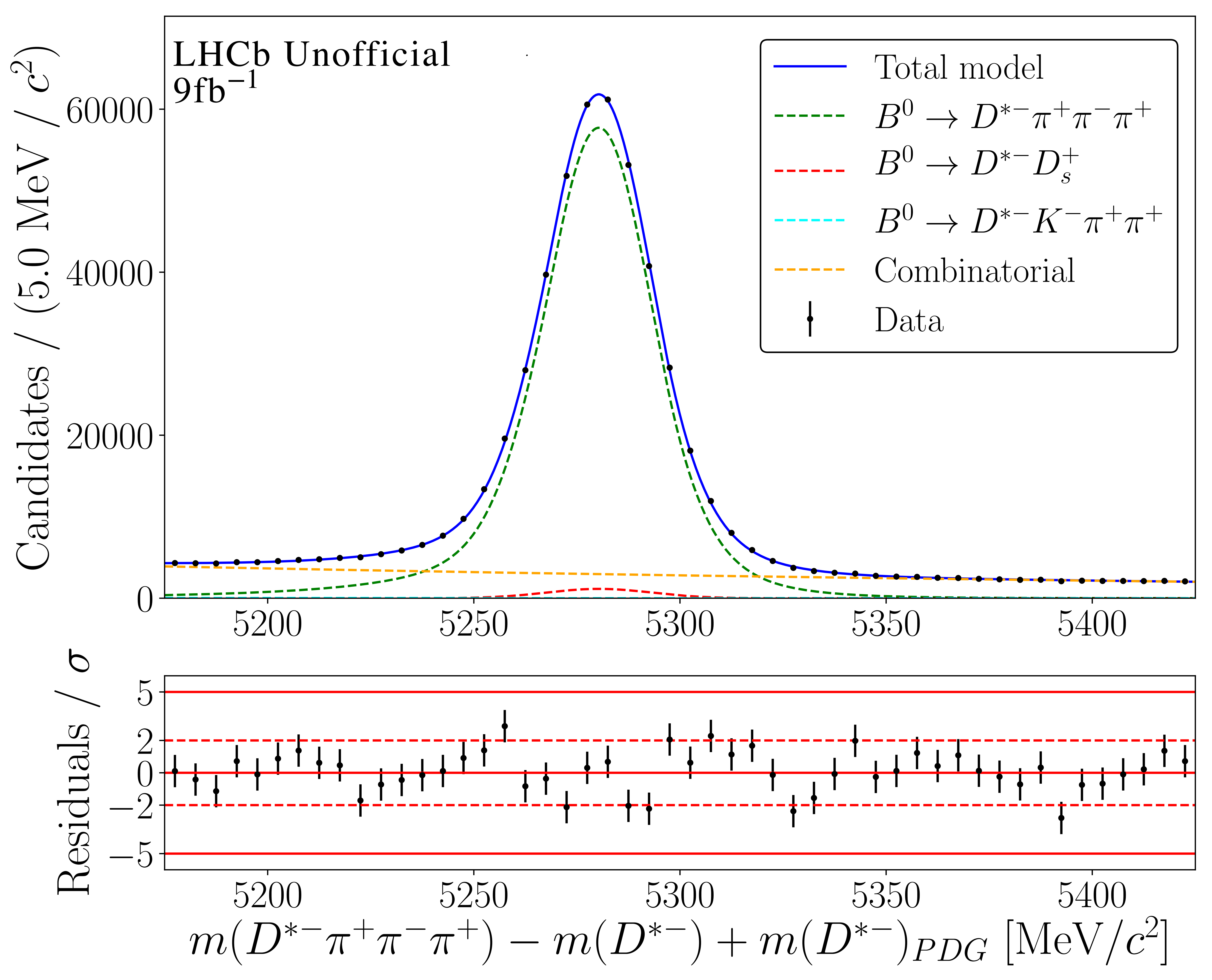
FULL $m(D^{*-}\pi^+\pi^-\pi^+)$ FIT

- Fit $m(D^{*-}\pi^+\pi^-\pi^+)$ with $B^0 \to D^{*-}D_s^+$ yield fixed

- No $m(\pi^+\pi^-\pi^+)$ constraints
- No sWeights

- Measure $B^0 \to D^{*-}\pi^+\pi^-\pi^+$ yield

- Optimisation loop then runs



REMOVING FAKE D^*

SIGNAL SELECTION

Variable	Condition
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$\mathrm{PV}(\tau^+)$	$= \mathrm{PV}(D^0)$
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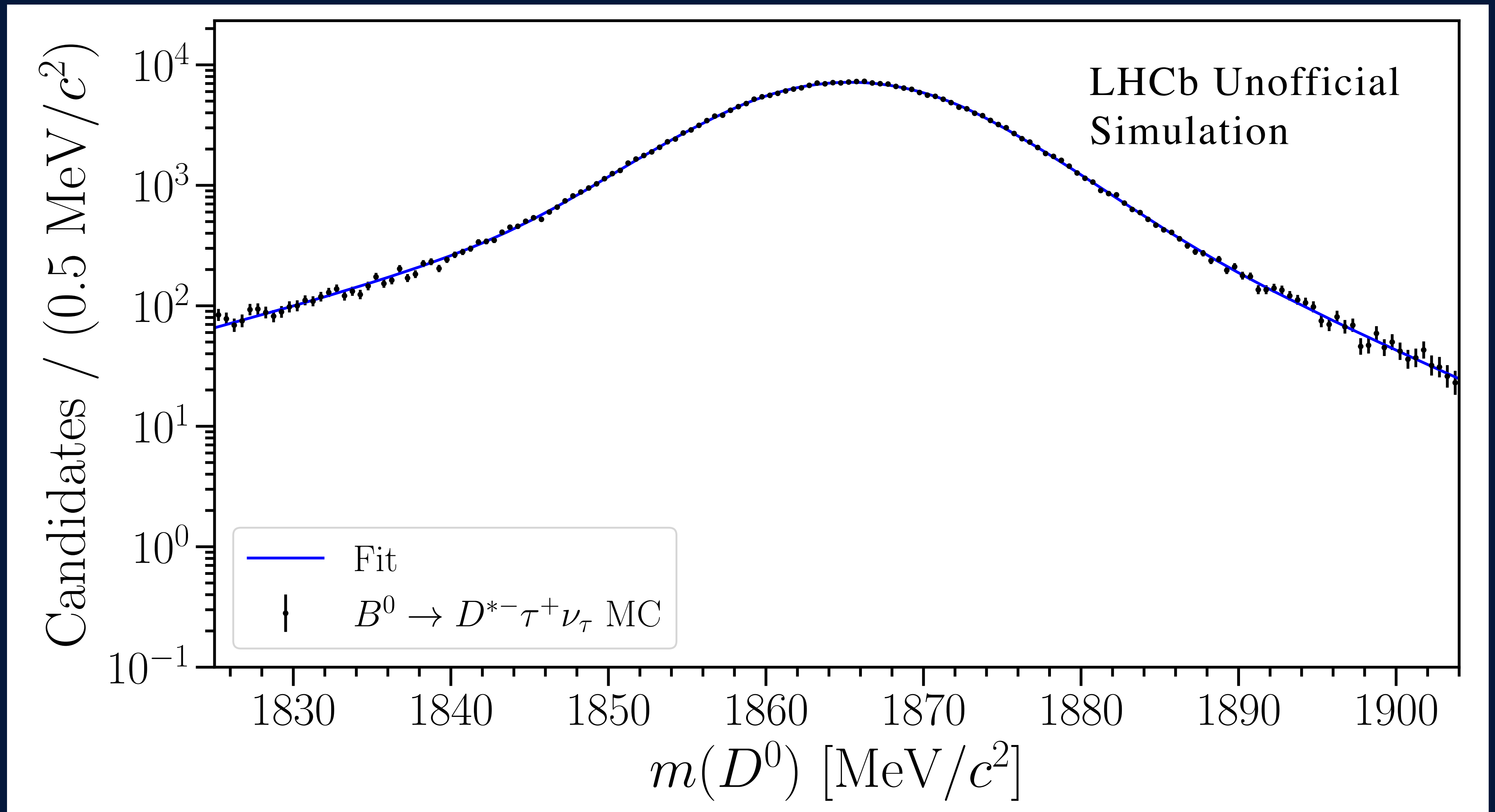
$m(D^* - D^0)$	$\in [140.0,\ 160.0]\ \mathrm{MeV}/c^2$
$m(D^0)$	$\in m(D^0)_{\mathrm{PDG}} \pm 40.0\ \mathrm{MeV}/c^2$
τ flight distance significance	> 3.0
Combinatorial BDT	> 0.6690
τ BDT	> 0.4816
Isolation BDT	> 0.8296

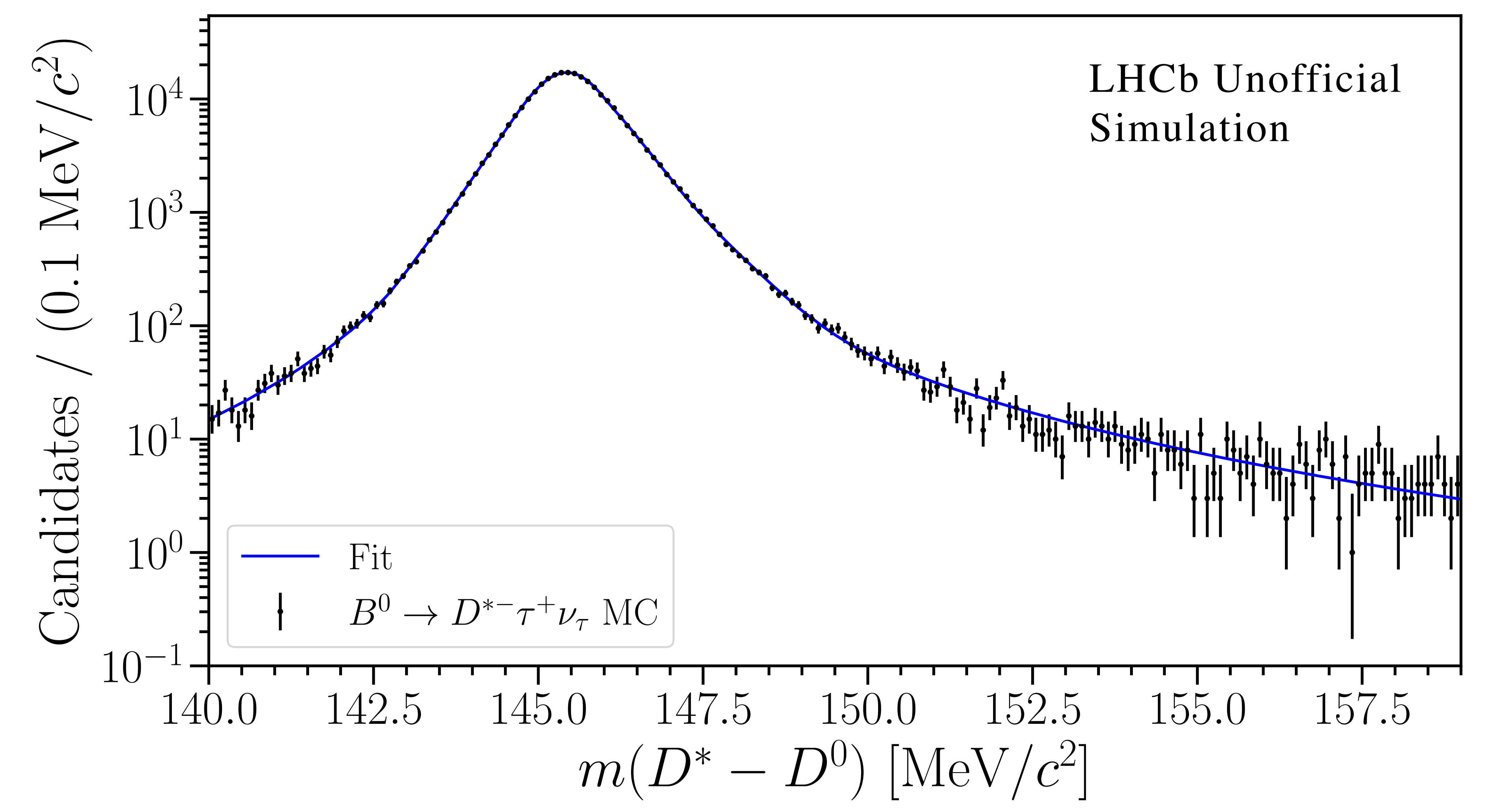
$D_s \to \pi^+\pi^-\pi^+(X)$ PID SELECTION

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

MEASURING FAKE D^* RATE - SIGNAL PDF

- After full selection the $B^0 \to D^{*-}\tau^+\nu_\tau$ 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

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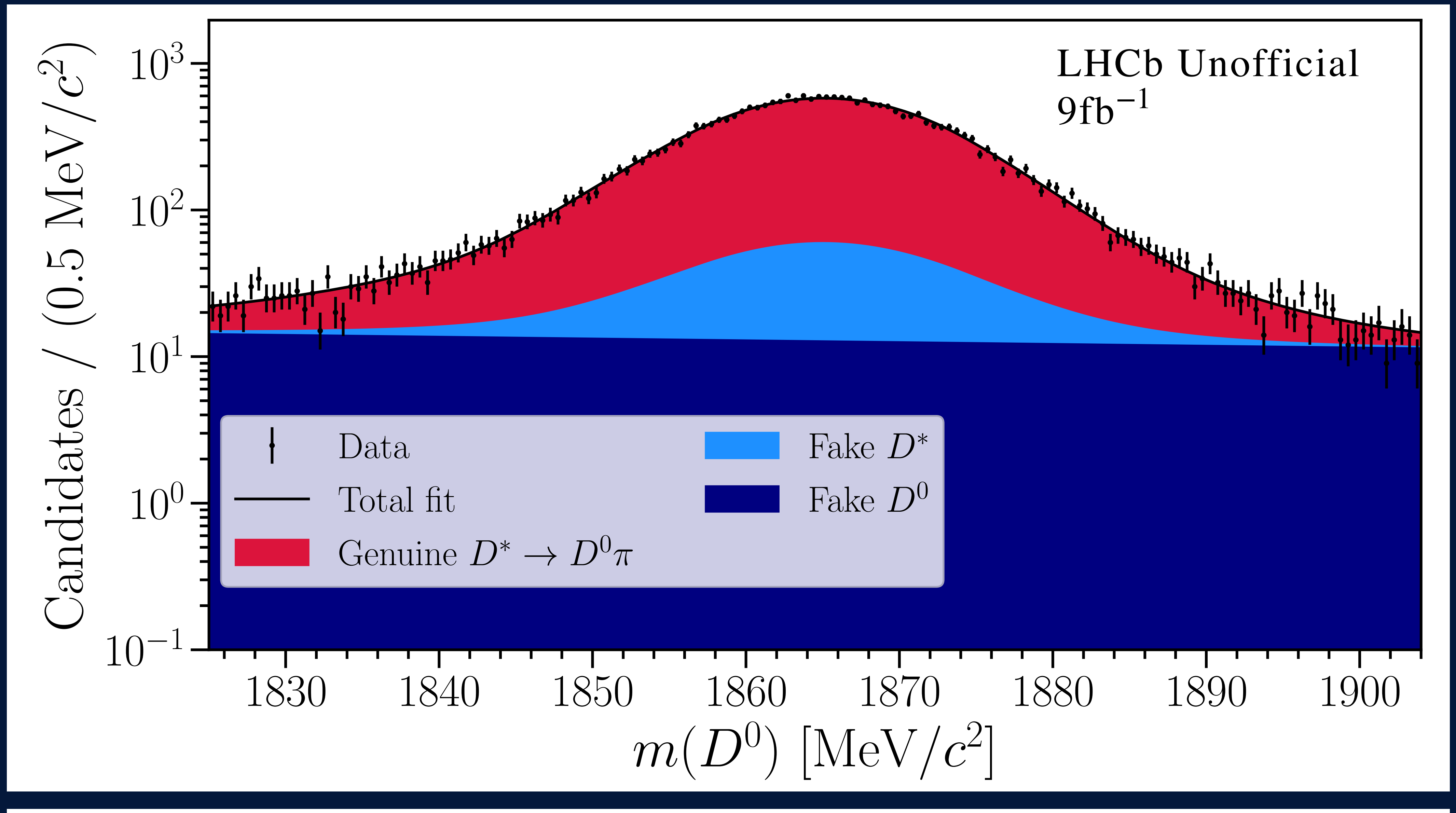
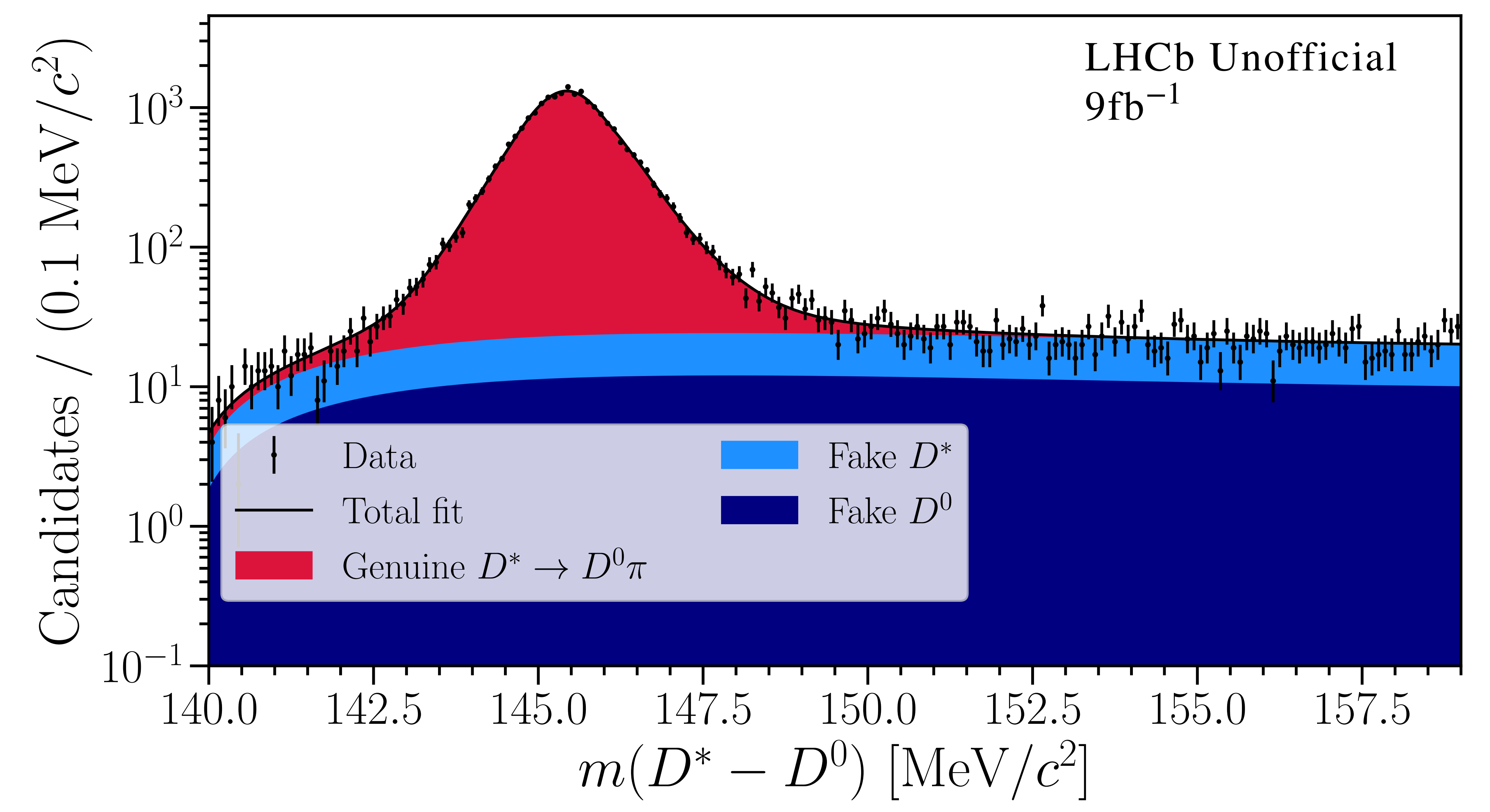




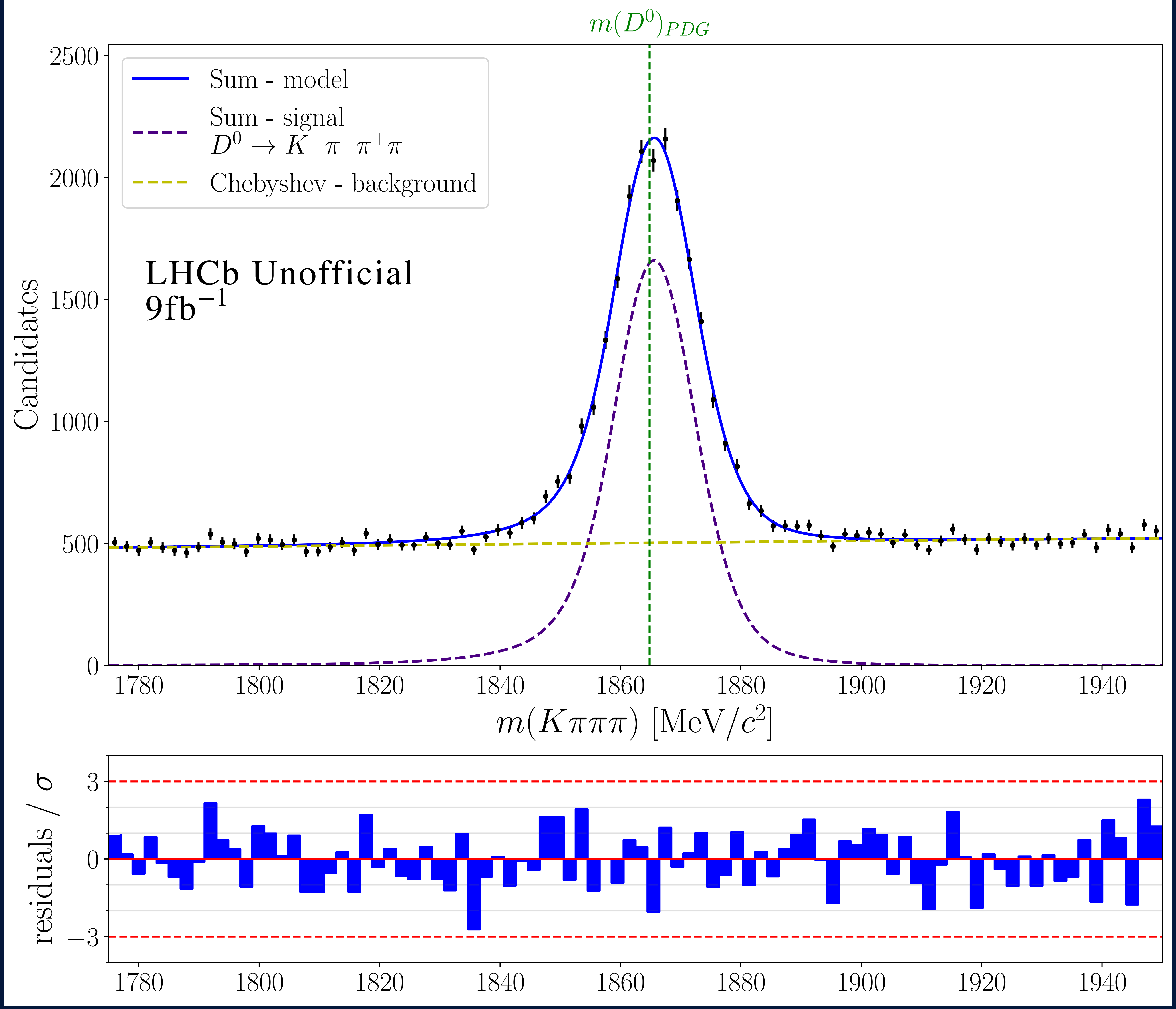
CONTROL STUDIES

CONTROL STUDIES

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

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

- Isolate $B \to D^*D^0(X)$ via $D^0 \to K^-\pi^+\pi^-\pi^+$
  - $m(K^-\pi^+\pi^-\pi^+) \in m(D^0)_{\text{PDG}} \pm 200.0\ \text{MeV}/c^2$
- 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 $B \to D^*D^0(X)$
- Perform data/MC reweighting to correct $B \to D^*D^0(X)$ MC



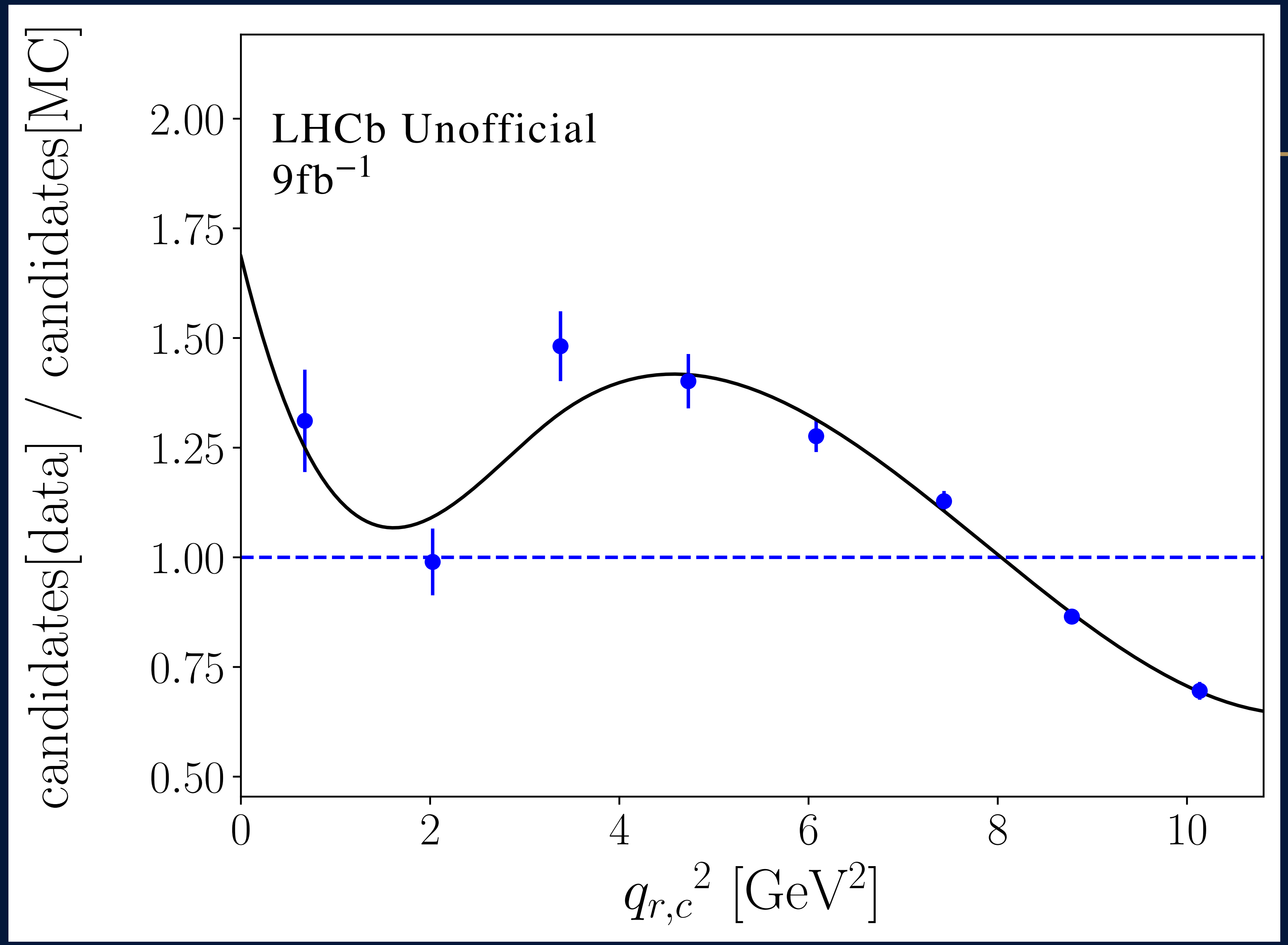
$B \to D^{*}D^{0}(X)$ REWEIGHTING

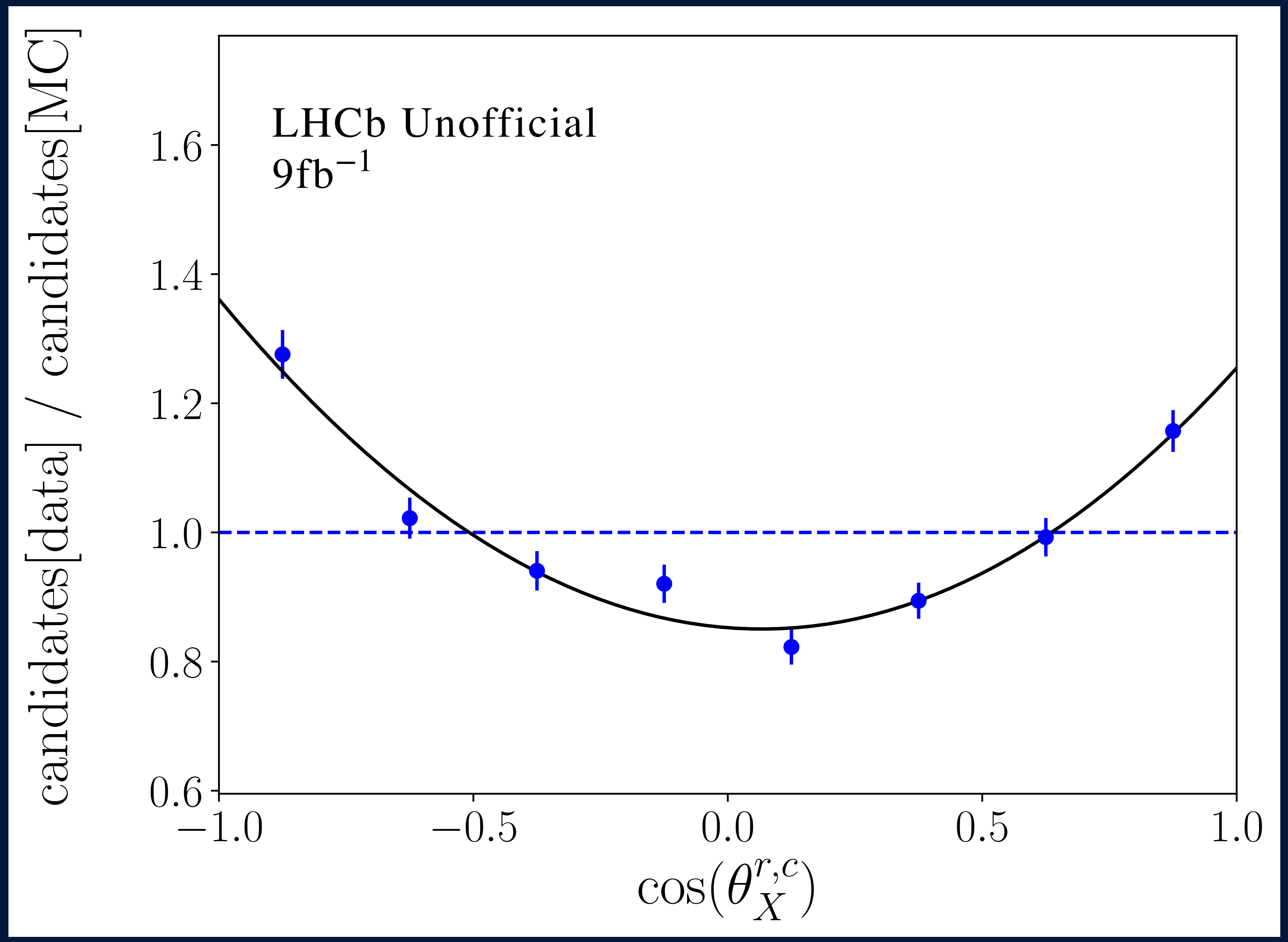
- Sequential reweighting using several variables

- 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

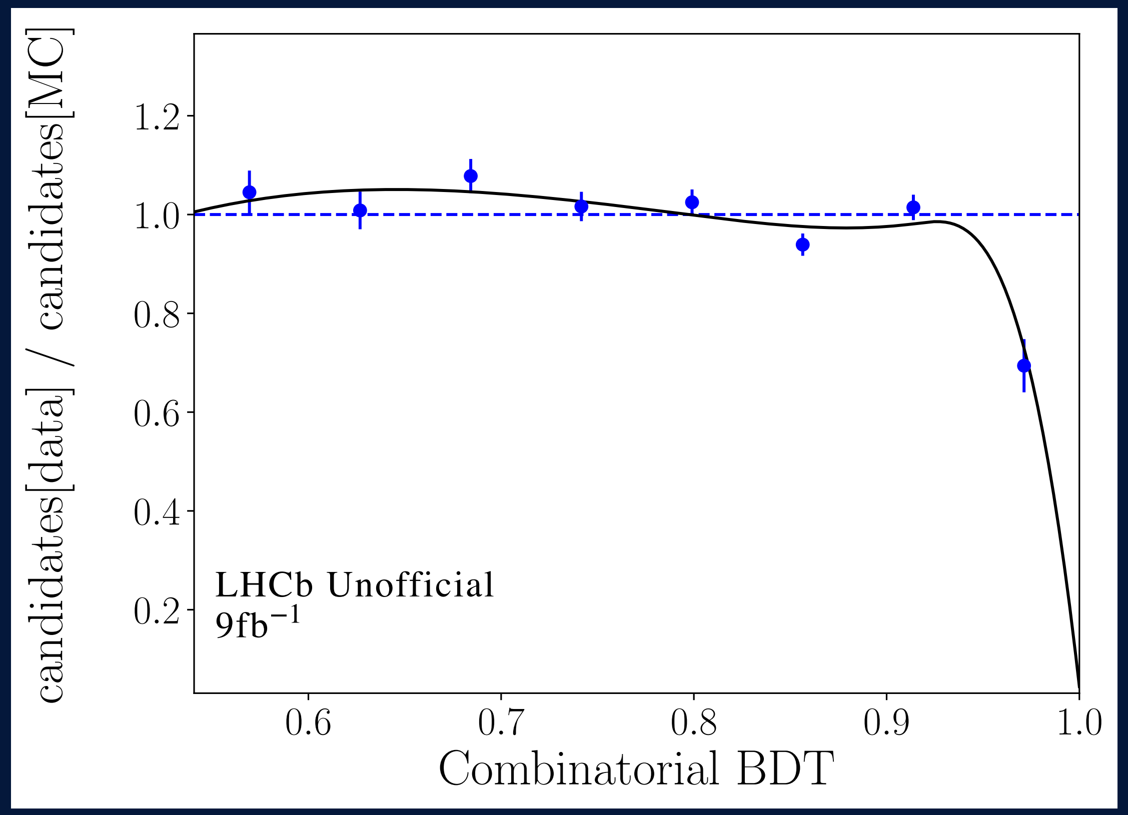
- Use spline to calculate weight for each MC event
  - Value of the spline at the variable value is used
  - Apply weight and move to next variable
    - Fit data/MC ratio with spline and update the weight

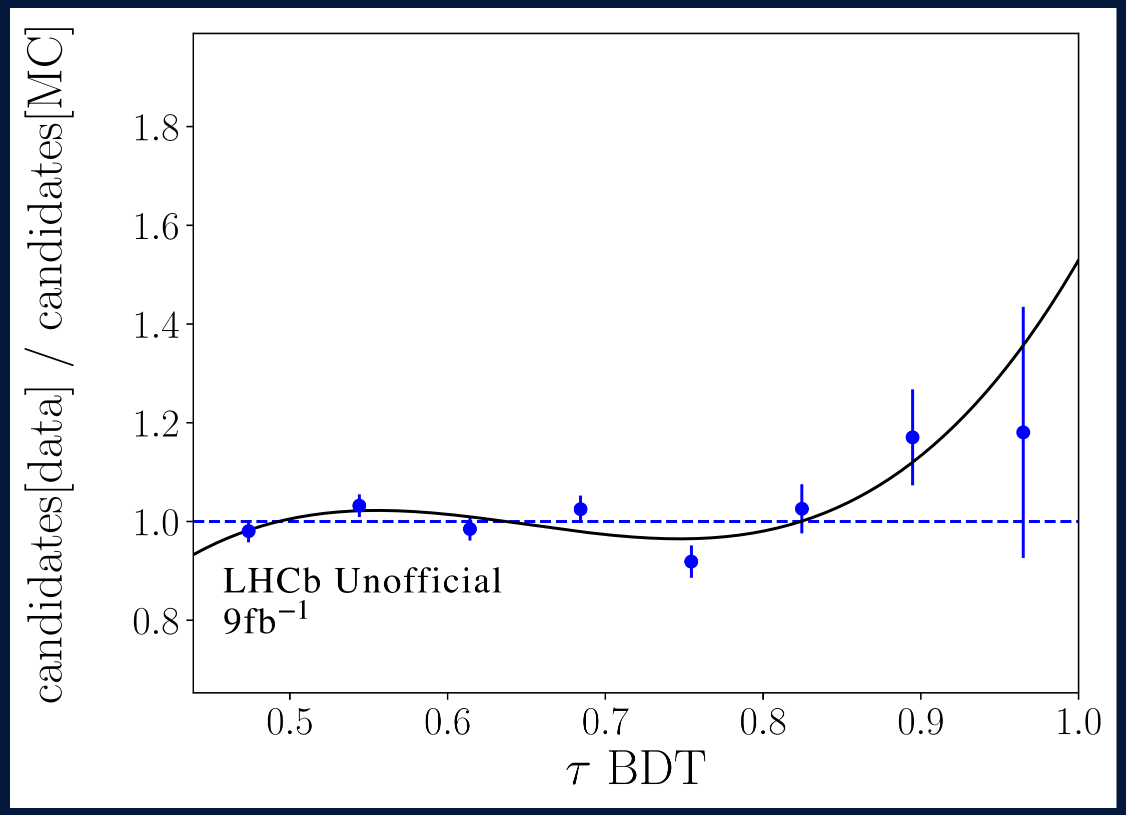
- Obtain single weight that corrects MC
  - Derived from $B \to D^{*}(D^{0} \to K^{-}\pi^{+}\pi^{-}\pi^{+})(X)$, but applied to all $B \to D^{*}D^{0}(X)$

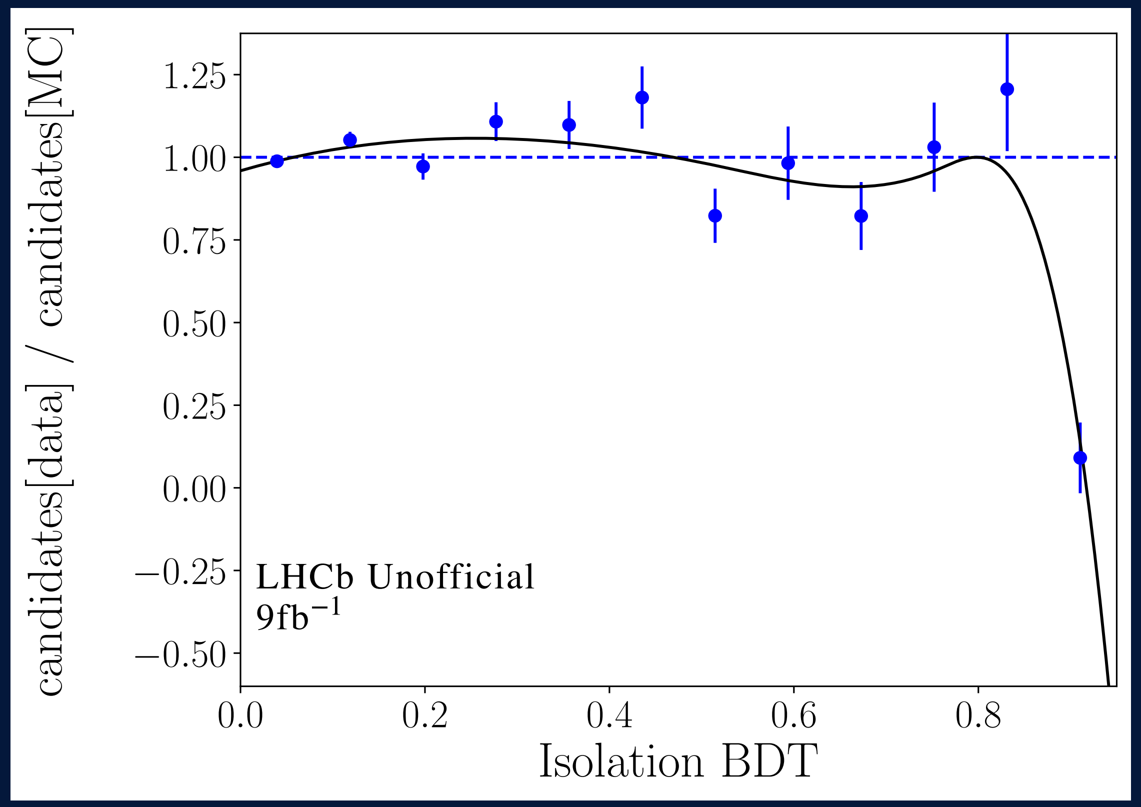


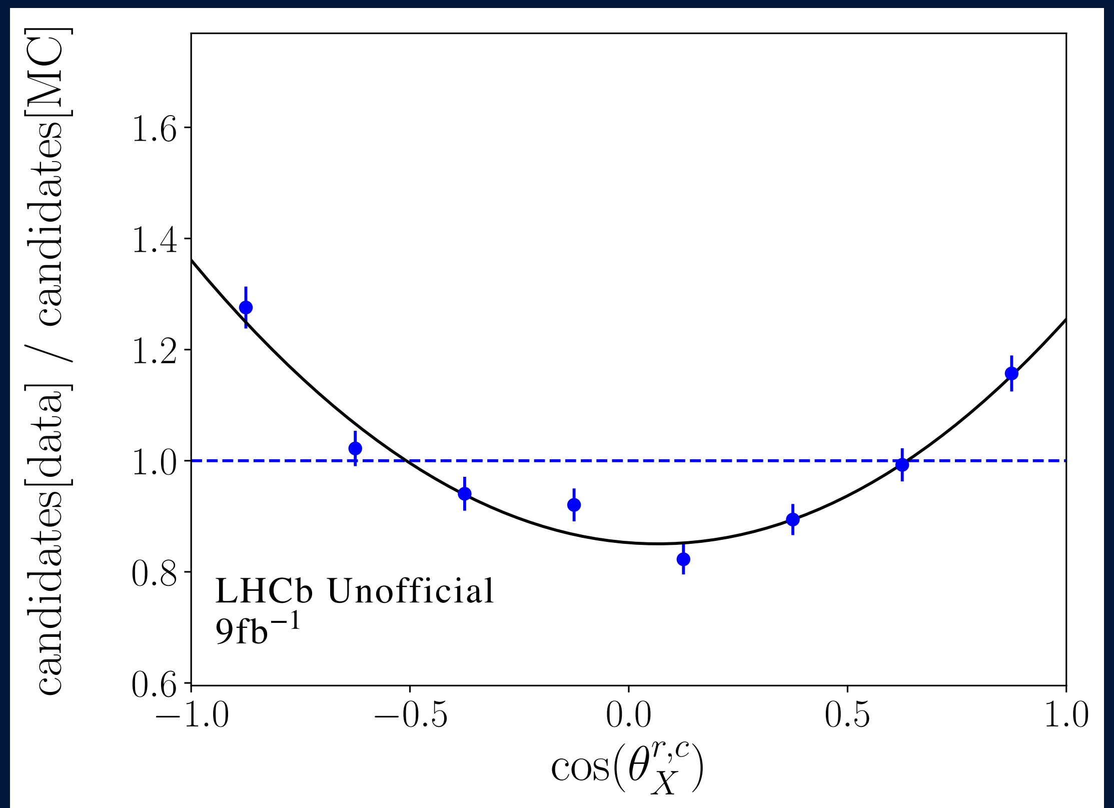


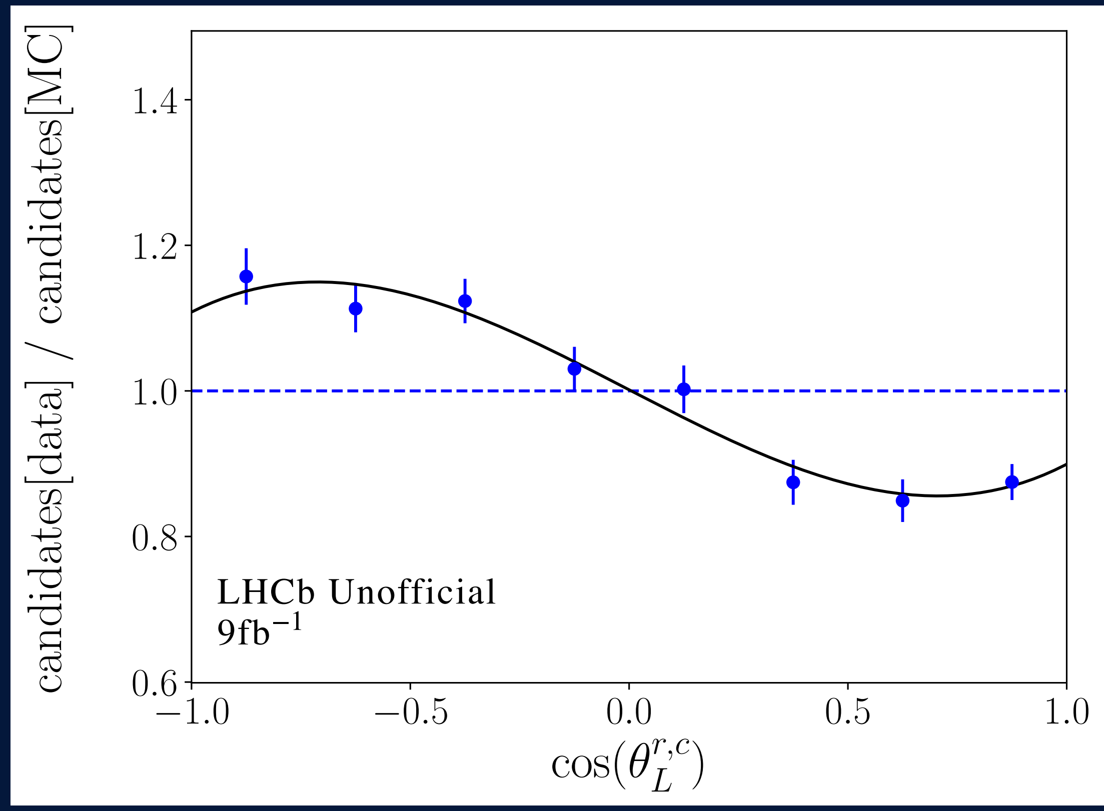
$B \to D^* D^0 (X)$ DATA/MC RATIO FITS

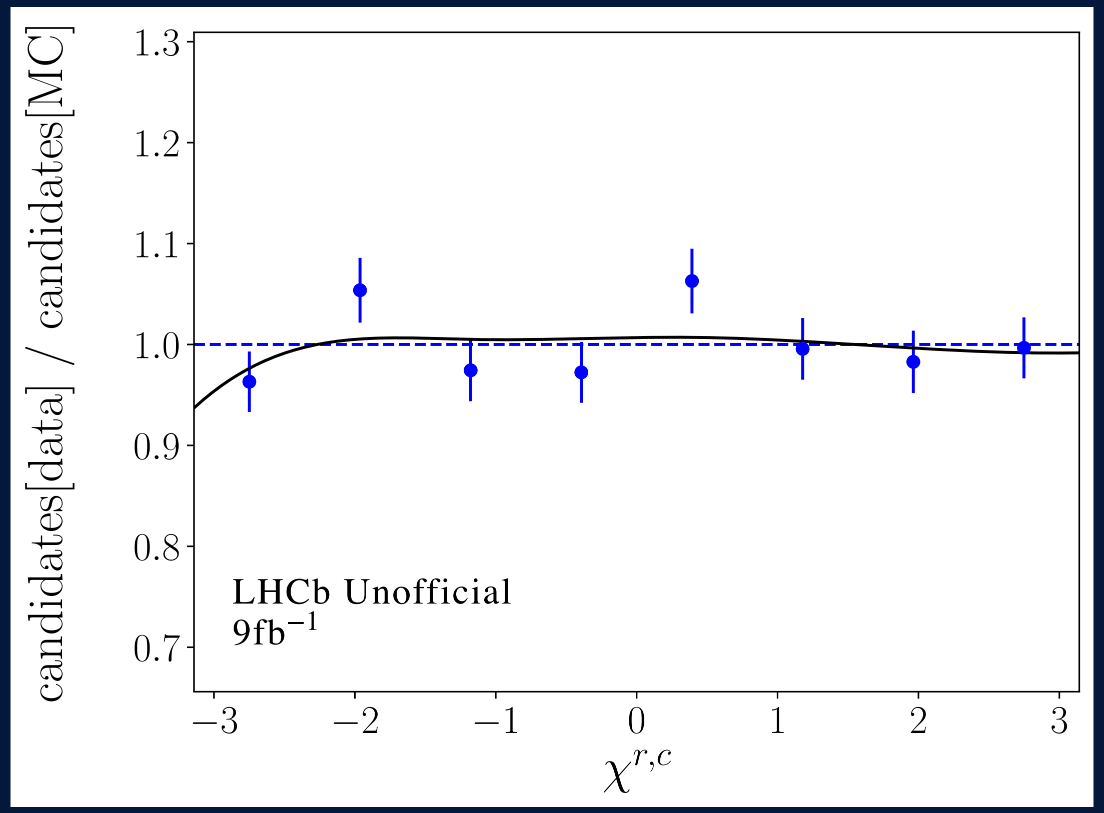


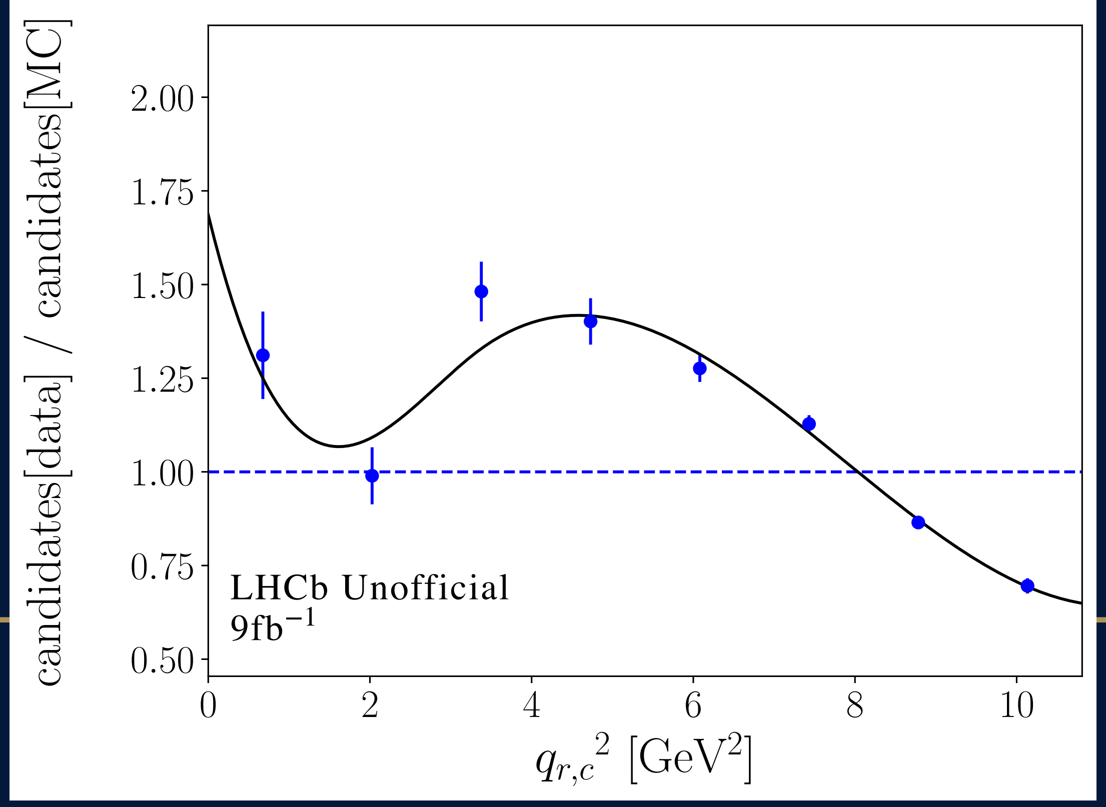


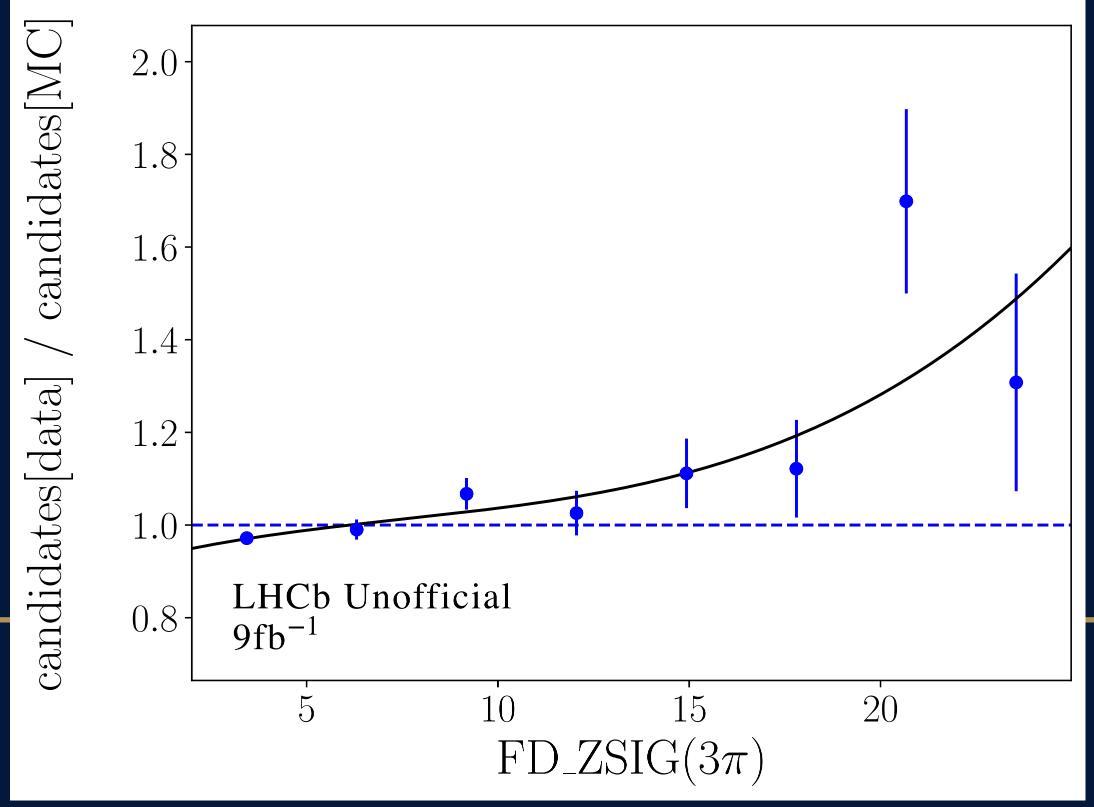




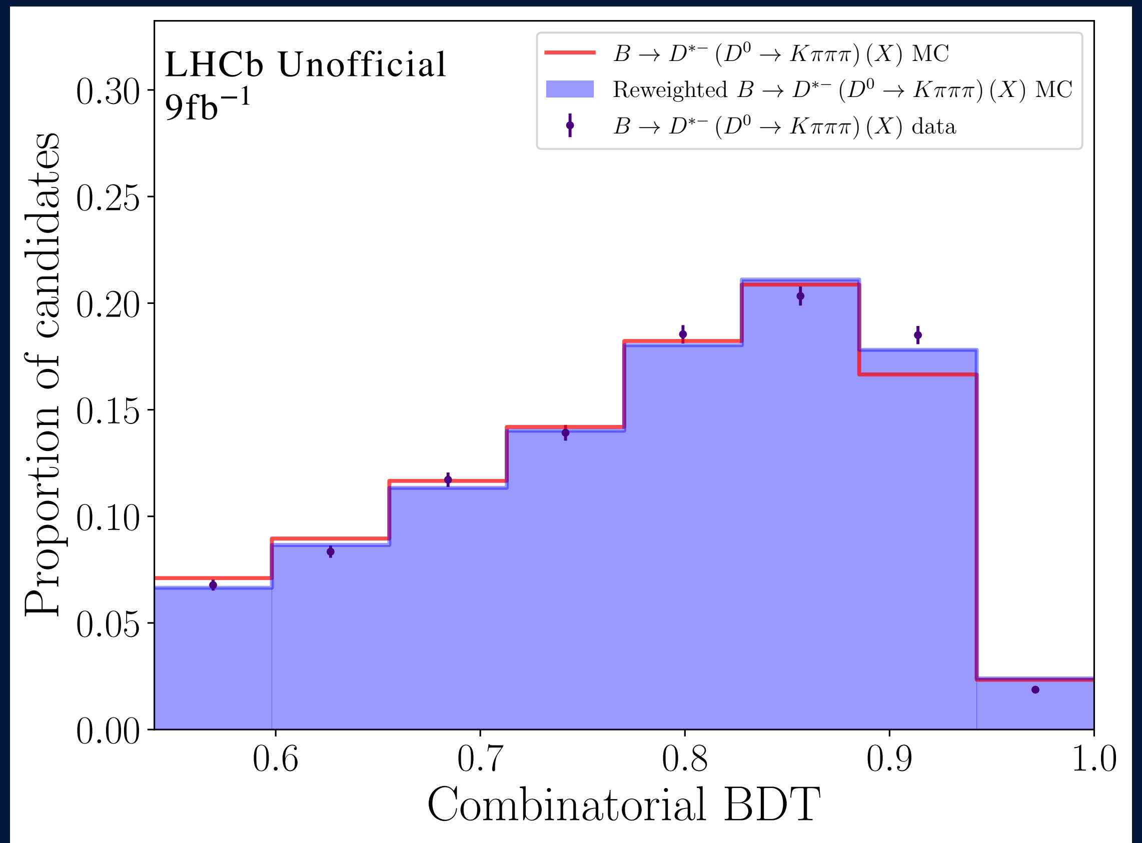


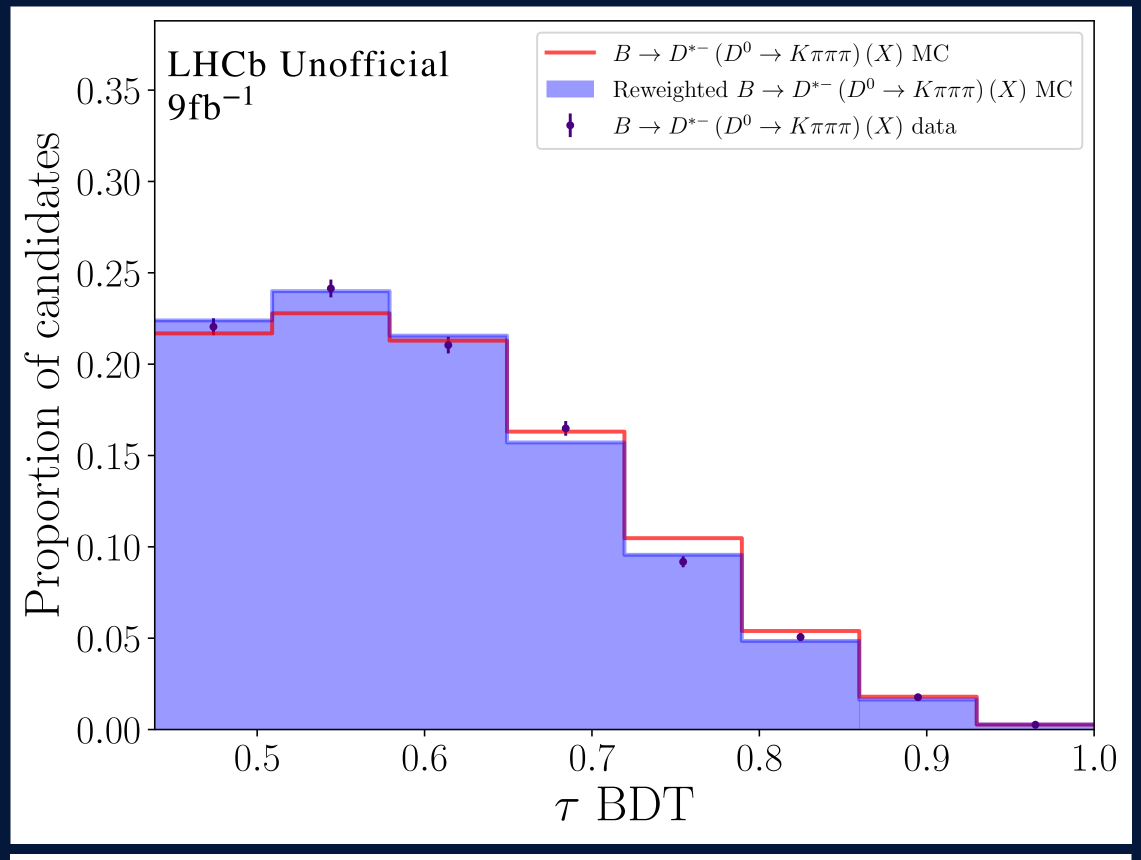


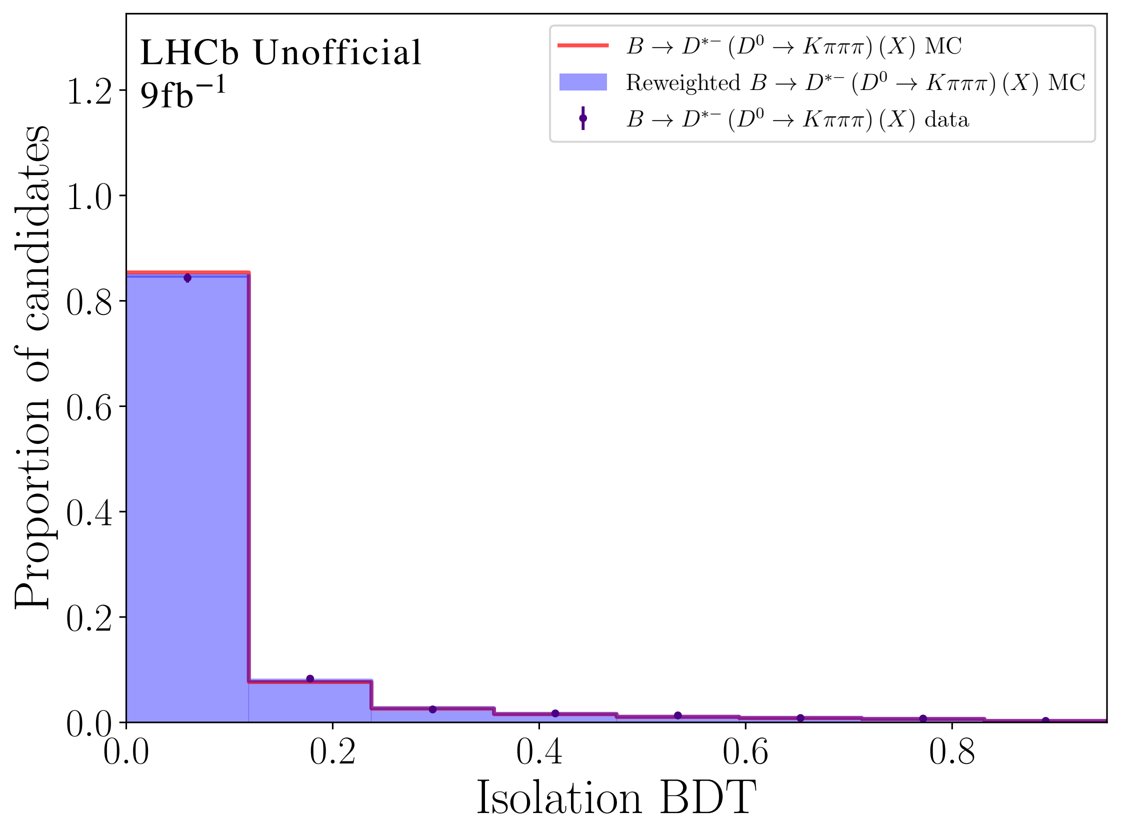


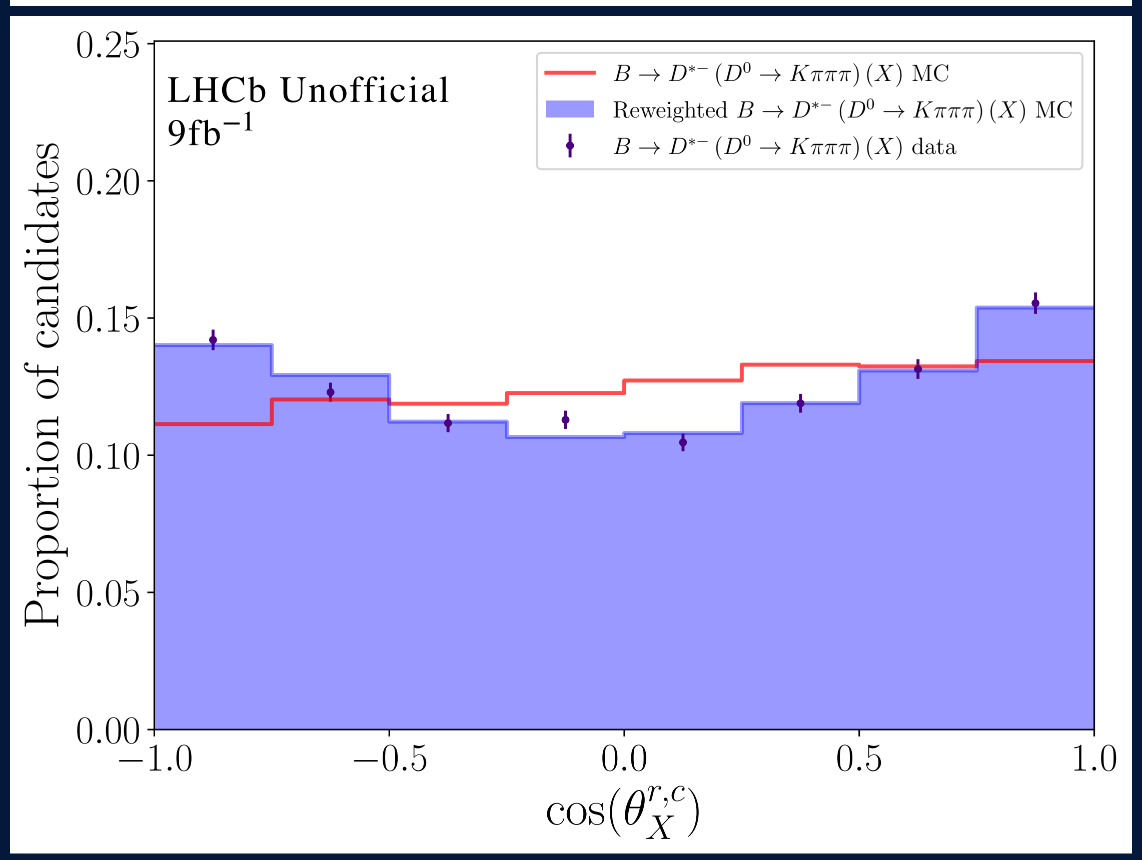


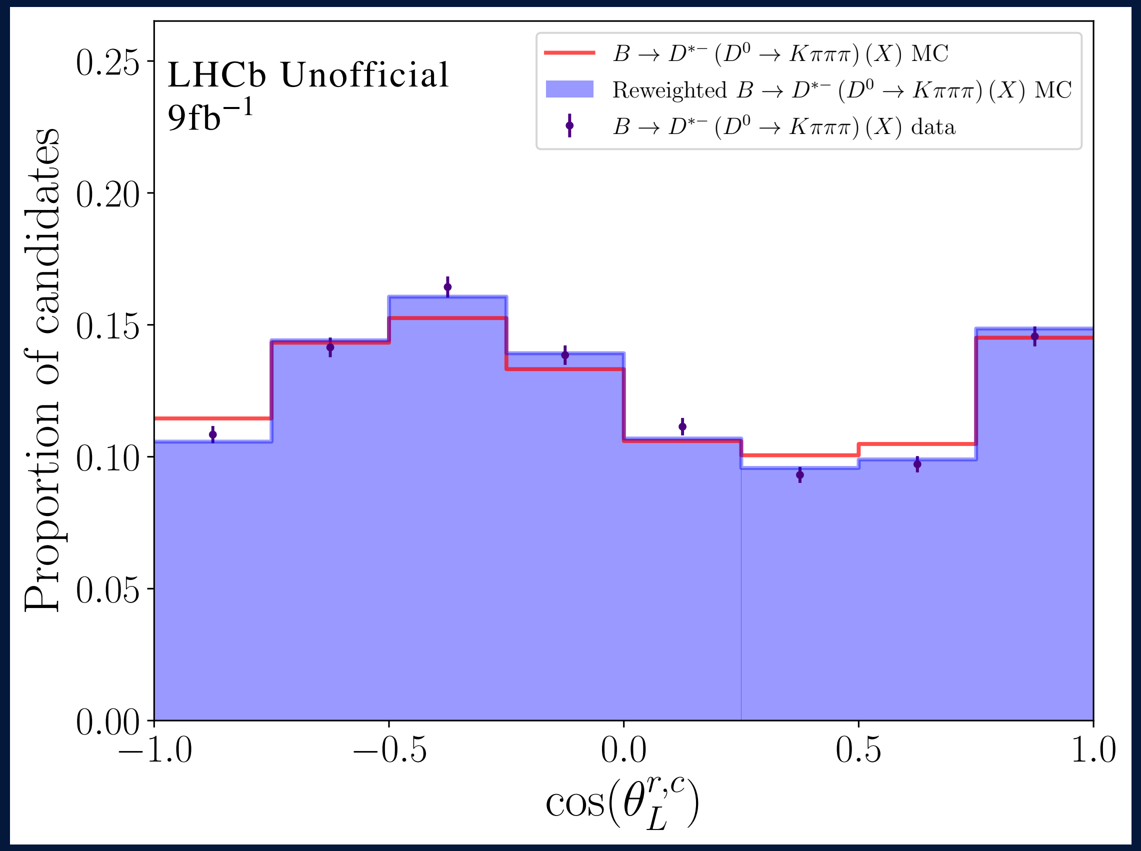
$B \to D^* D^0 (X)$ VARIABLES AFTER REWEIGHTING

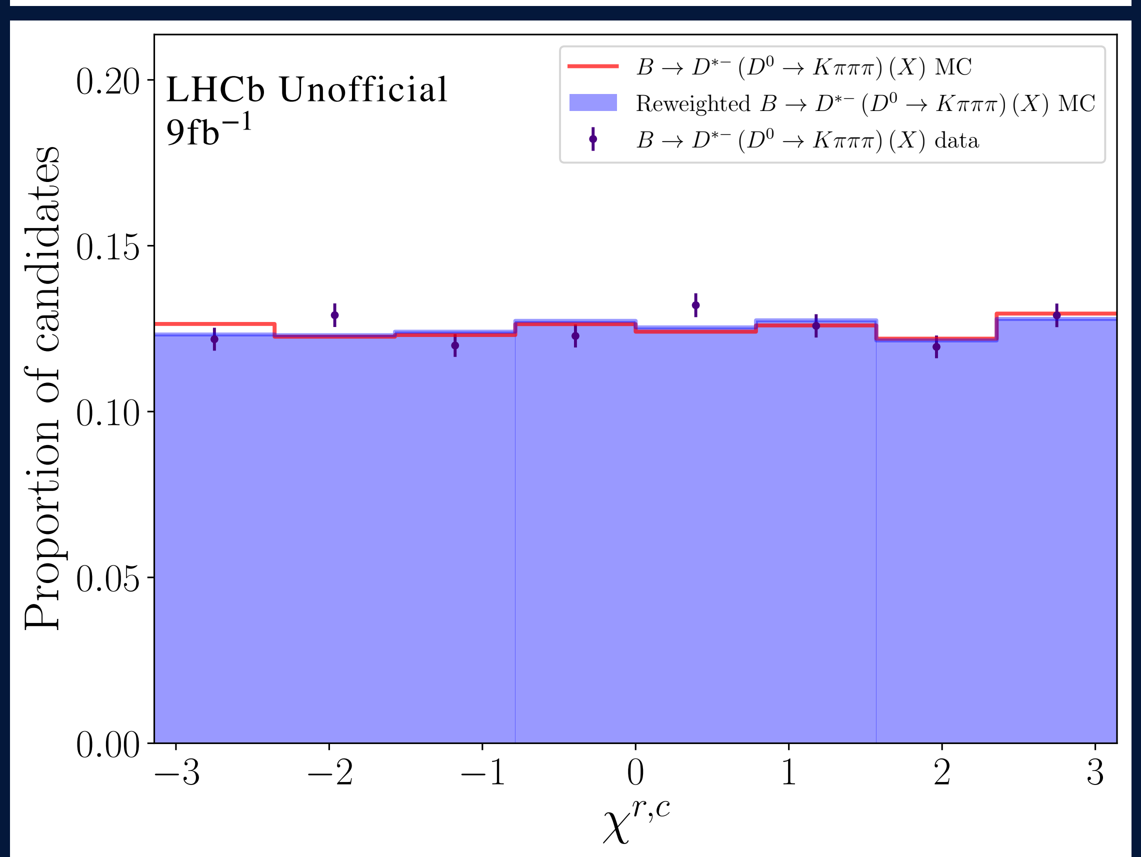


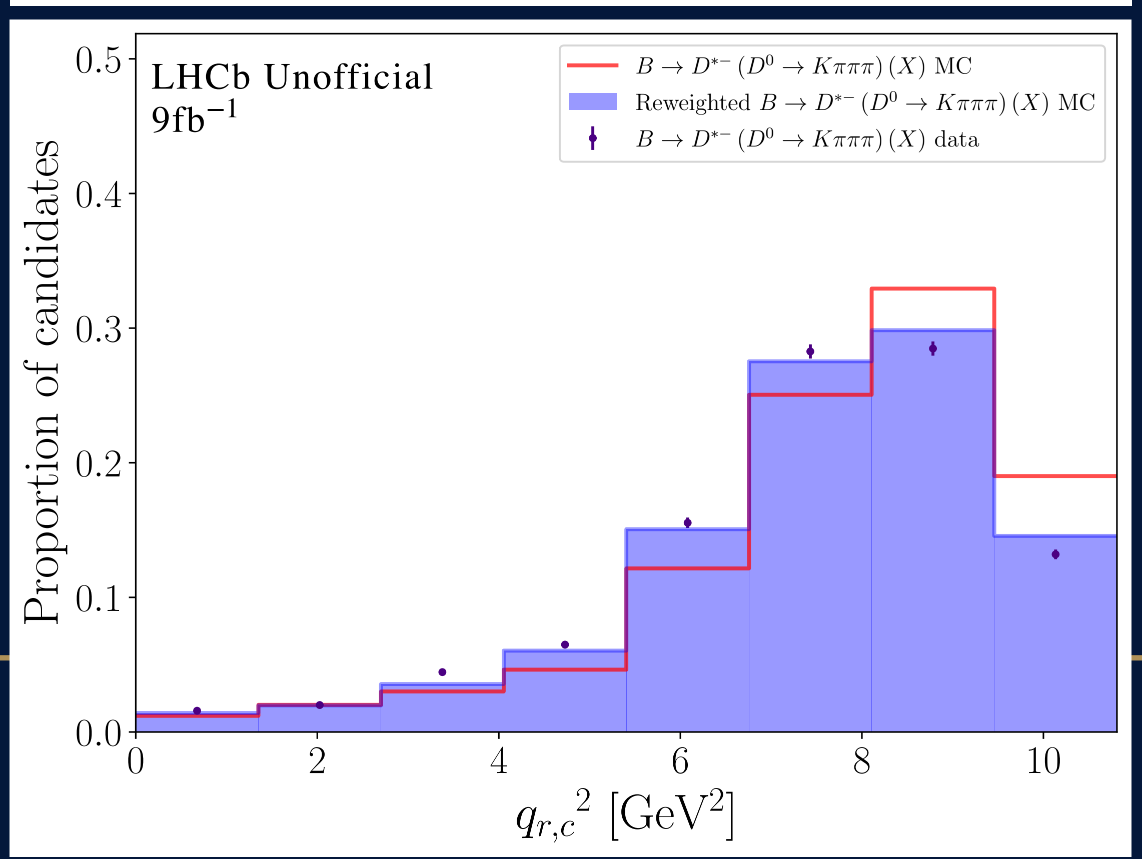


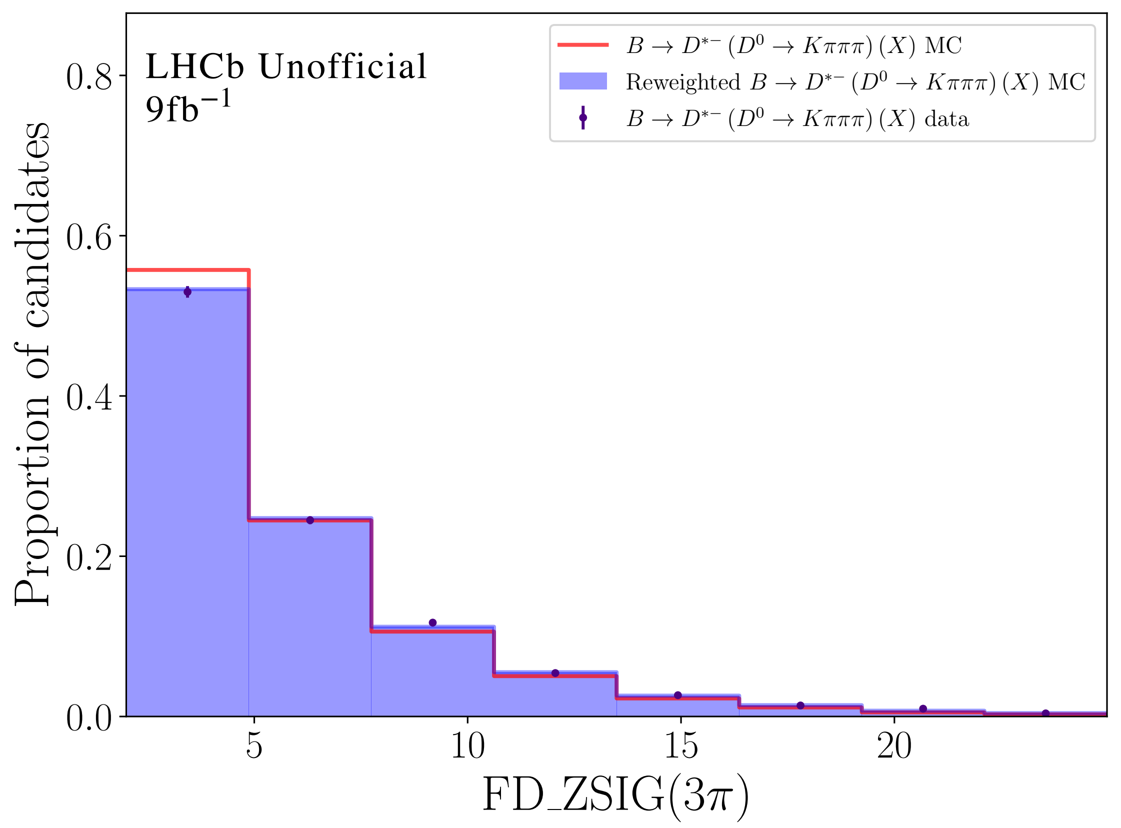










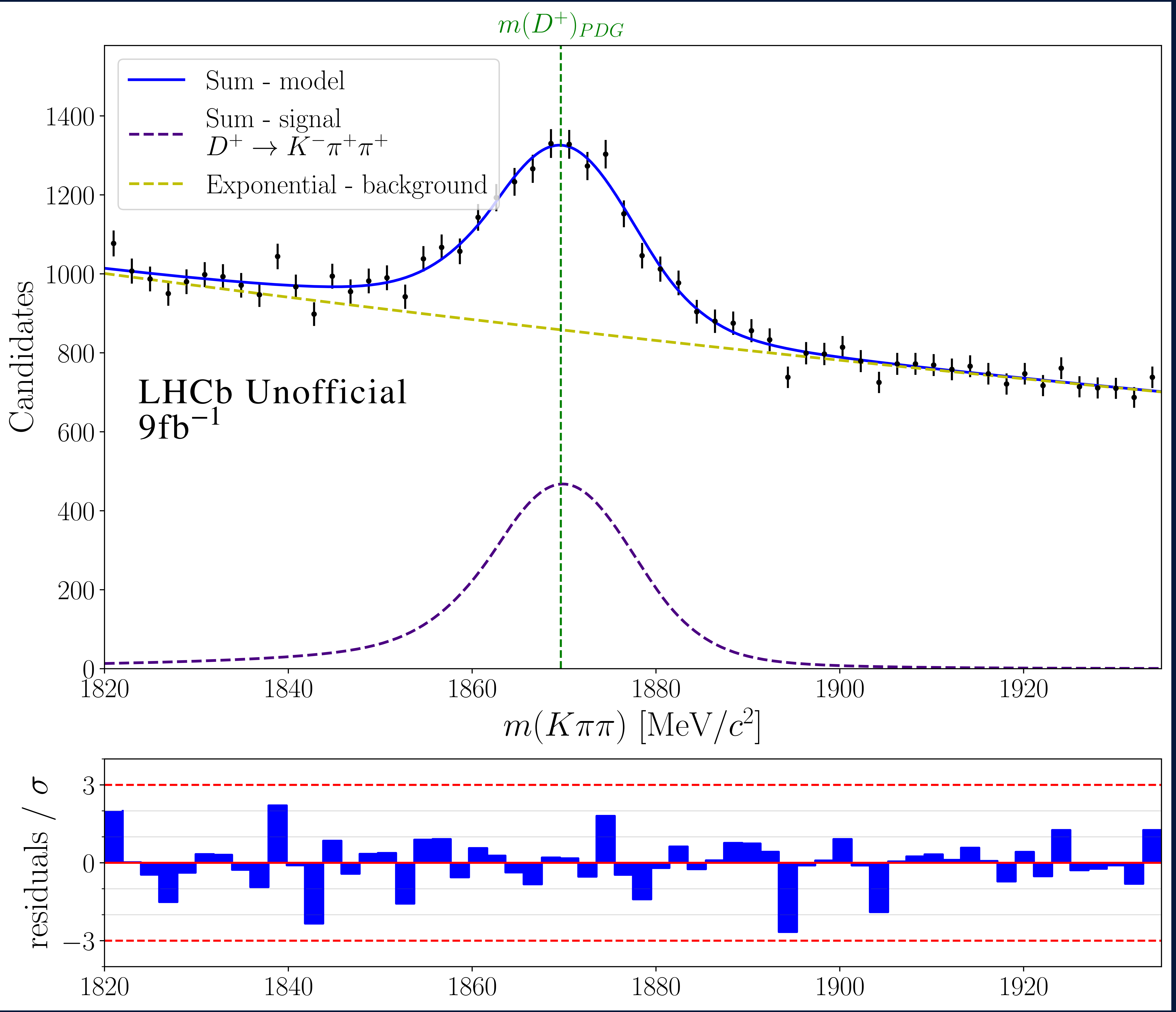


CONTROL STUDIES

- Several control studies
  - $B \to D^{*-}D^0(X)$: Weights for data/MC agreement
    - Isolate $B \to D^{*-}D^0(X)$ via $D^0 \to K^-\pi^+\pi^-\pi^+$ using $_s$Weights
  - $B \to D^{*-}D^+(X)$: Weights for data/MC agreement
    - Isolate $B \to D^{*-}D^+(X)$ via $D^+ \to K^-\pi^+\pi^+$ using $_s$Weights
  - $B \to D^{*-}D_s(X)$: Weights for data/MC agreement and for relative decay fractions
    - Isolate $D_s \to \pi^+\pi^-\pi^+$ using $_s$Weights
    - Fit $m(D^{*-}D_s)$ to measure decay fractions
  - $D_s \to \pi^+\pi^-\pi^+(X)$: 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

$B \to D^{*}D^{+}(X)$ CONTROL STUDY

- Isolate $B \to D^{*}D^{+}(X)$ via $D^{+} \to K^{-}\pi^{+}\pi^{+}$
  - $m(K^{-}\pi^{+}\pi^{+}) \in m(D^{+})_{\text{PDG}} \pm 200.0\ \text{MeV}/c^{2}$
- 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 $B \to D^{*}D^{+}(X)$
- Perform data/MC reweighting to correct $B \to D^{*}D^{+}(X)$ MC



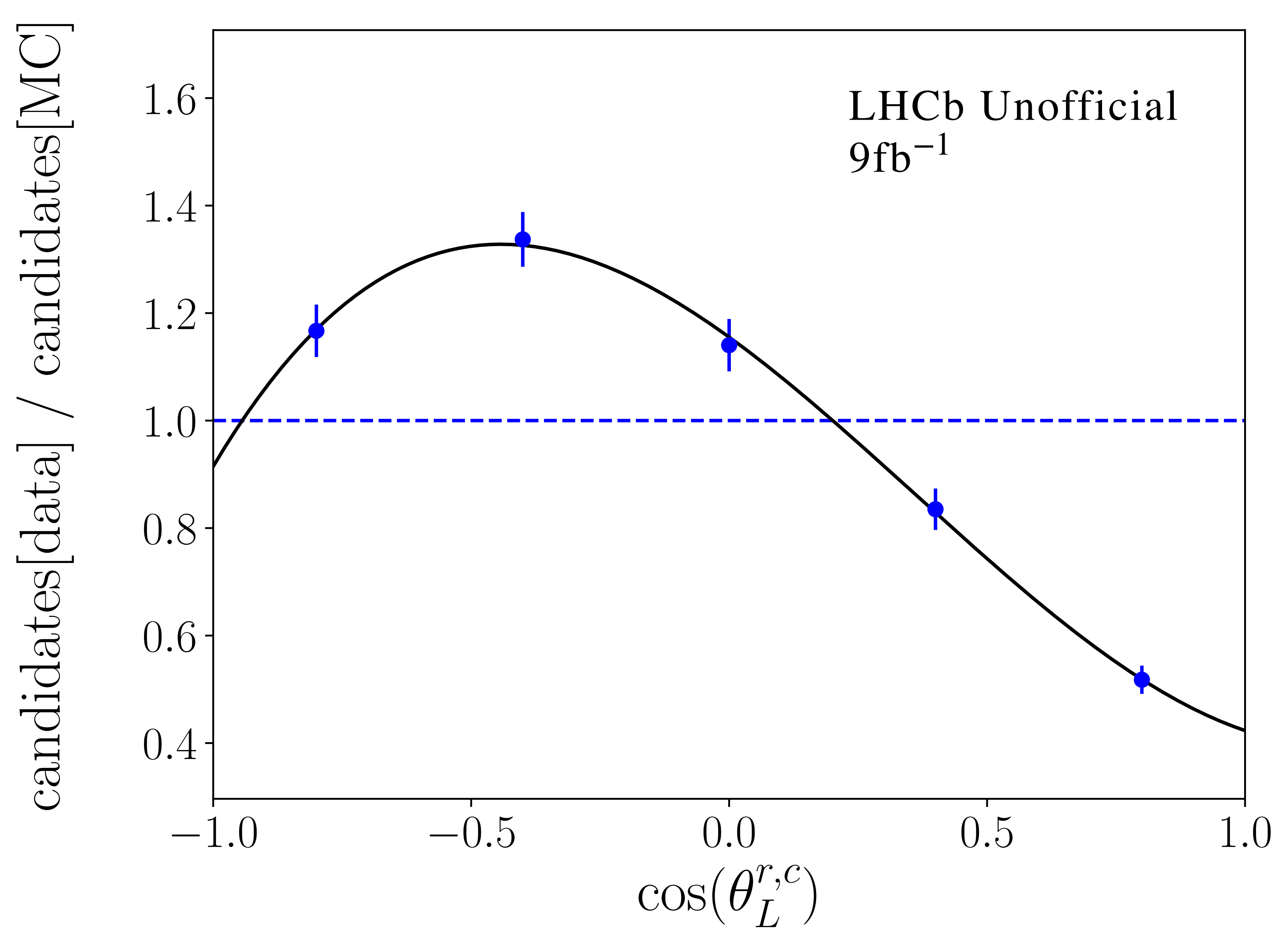
$B \to D^*D^+(X)$ REWEIGHTING

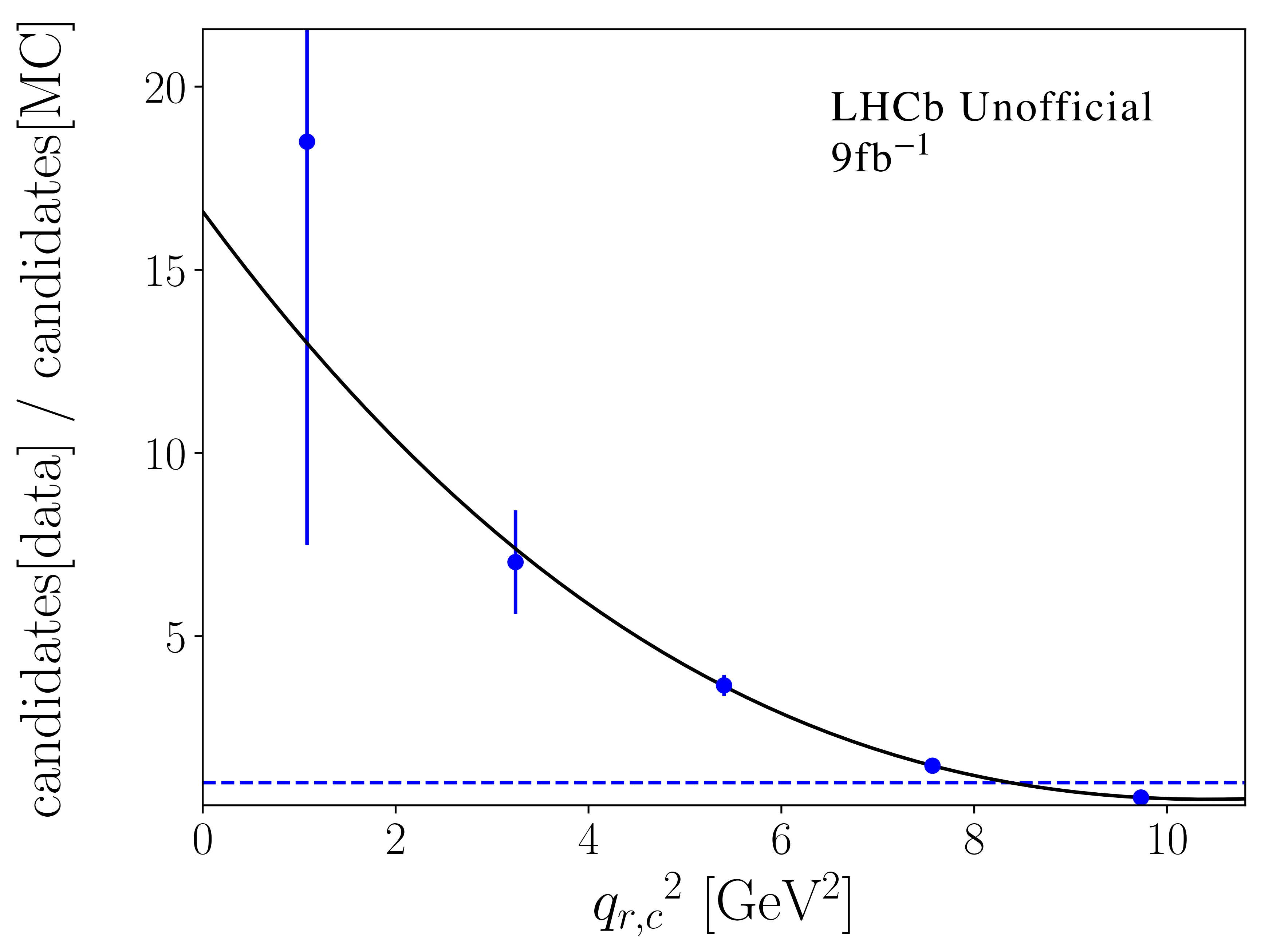
- Sequential reweighting using several variables

- 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

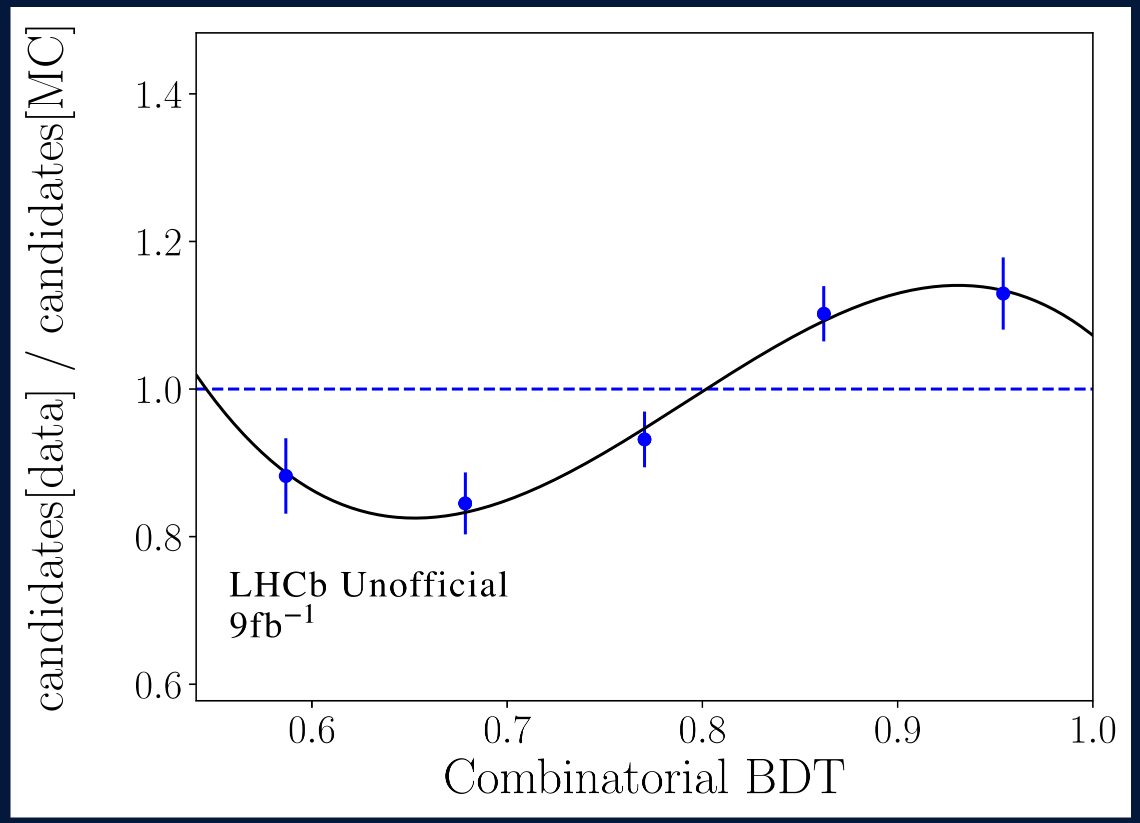
- Use spline to calculate weight for each MC event
  - Value of the spline at the variable value is used
  - Apply weight and move to next variable
    - Fit data/MC ratio with spline and update the weight

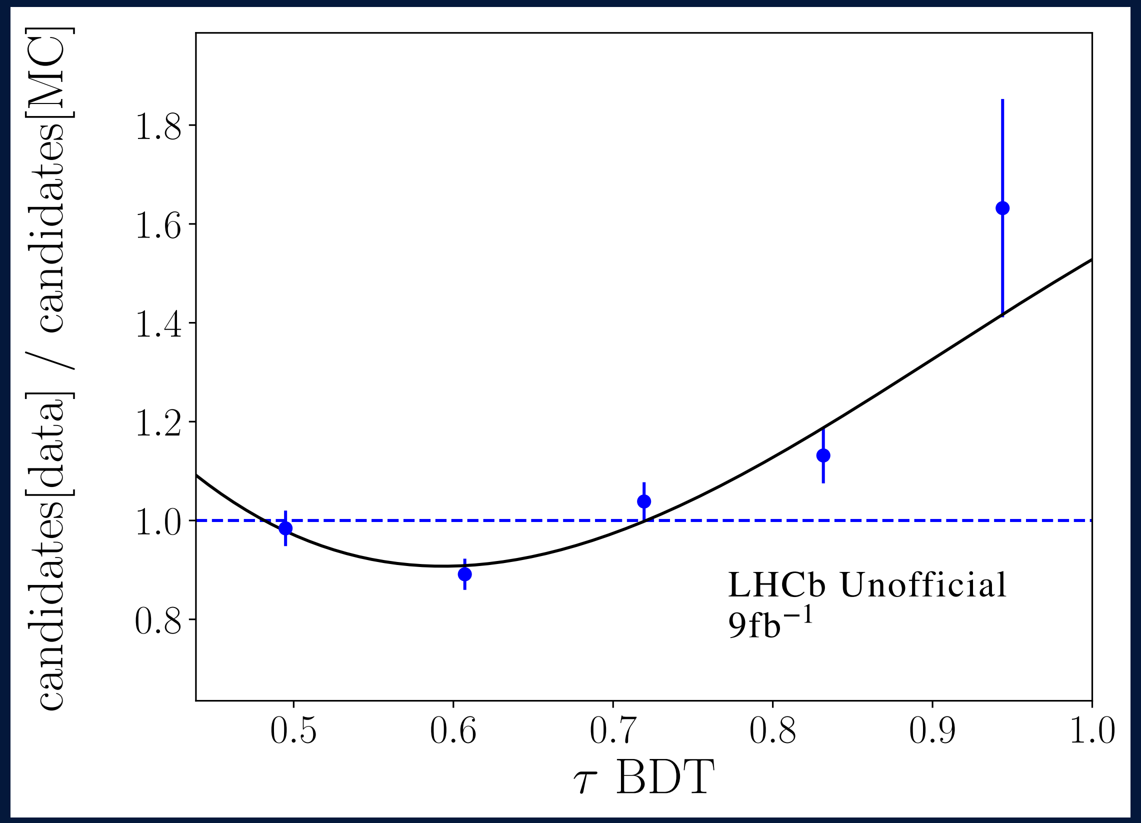
- Obtain single weight that corrects MC
  - Derived from $B \to D^*(D^+ \to K^-\pi^+\pi^+)(X)$, but applied to all $B \to D^*D^+(X)$

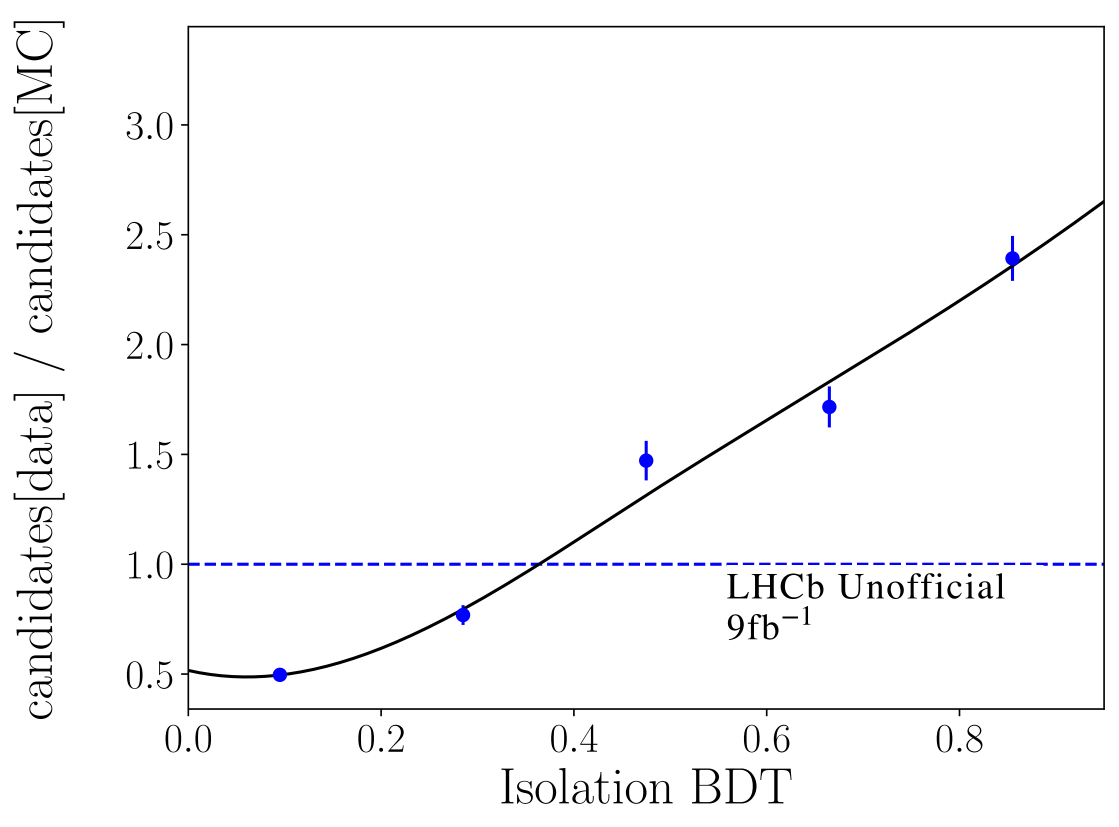


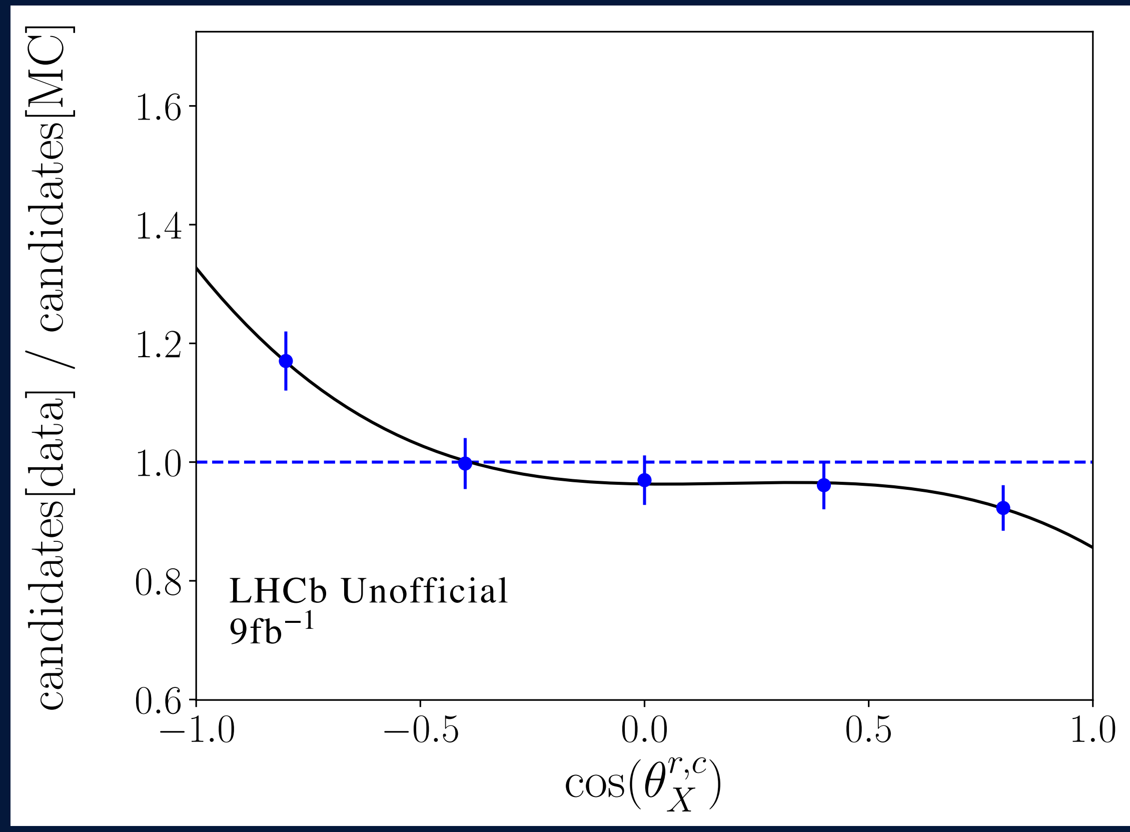


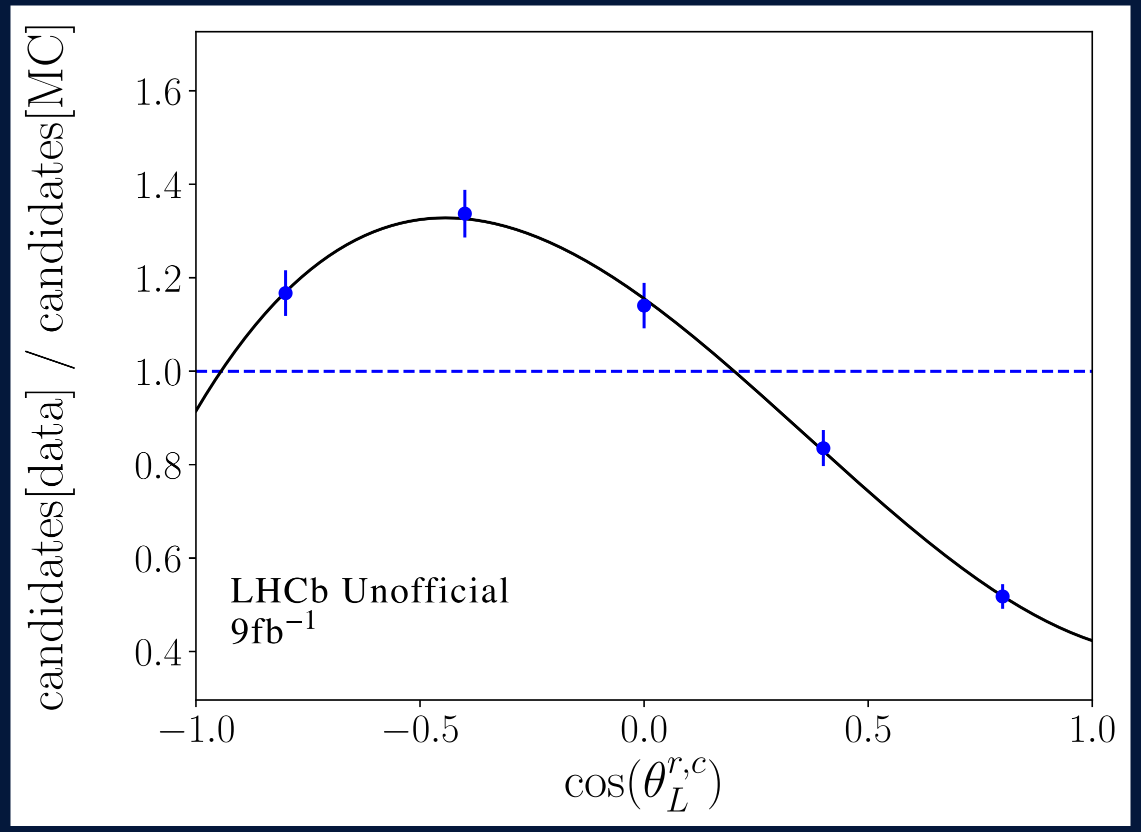
$B \to D^{*}D^{+}(X)$ DATA/MC RATIO FITS

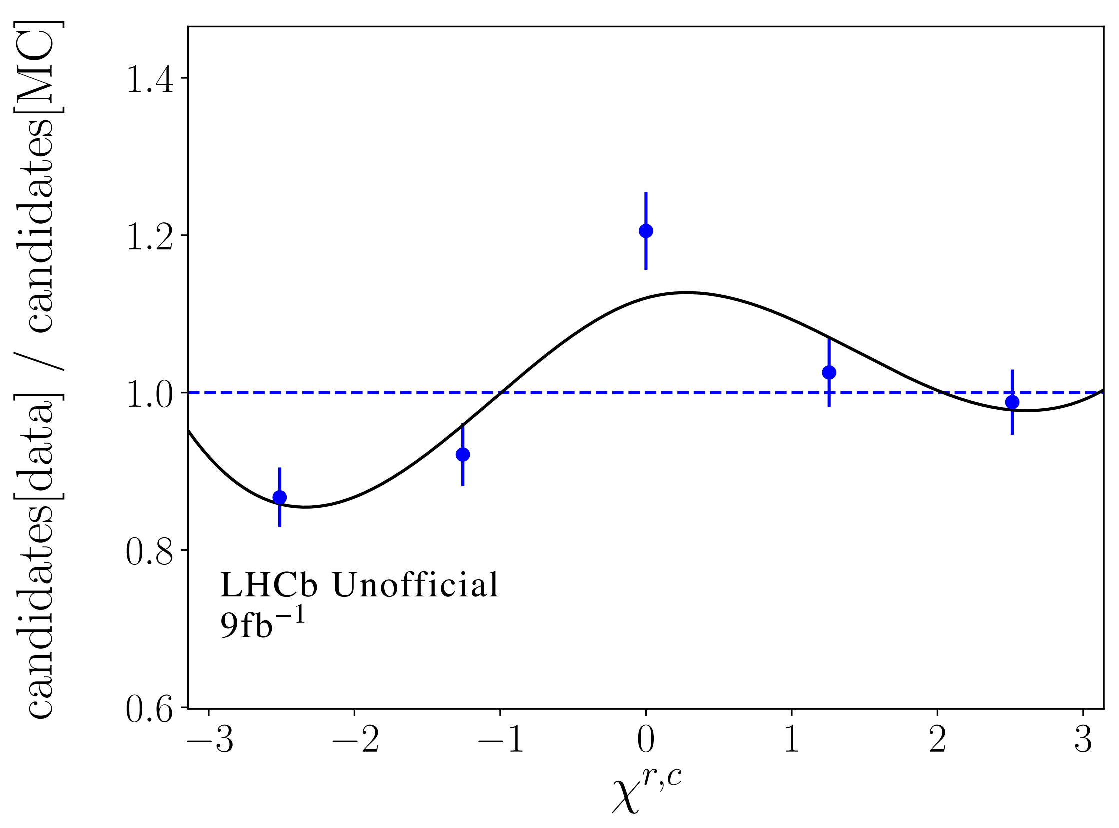


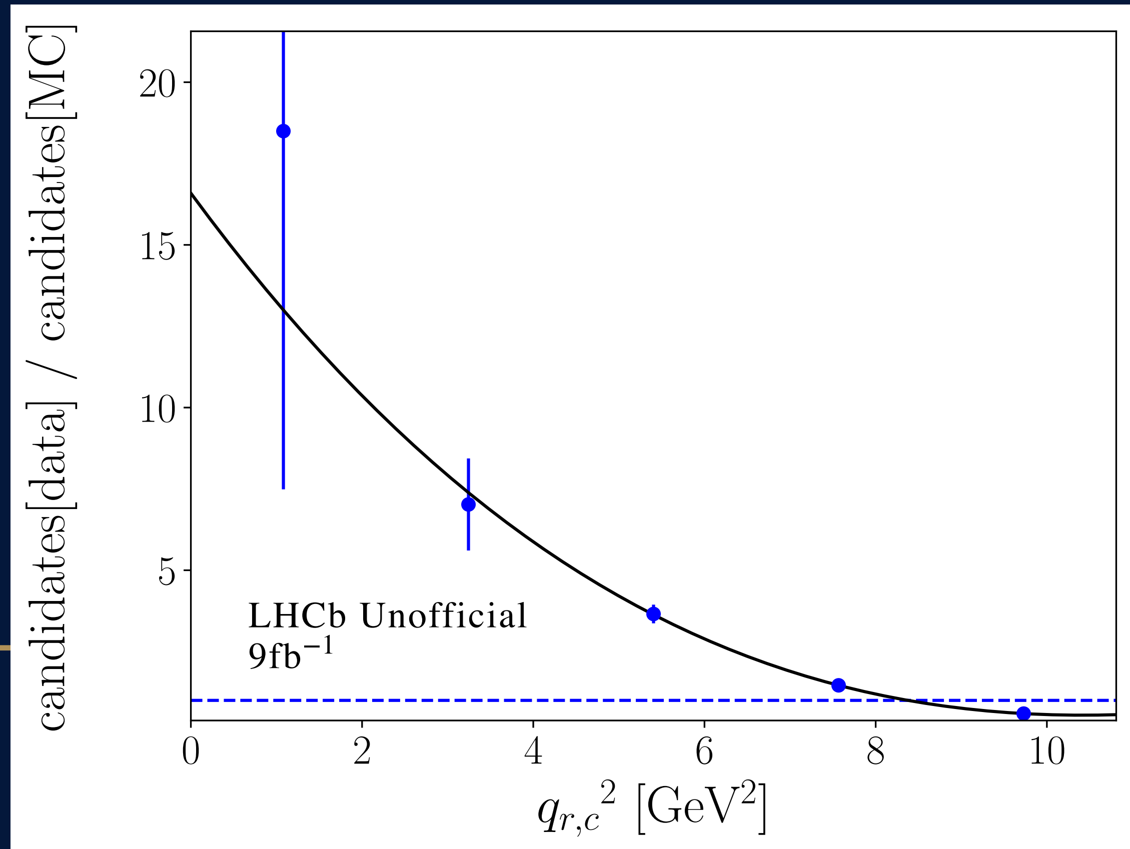


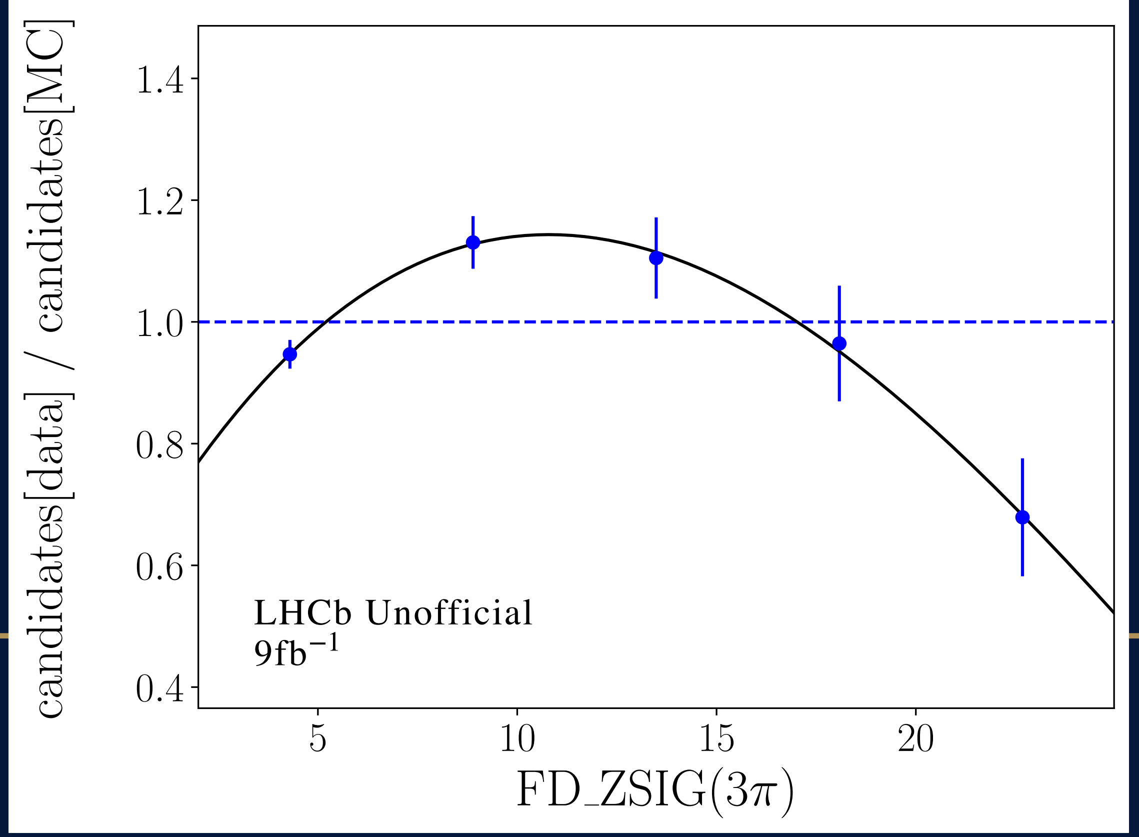




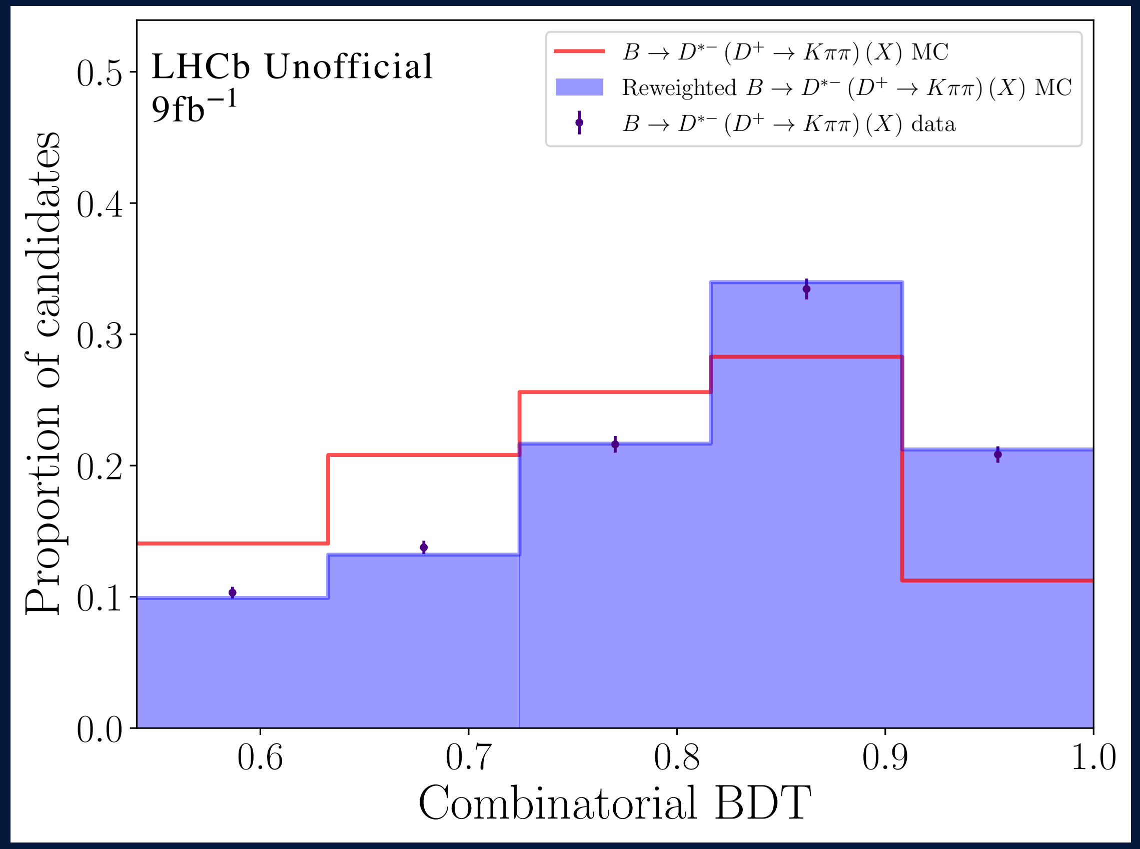


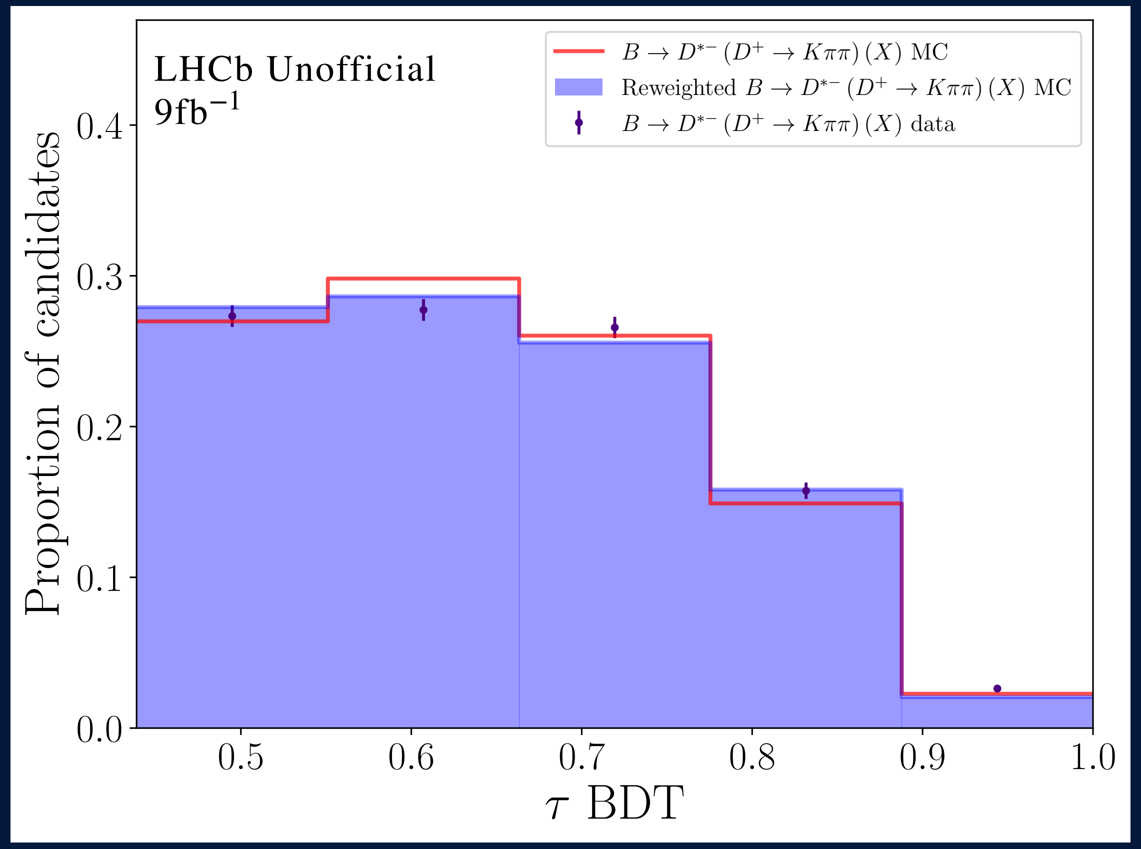


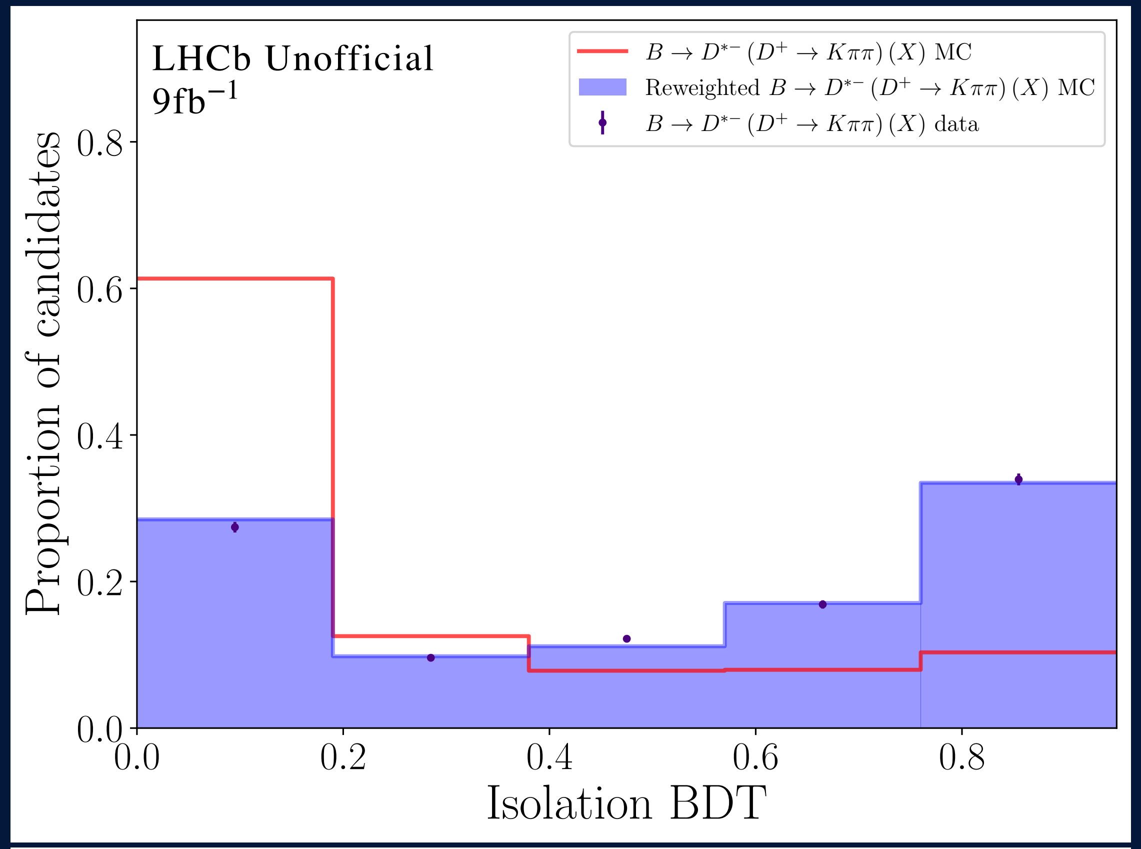


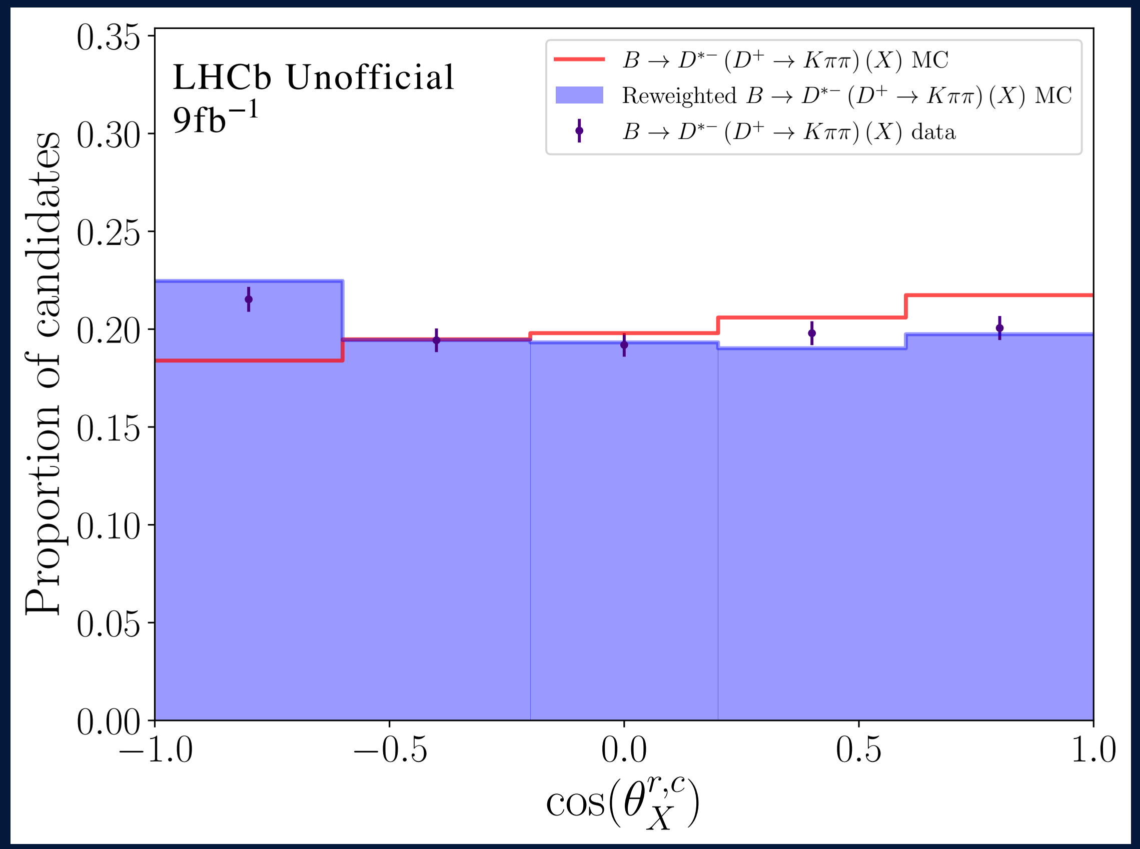


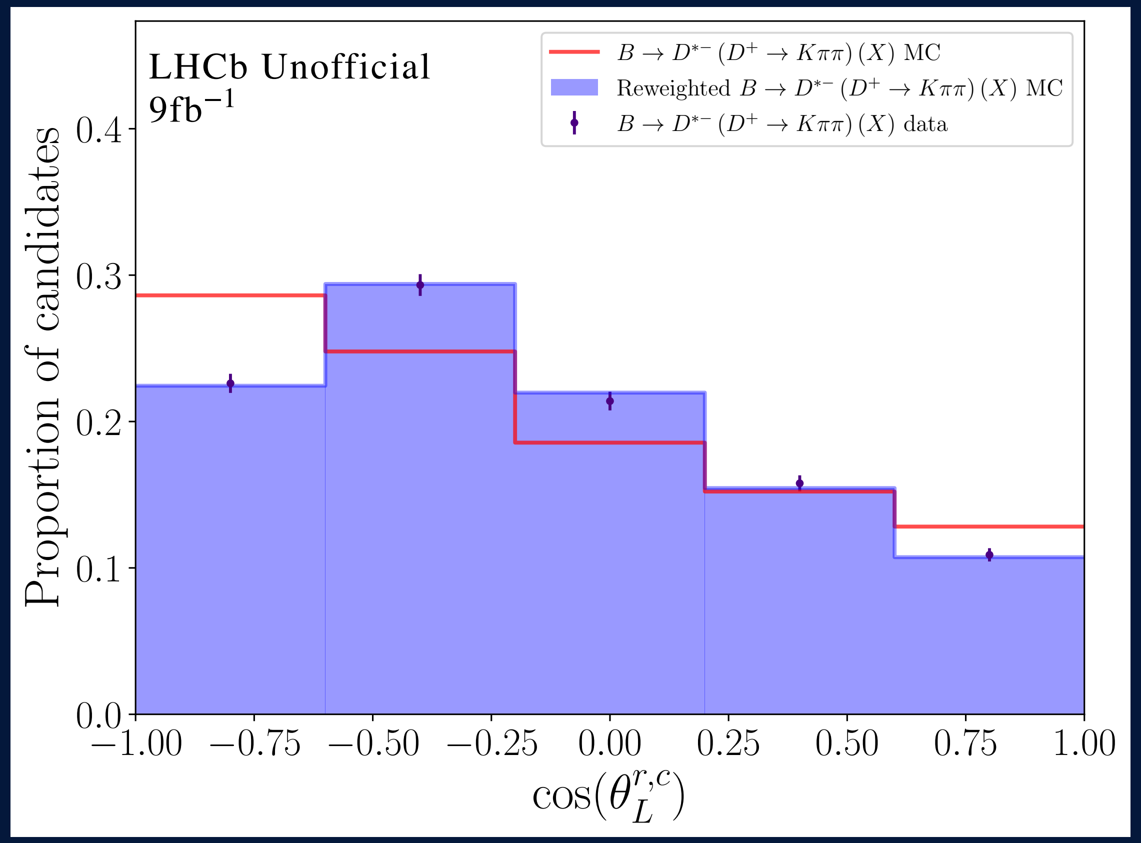
$B \to D^*D^+(X)$ VARIABLES AFTER REWEIGHTING

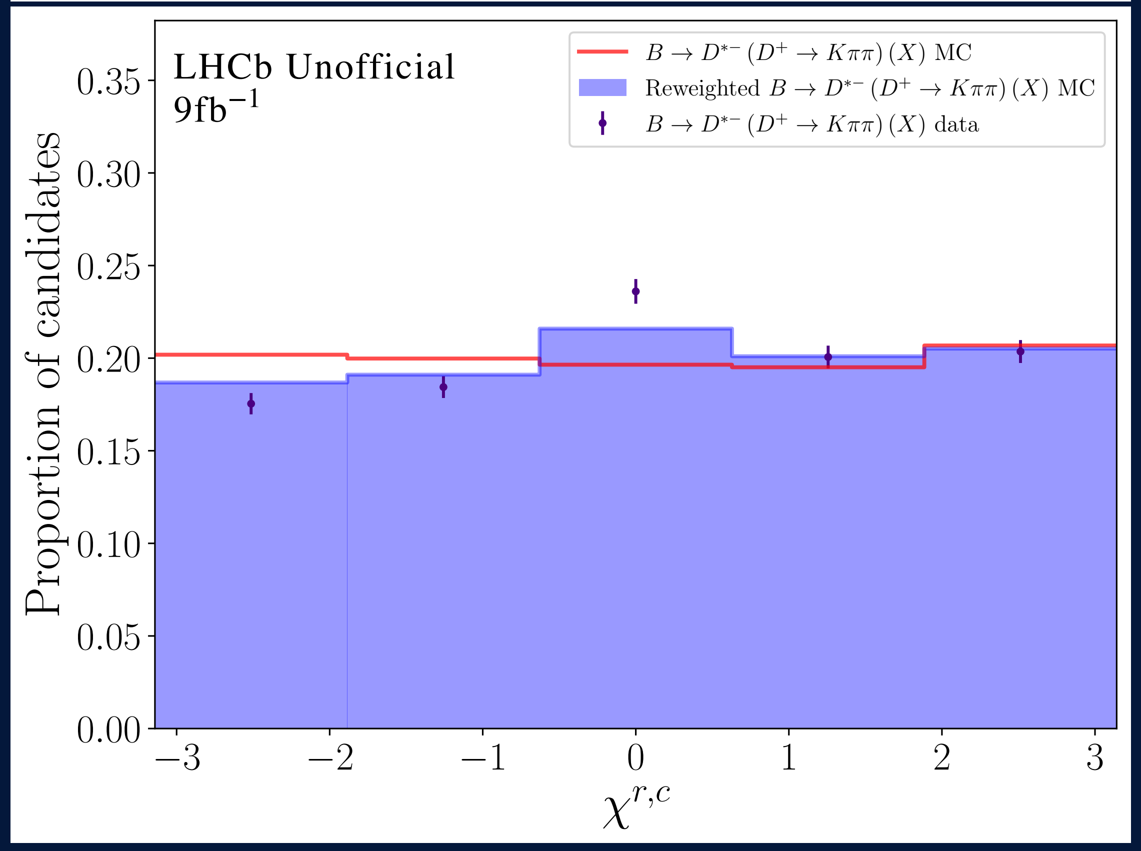


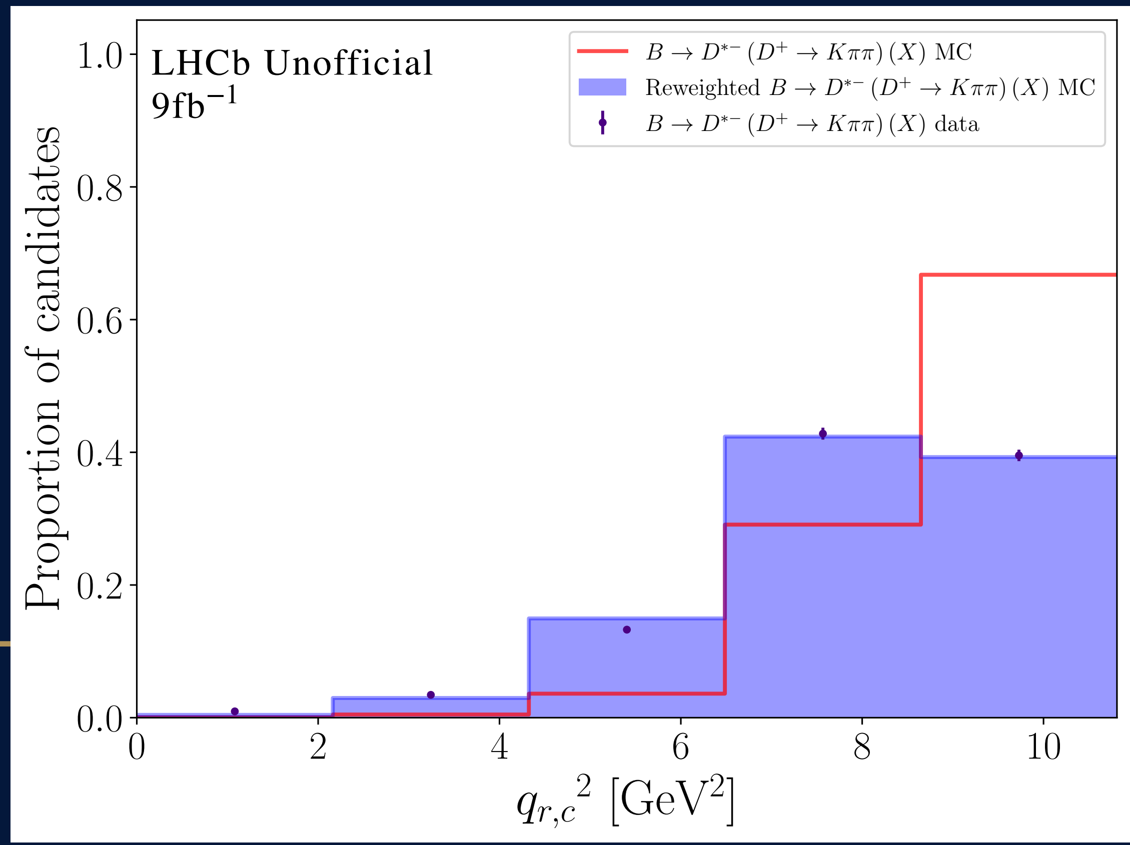


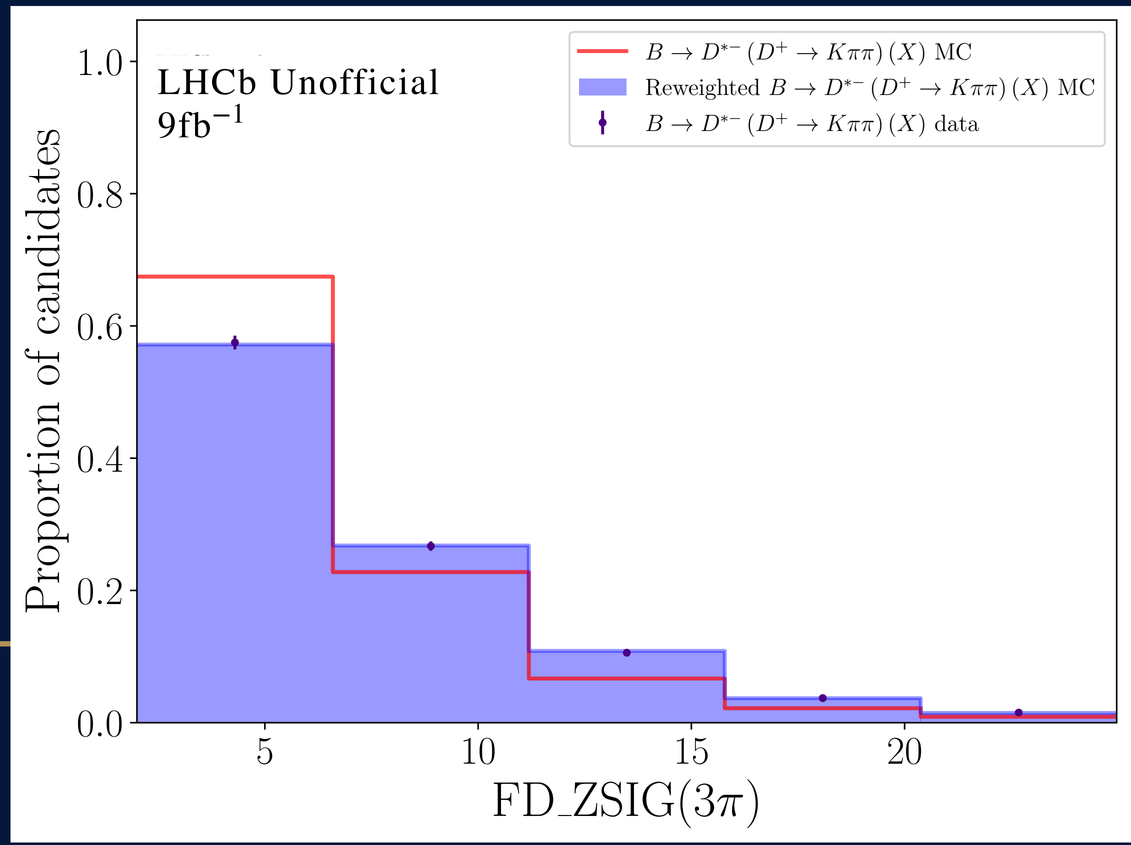










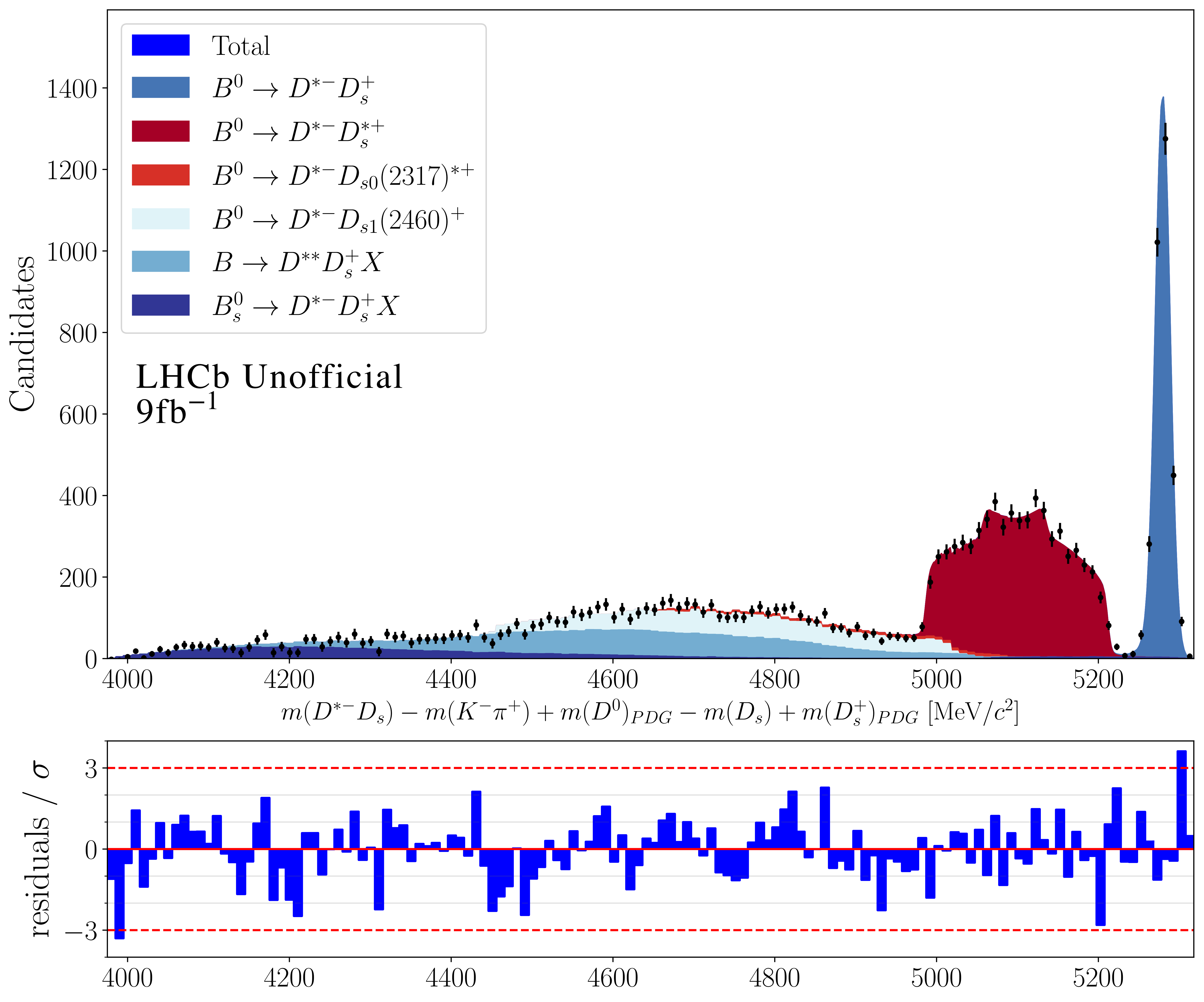


CONTROL STUDIES

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

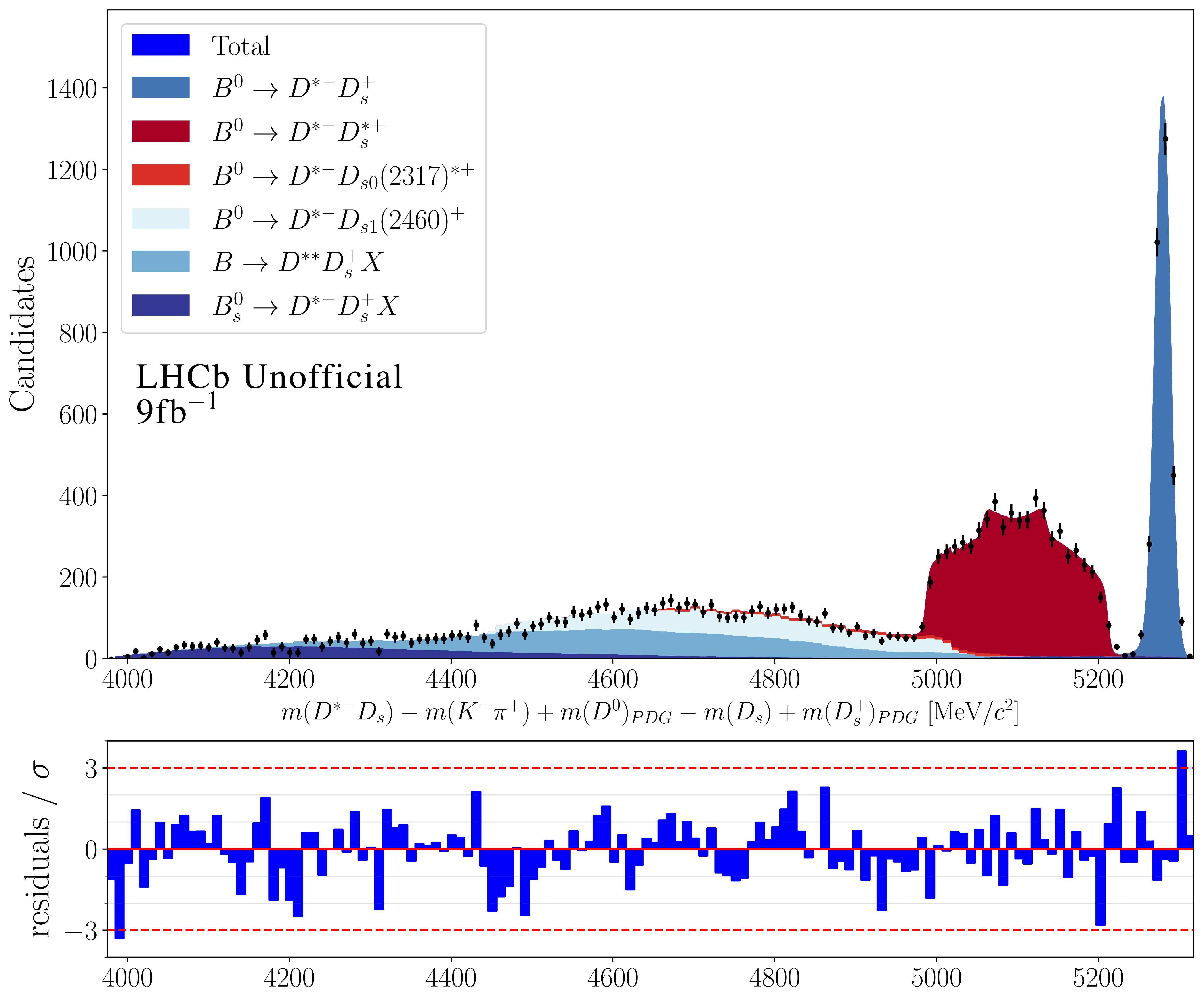
$B \to D^*D_s(X)$ CONTROL STUDY

- Isolate $D_s \to \pi^+\pi^-\pi^+$ 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 $B \to D^*D_s(X)$ decays
- Compare to fractions of $B \to D^*D_s(X)$ decays generated in MC
- Calculate weights to correct these fractions



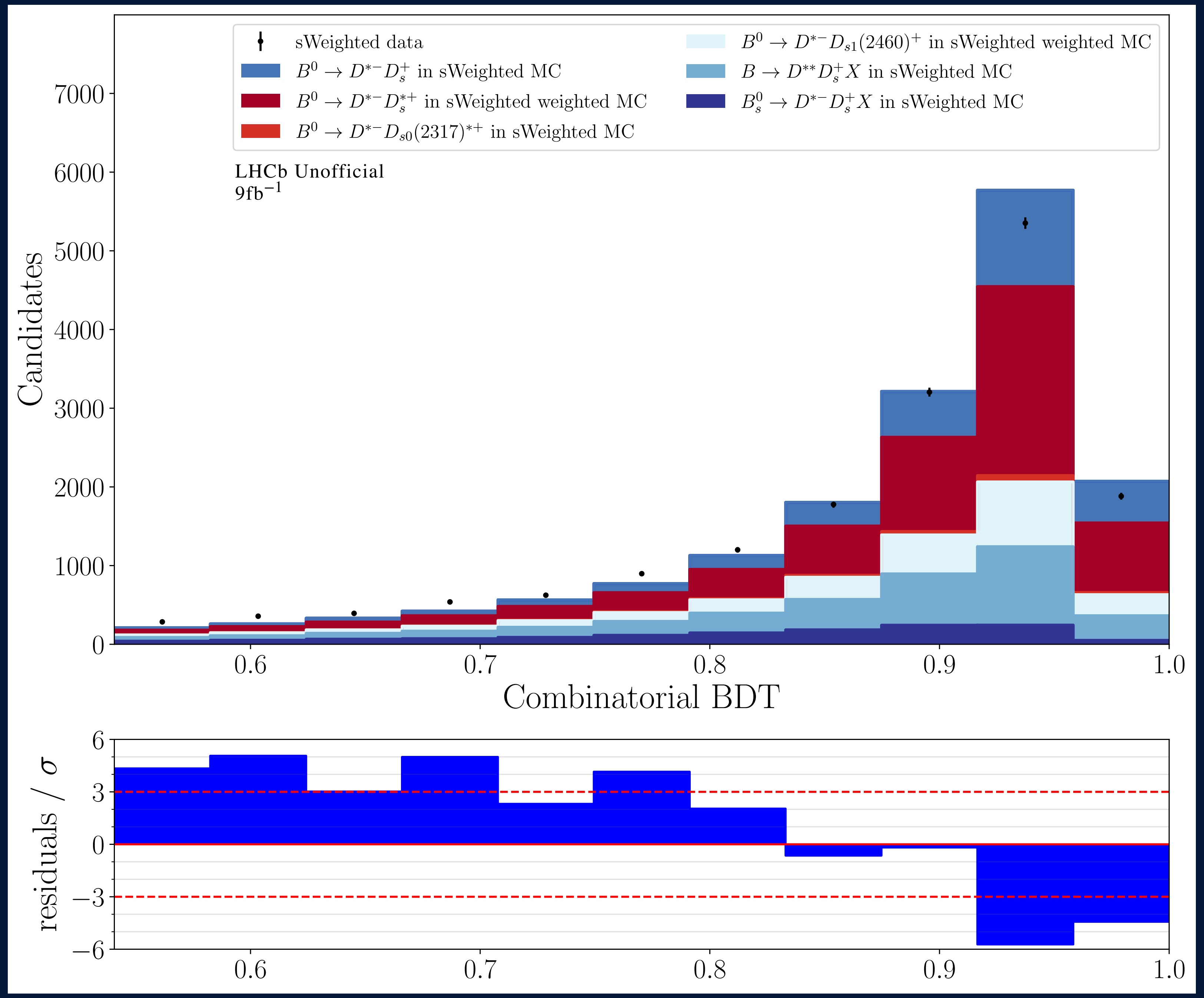
$B \to D^*D_s(X)$ TEMPLATES AND PDFS

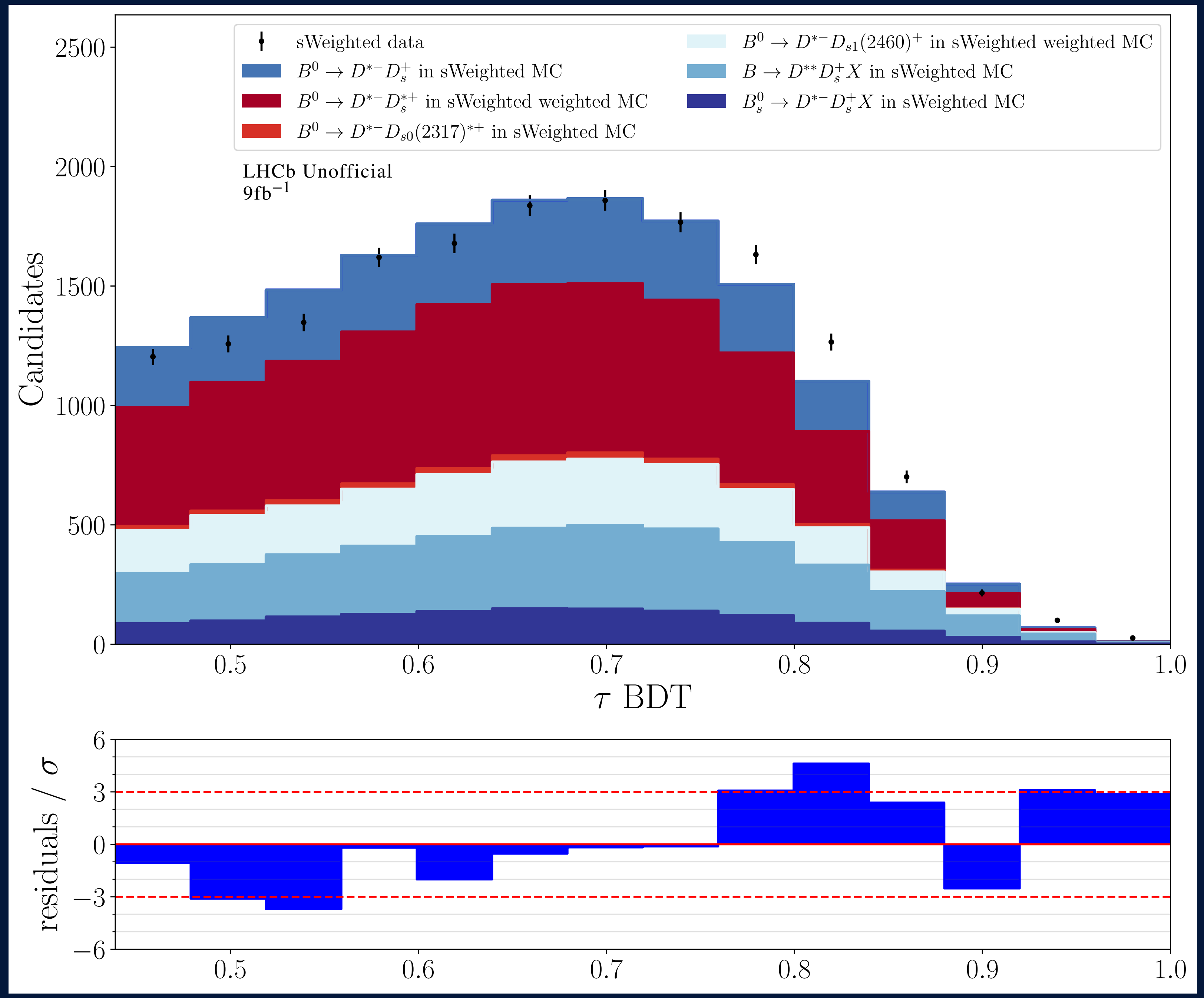
- Fit $B^0 \to D^*D_s^*$ RooHORNSdini and RooHILLdini PDFs from the published $B^0 \to D^*D_s^*$ analysis: https://arxiv.org/abs/2105.02596
  - Also use $f_L = 0.578$ from that analysis
- Fit $B^0 \to D^*D_s$ using a sum of Crystal Balls
- Lower mass components are templates taken from MC

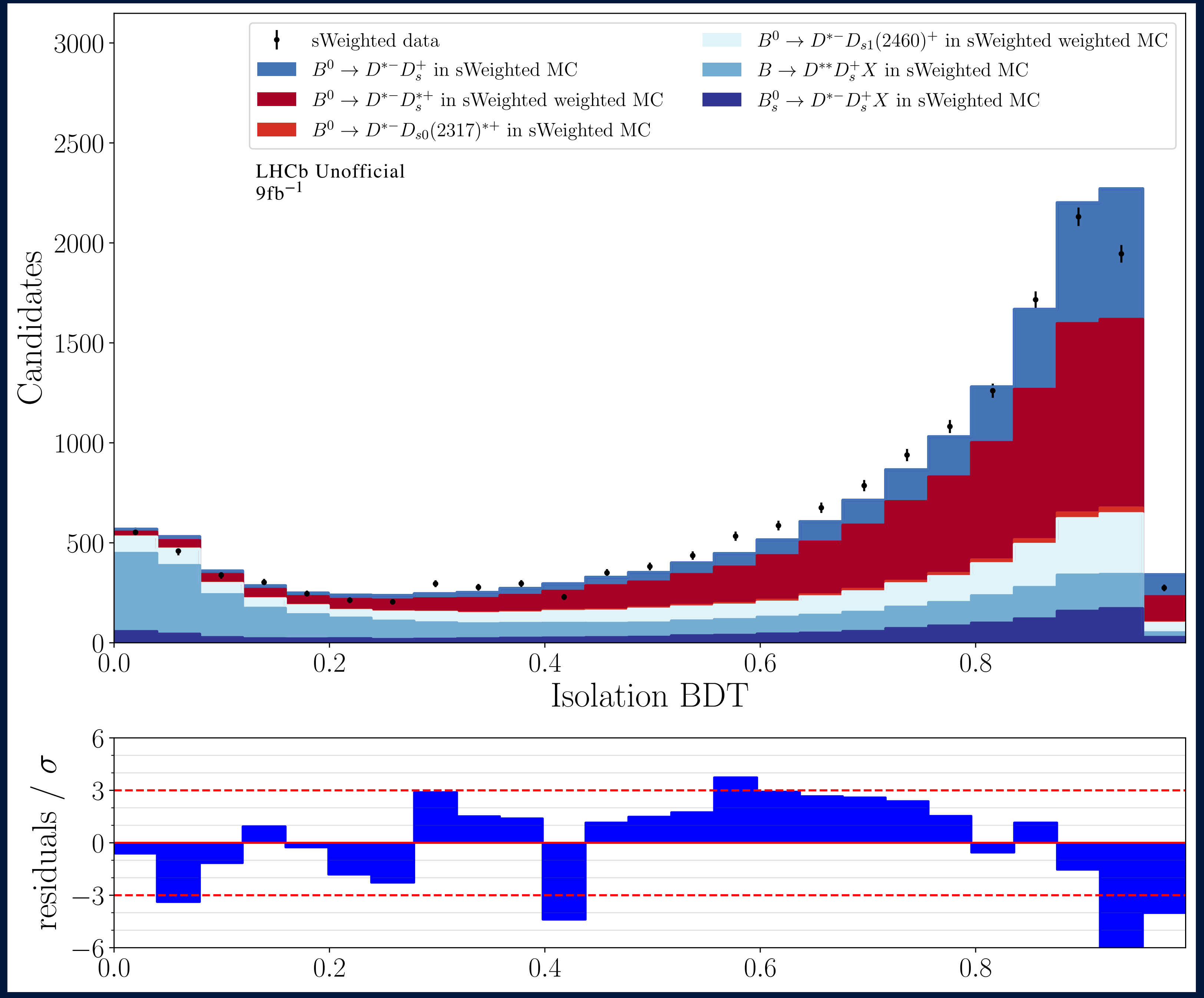


$B \to D^*D_s(X)$ CONTROL STUDY - BDTS

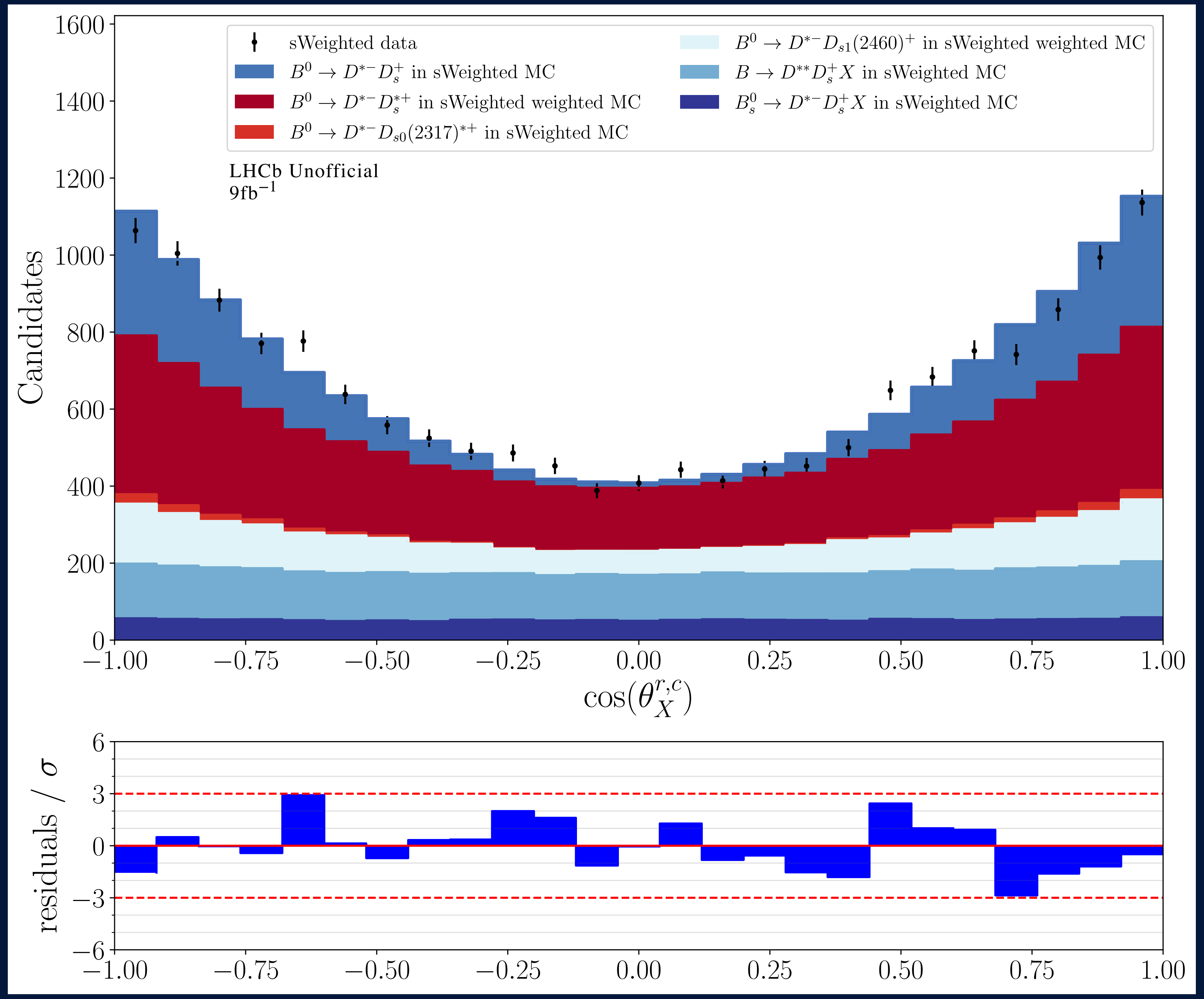
- $B \to D^*(D_s \to \pi^+\pi^-\pi^+)(X)$ data
- $B \to D^*(D_s \to \pi^+\pi^-\pi^+)(X)$ MC summed using the fractions measured in $m(D^*\pi^+\pi^-\pi^+)$ fit

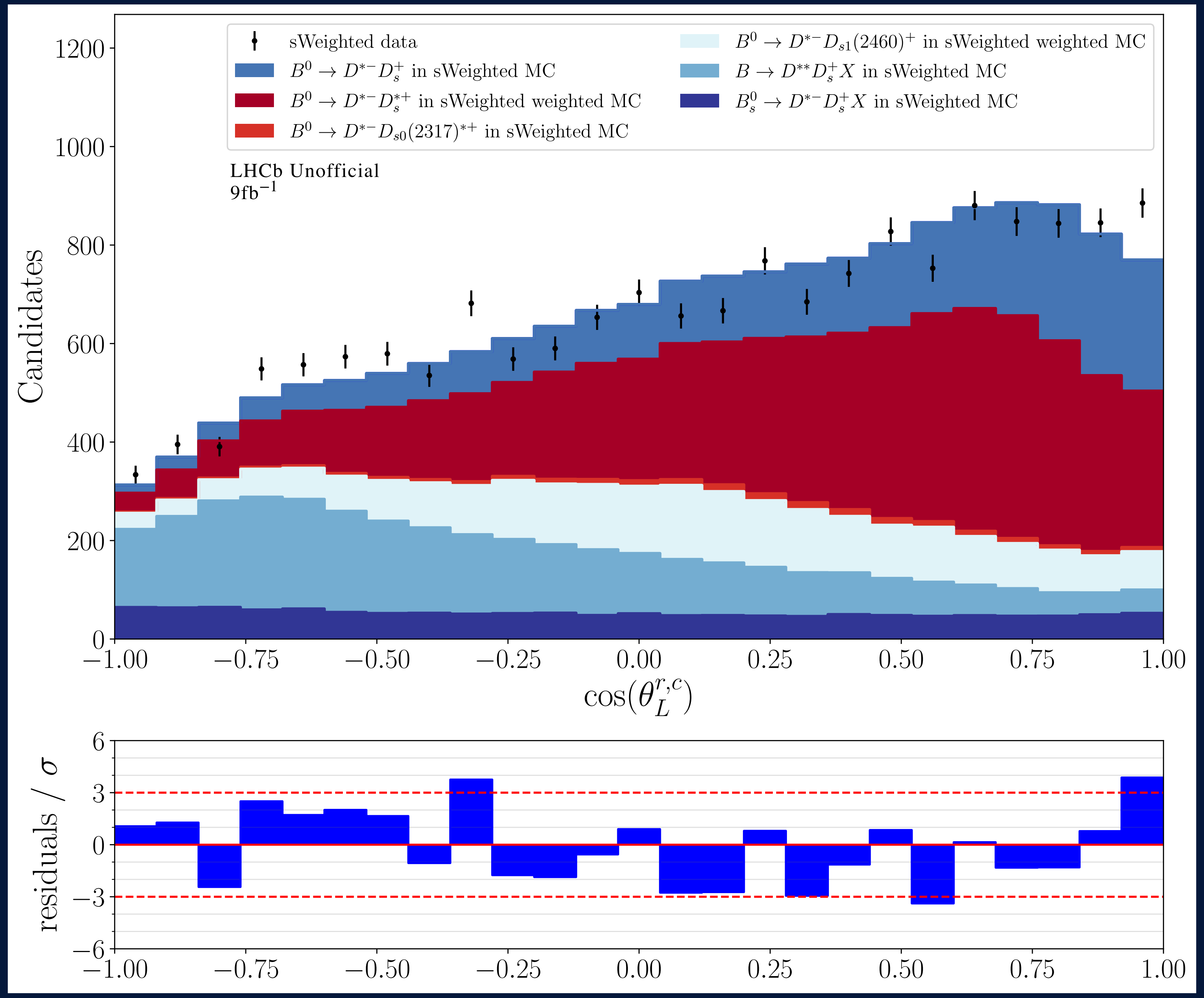


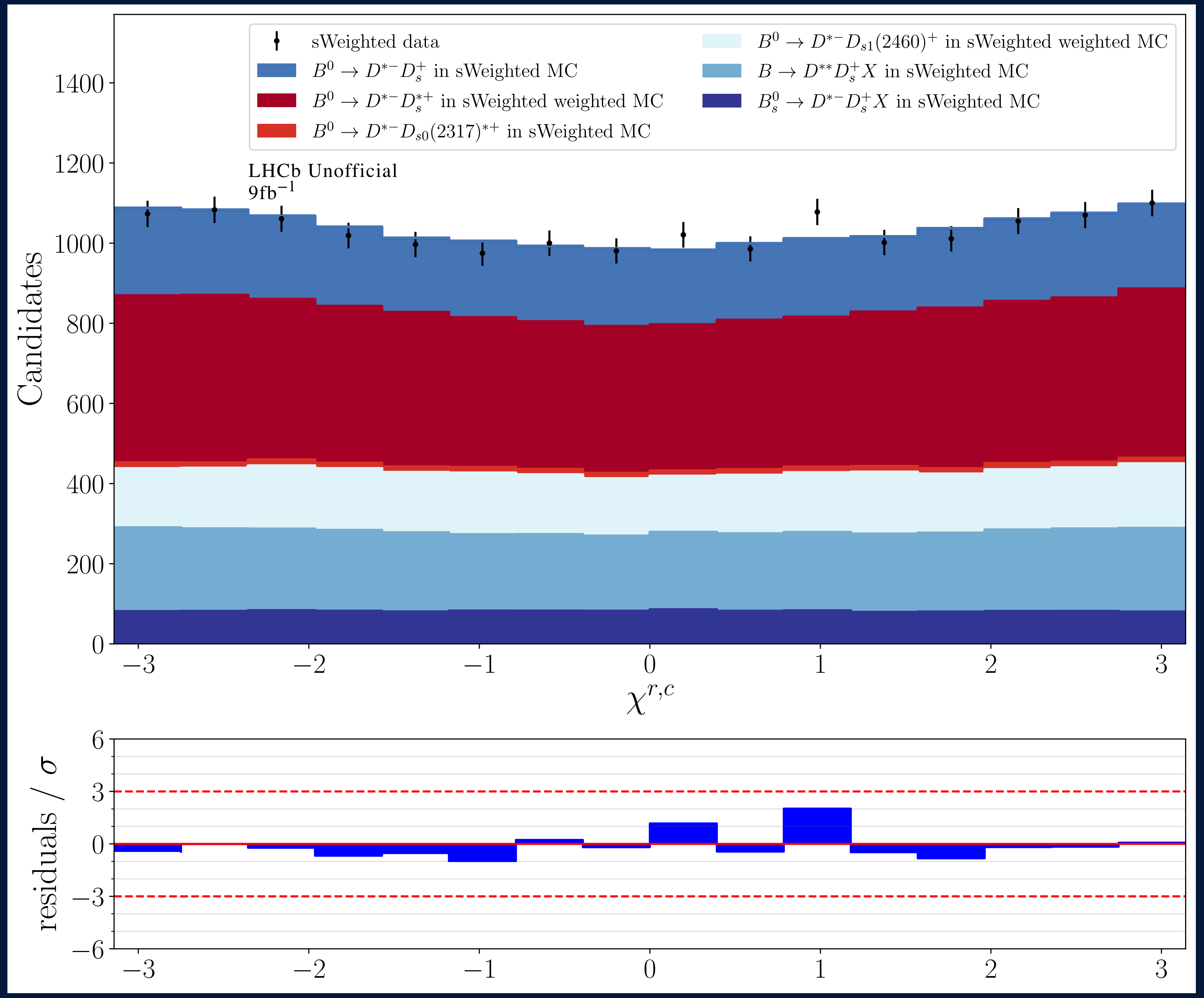




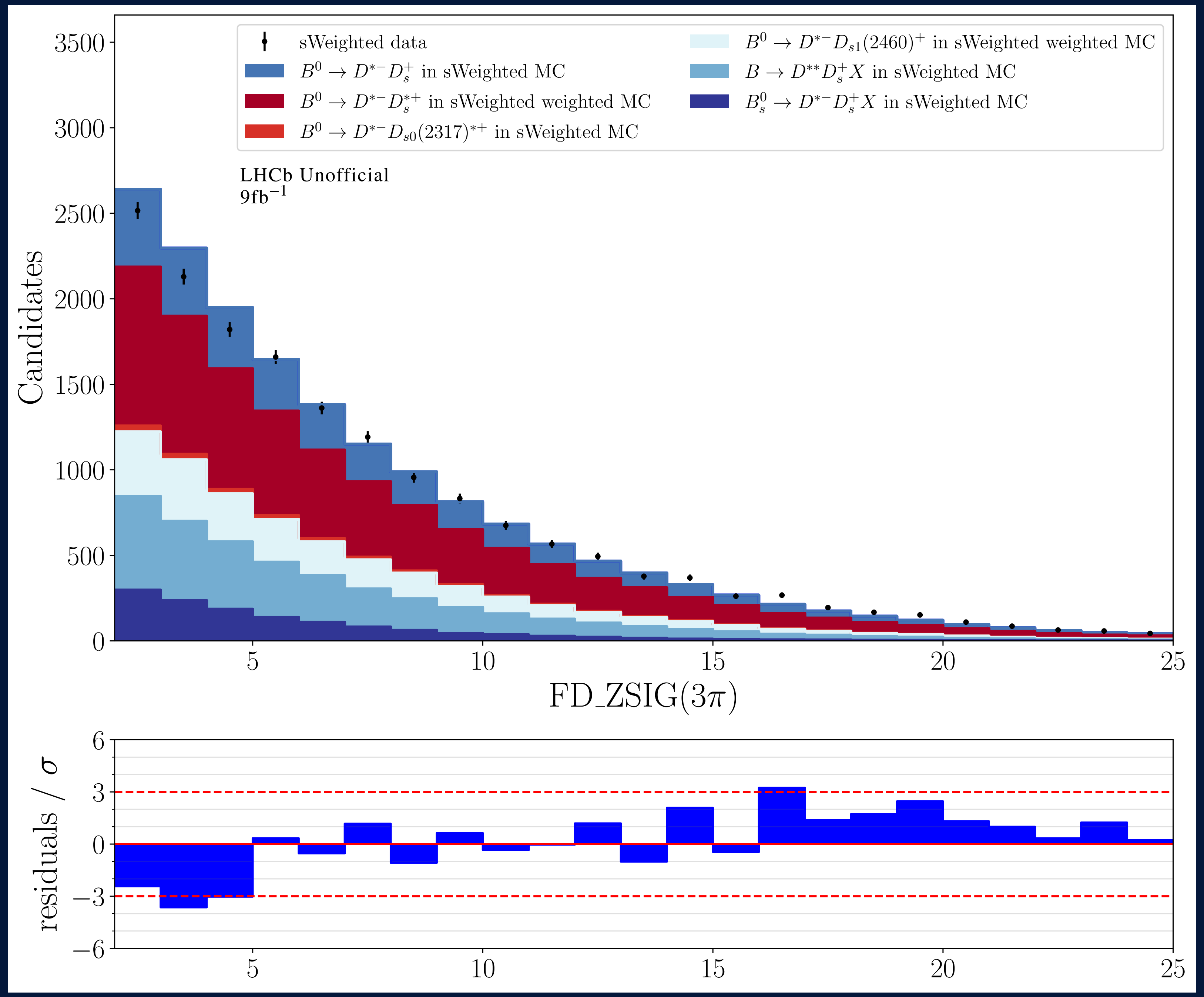
$B \to D^* D_s(X)$ CONTROL STUDY - DECAY ANGLES

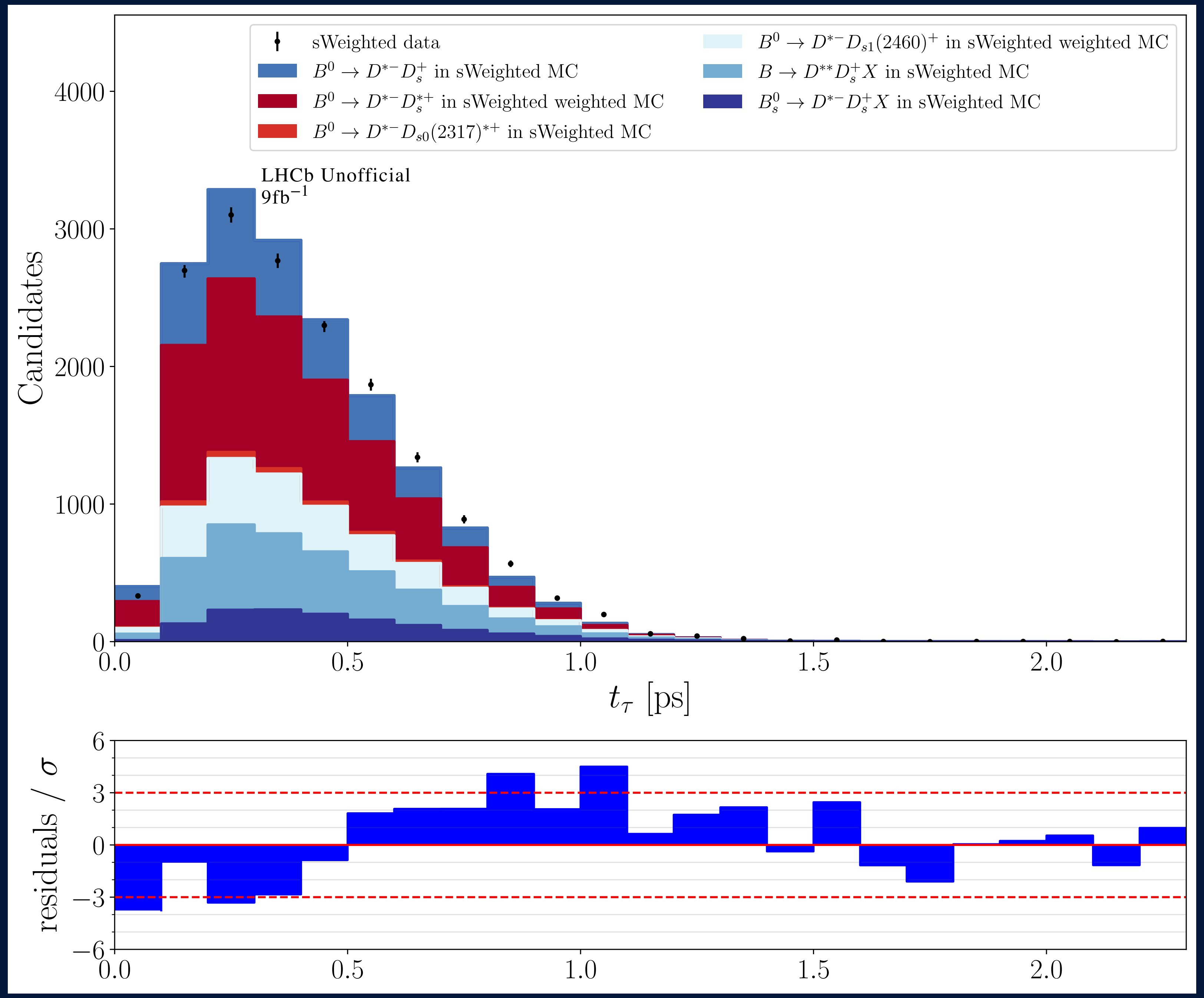


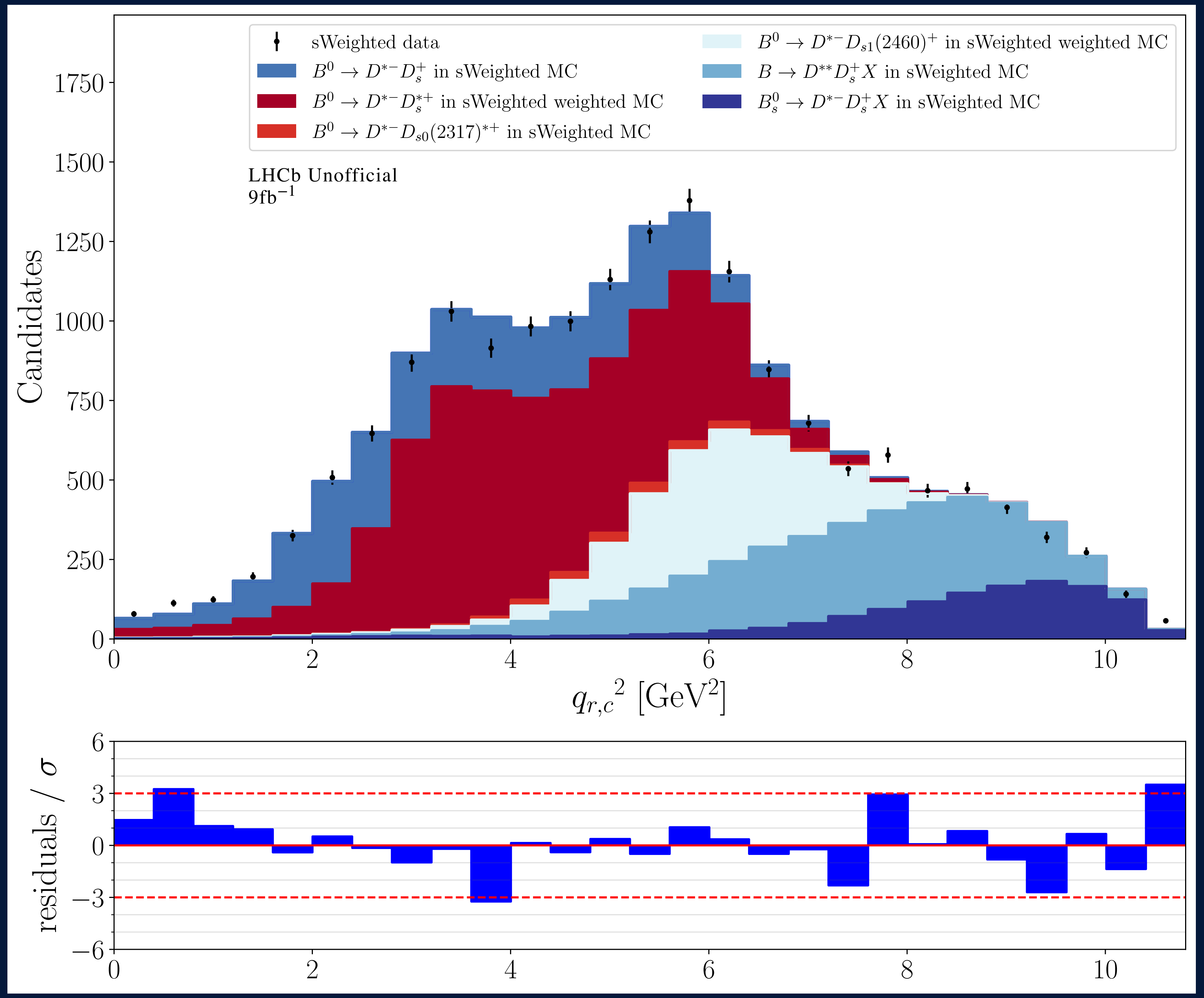




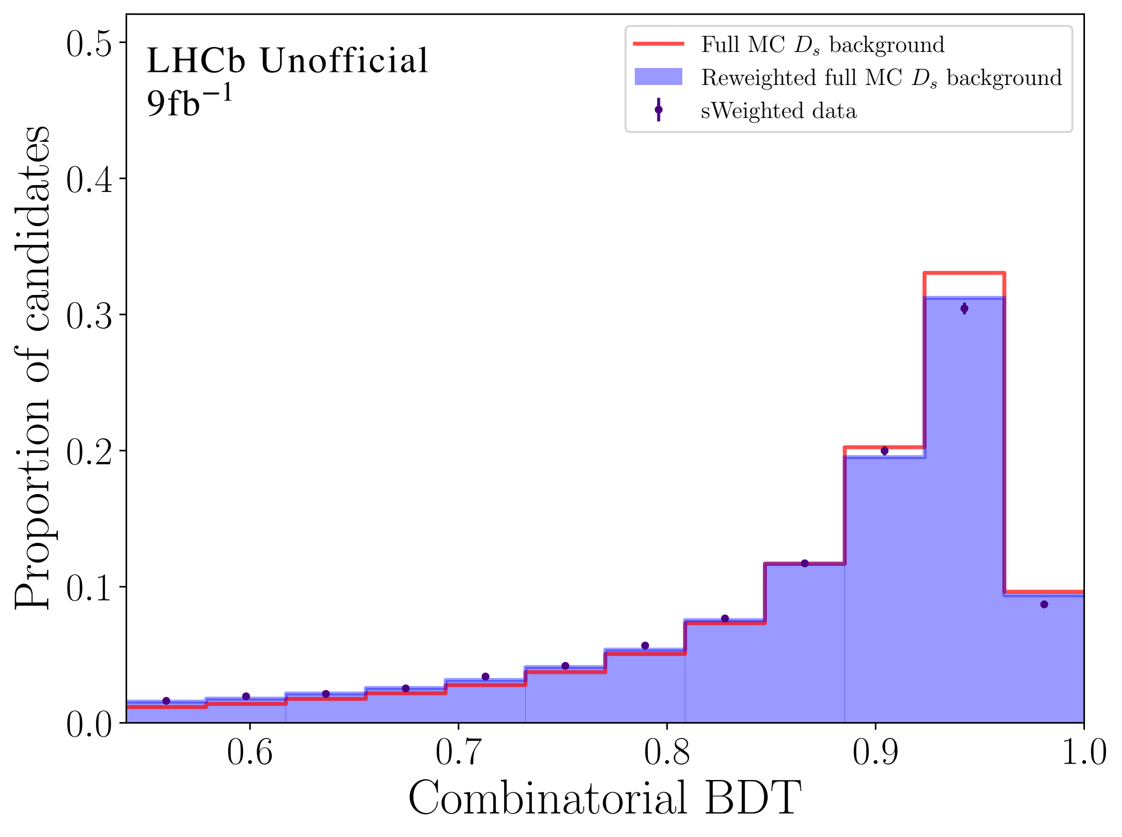
$B \to D^*D_s(X)$ CONTROL STUDY - OTHER VARIABLES

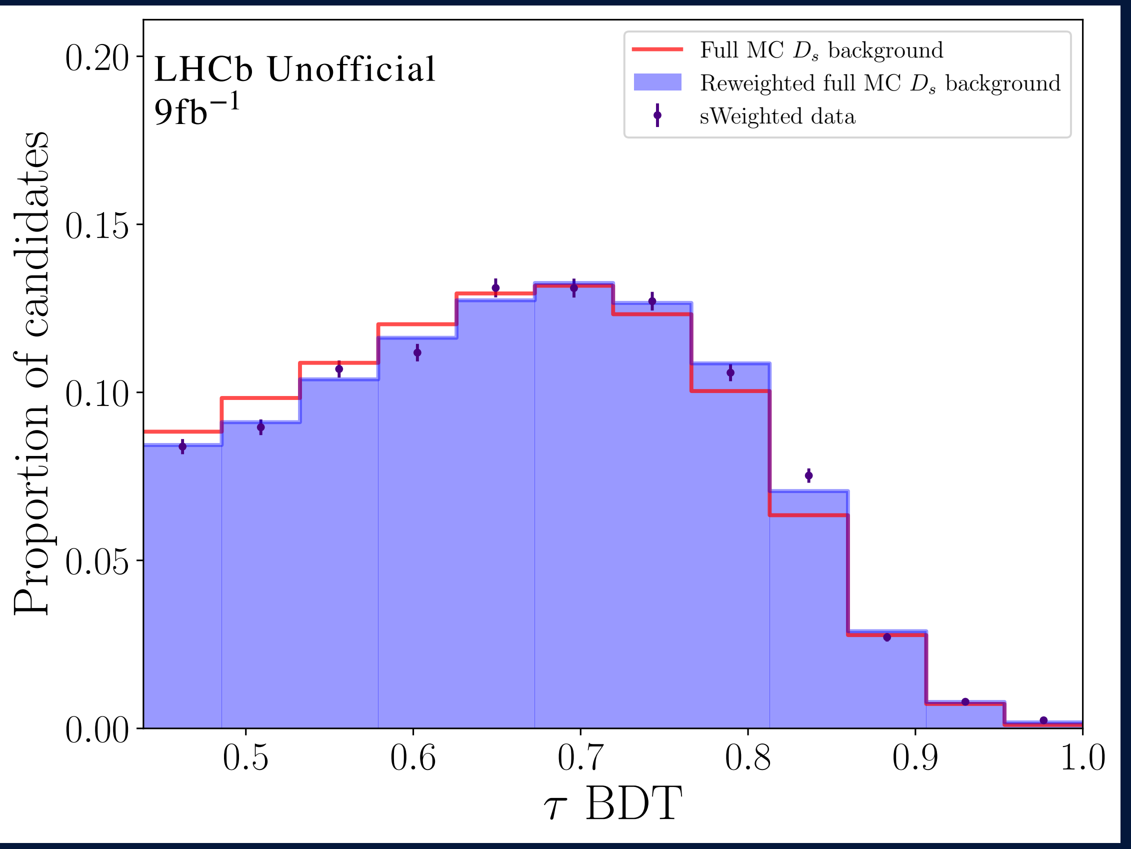


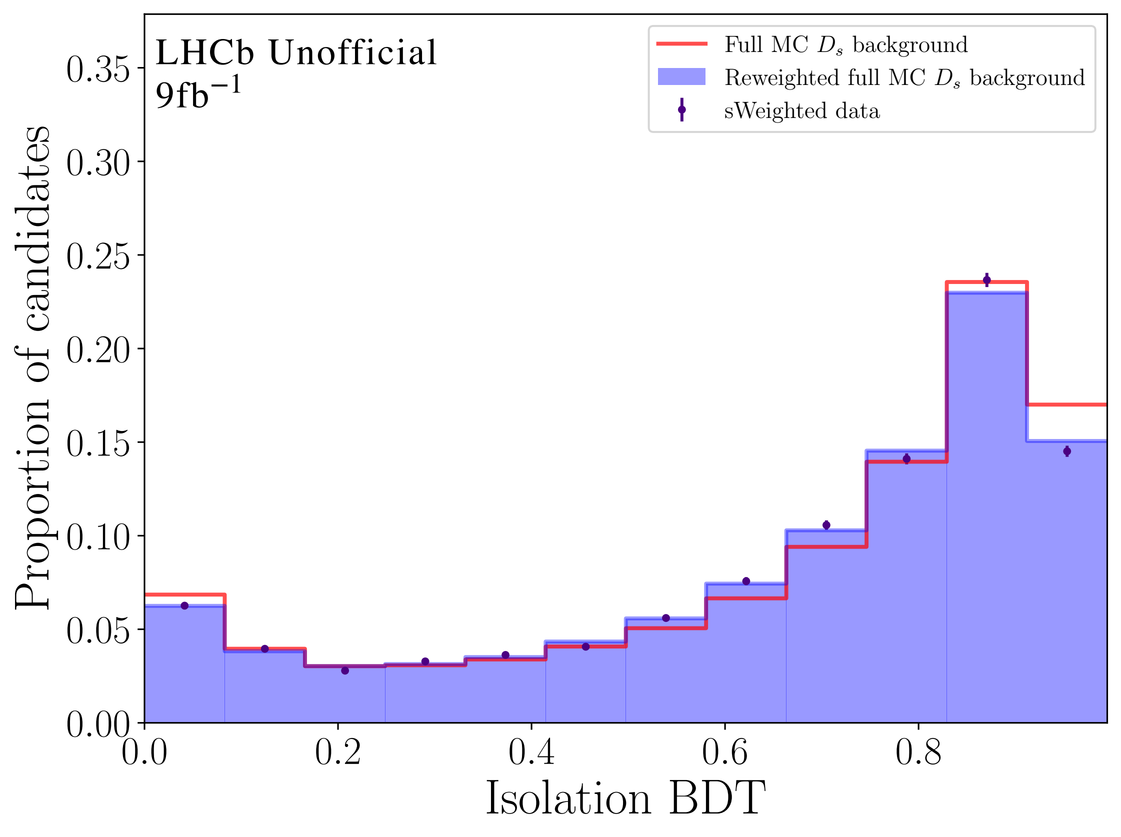


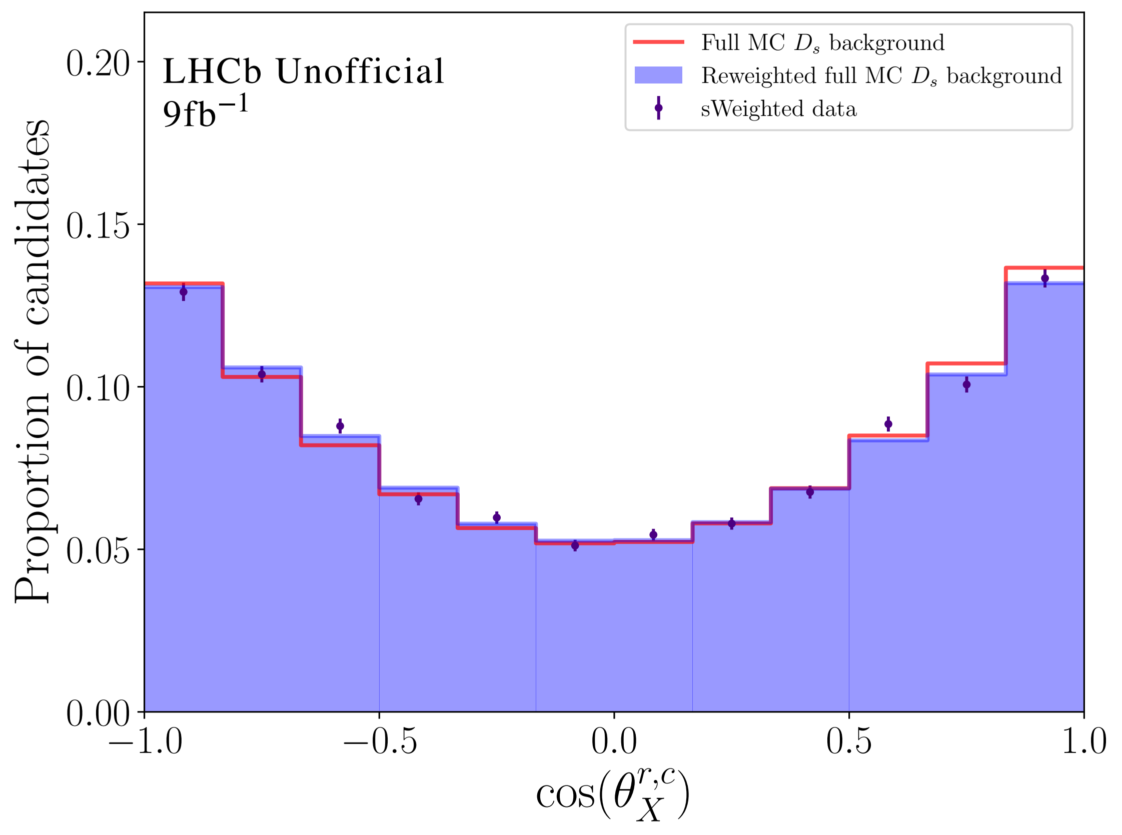


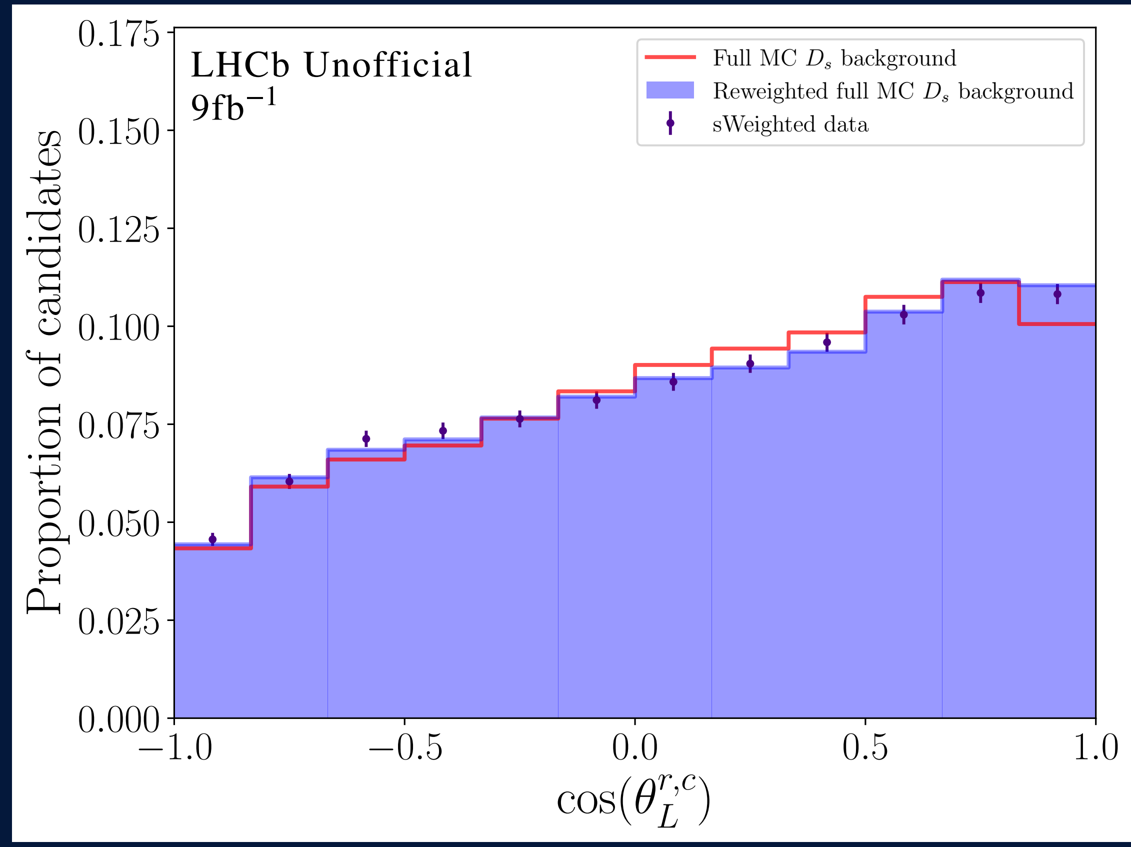
$B \rightarrow D^{*}D_s(X)$ VARIABLES AFTER REWEIGHTING

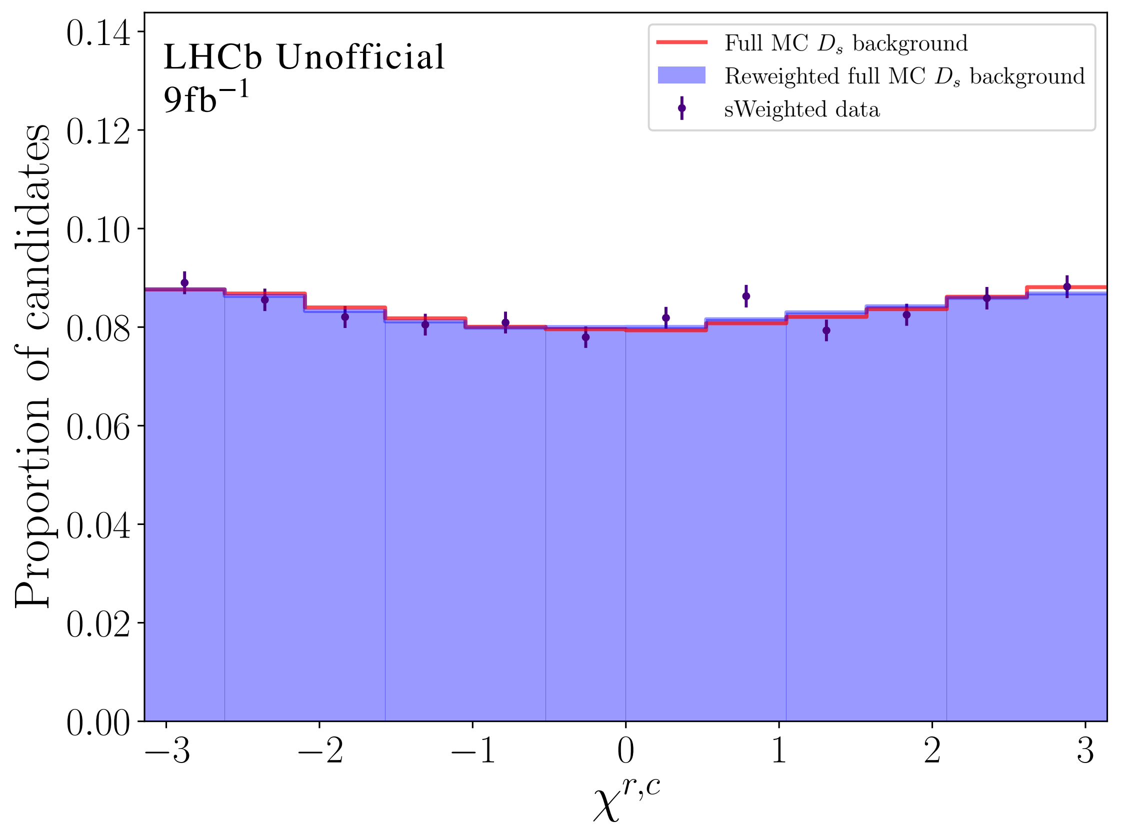


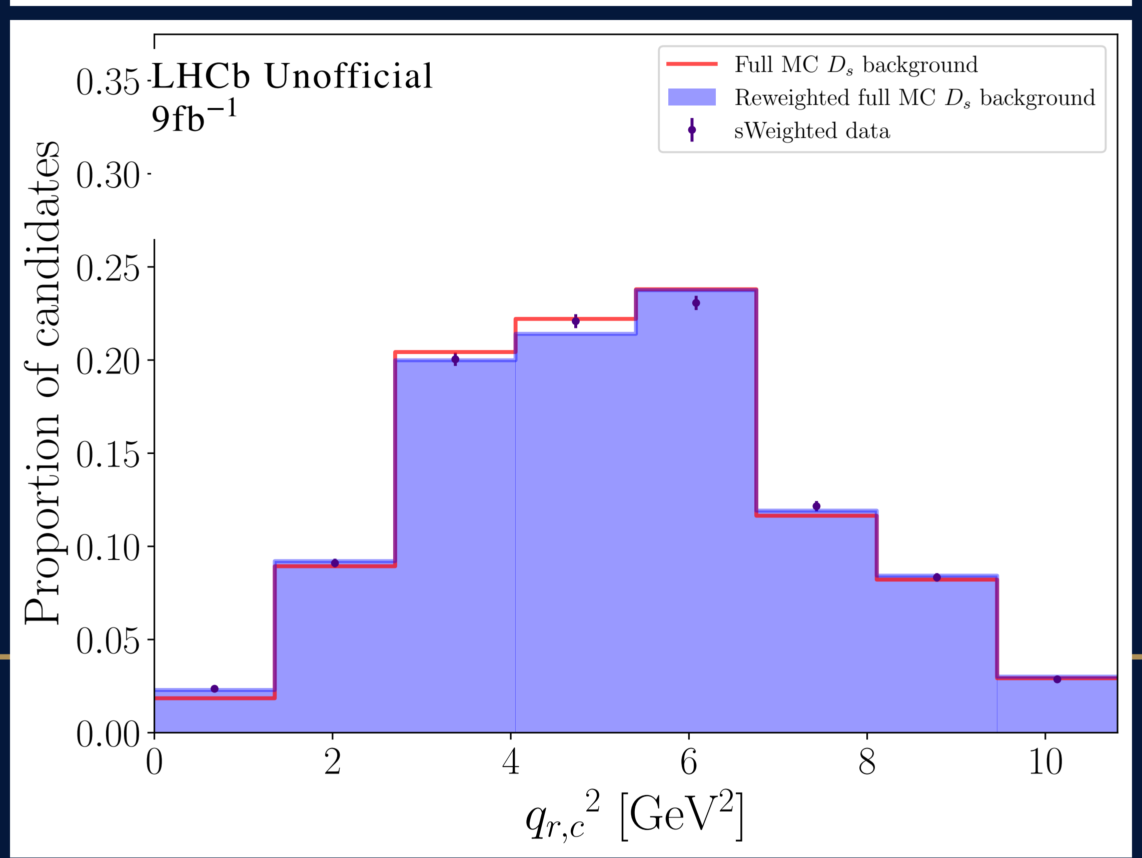






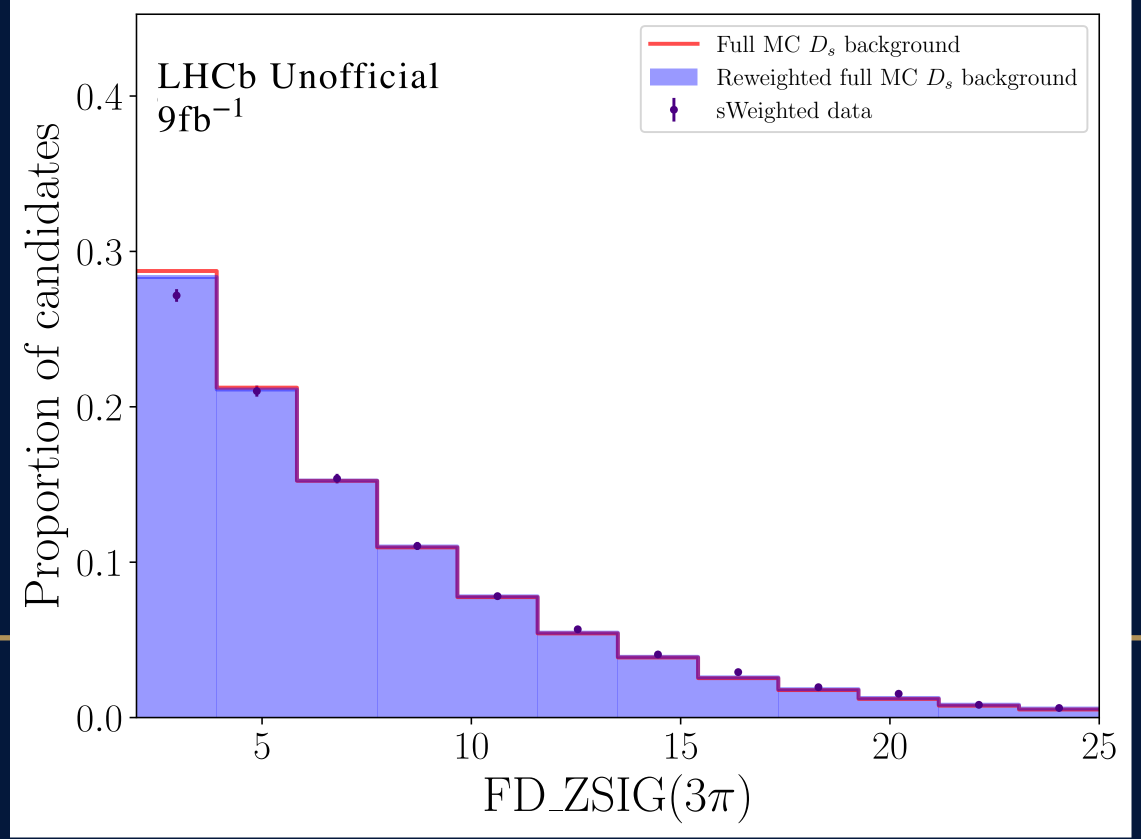






Use spline reweighting to correct residual discrepancies

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



CONTROL STUDIES

- Several control studies
  - $B \to D^{*-}D^0(X)$: Weights for data/MC agreement
    - Isolate $B \to D^{*-}D^0(X)$ via $D^0 \to K^-\pi^+\pi^-\pi^+$ using $_s$Weights
  - $B \to D^{*-}D^+(X)$: Weights for data/MC agreement
    - Isolate $B \to D^{*-}D^+(X)$ via $D^+ \to K^-\pi^+\pi^+$ using $_s$Weights
  - $B \to D^{*-}D_s(X)$: Weights for data/MC agreement and for relative decay fractions
    - Isolate $D_s \to \pi^+\pi^-\pi^+$ using $_s$Weights
    - Fit $m(D^{*-}D_s)$ to measure decay fractions
  - $D_s \to \pi^+\pi^-\pi^+(X)$: 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

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

- MC contains certain fractions of $D_s \to \pi^+\pi^-\pi^+(X)$ 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
  - $m(\pi^+\pi^+)$
  - $\min[m(\pi^+\pi^-)]$
  - $\max[m(\pi^+\pi^-)]$
  - $m(\pi^+\pi^-\pi^+)$

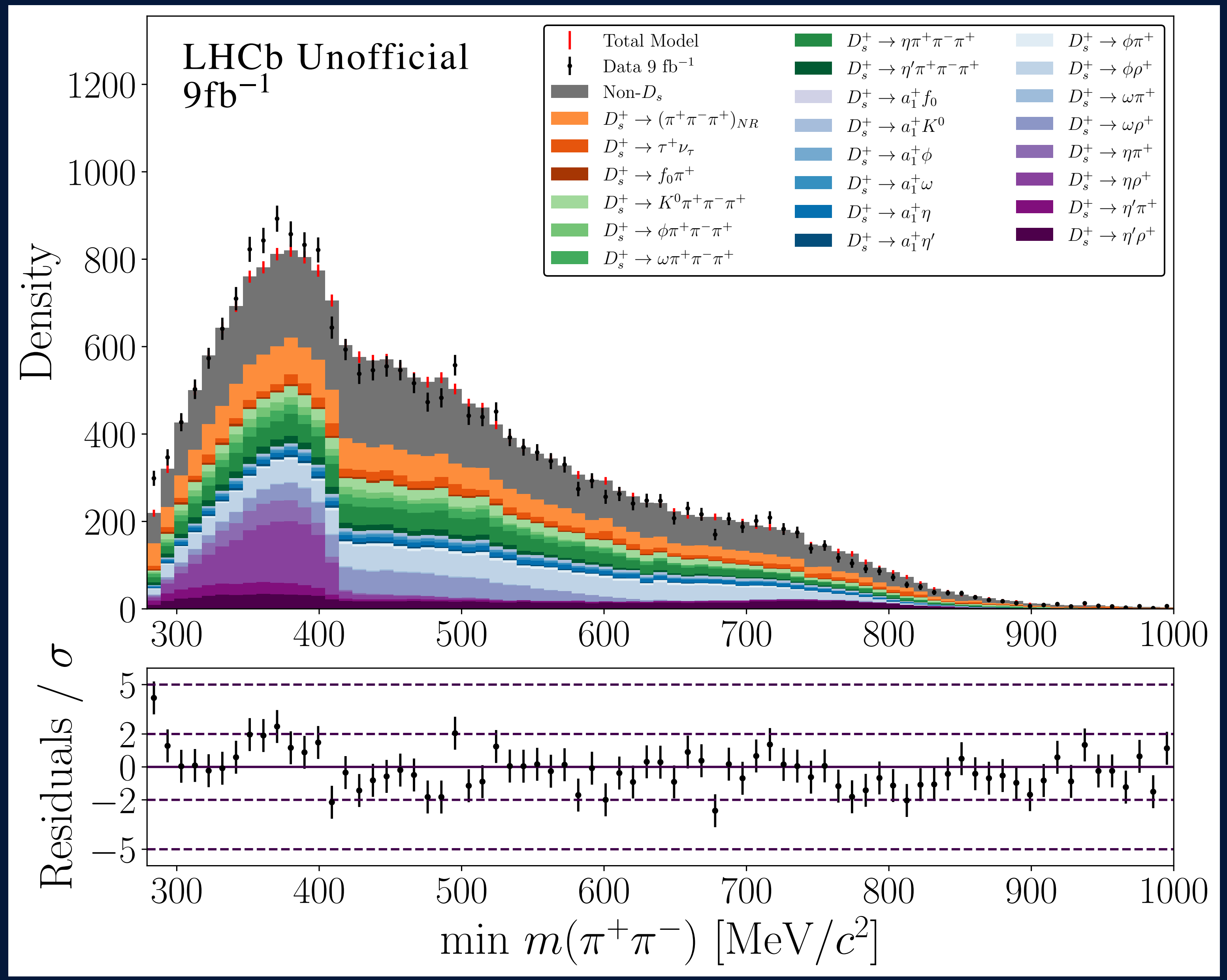
$D_s \to \pi^+\pi^-\pi^+(X)$ SELECTION

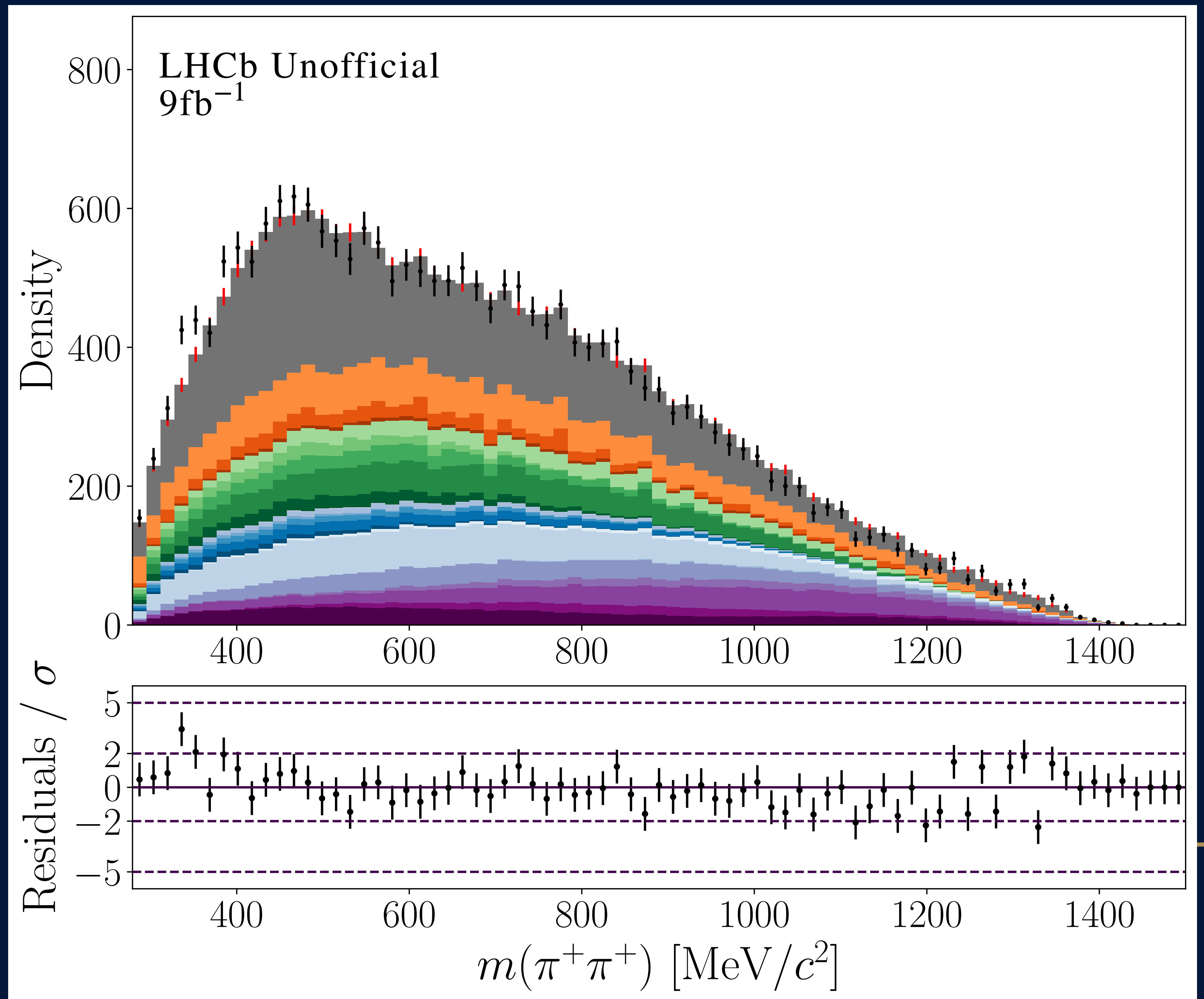
Variable	Condition
Trigger	(B0_L0HadronDecision_TOS or B0_L0Global_TIS) and (B0_Hlt1TrackMVADecision_TOS or B0_Hlt1TwoTrackMVADecision_TOS) and (B0_Hlt2Topo2BodyDecision_TOS or B0_Hlt2Topo3BodyDecision_TOS or B0_Hlt2Topo4BodyDecision_TOS)
$\mathrm{PV}(\tau^+)$	$= \mathrm{PV}(D^0)$
$\mathrm{V}_z(\tau^+)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

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

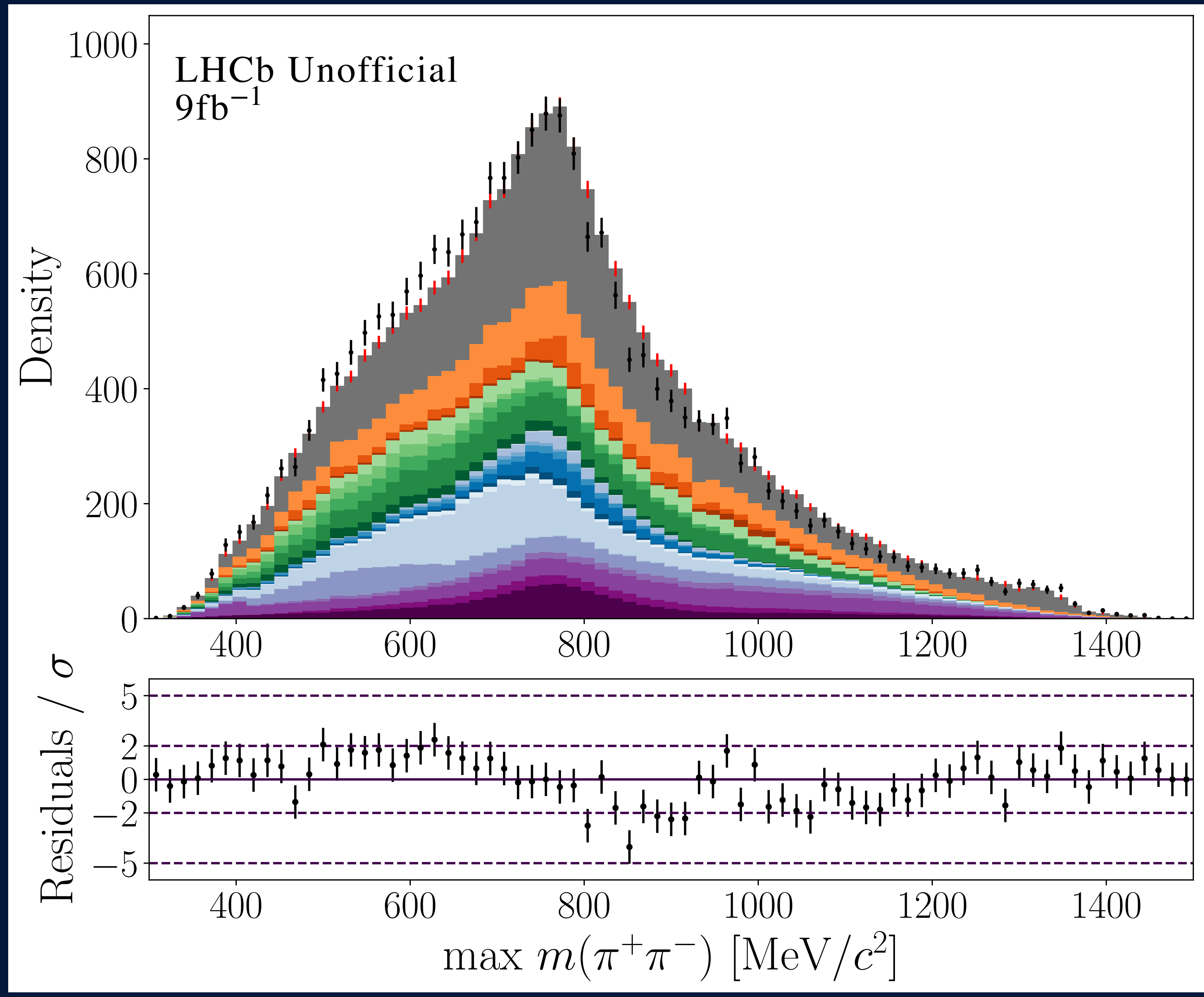
	Variable	Condition
π^+	PIDK	< 4
	p	$\in [3000,\ 100{,}000]$ MeV/c
	p_T	$\in [300,\ 10{,}000]$ MeV/c
π^-	PIDK	< 1
	p	$\in [3000,\ 100{,}000]$ MeV/c
	p_T	$\in [300,\ 10{,}000]$ MeV/c

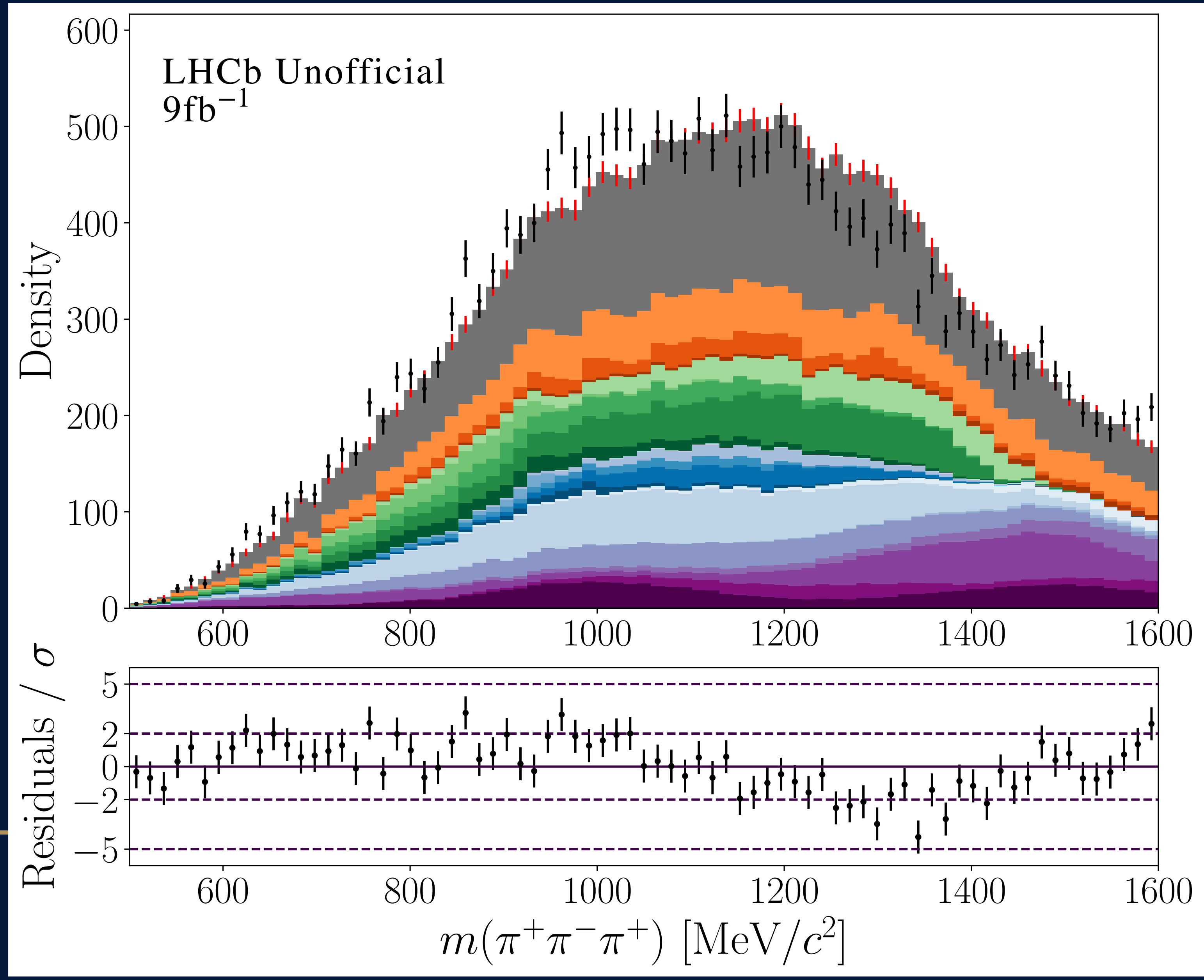
$D_s \to \pi^+\pi^-\pi^+(X)$ RESULTS - FIT VARIABLES





- Simultaneous fit in four variables
  - $m(\pi^+\pi^+)$
  - $\min[m(\pi^+\pi^-)]$
  - $\max[m(\pi^+\pi^-)]$
  - $m(\pi^+\pi^-\pi^+)$





SIGNAL FIT

SIGNAL FIT - SIGNAL PDF

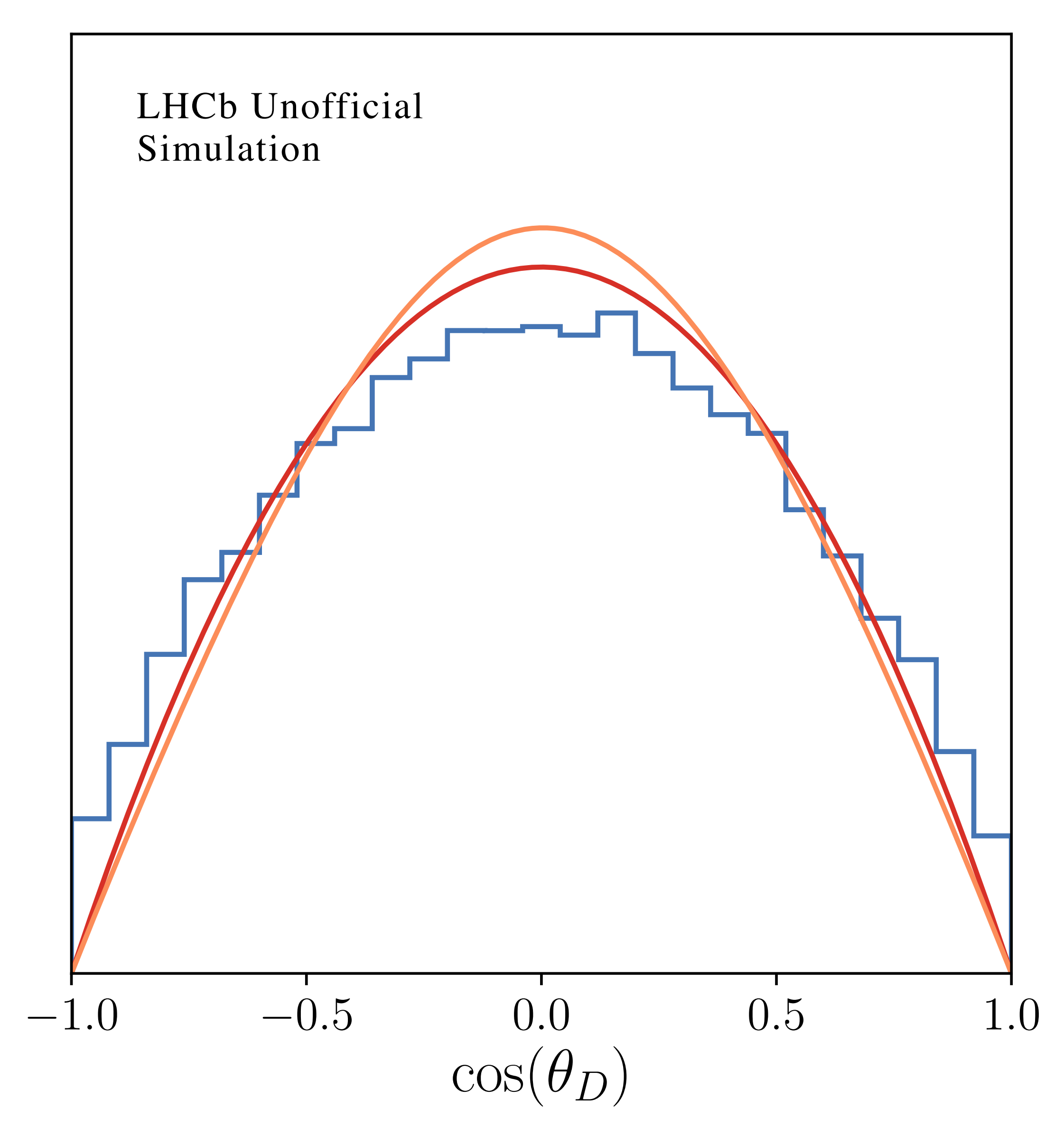
- Simultaneous multidimensional template fit
  - 3D fit in the decay angles
  - 3D fit in BDT, q^2, τ z flight distance significance

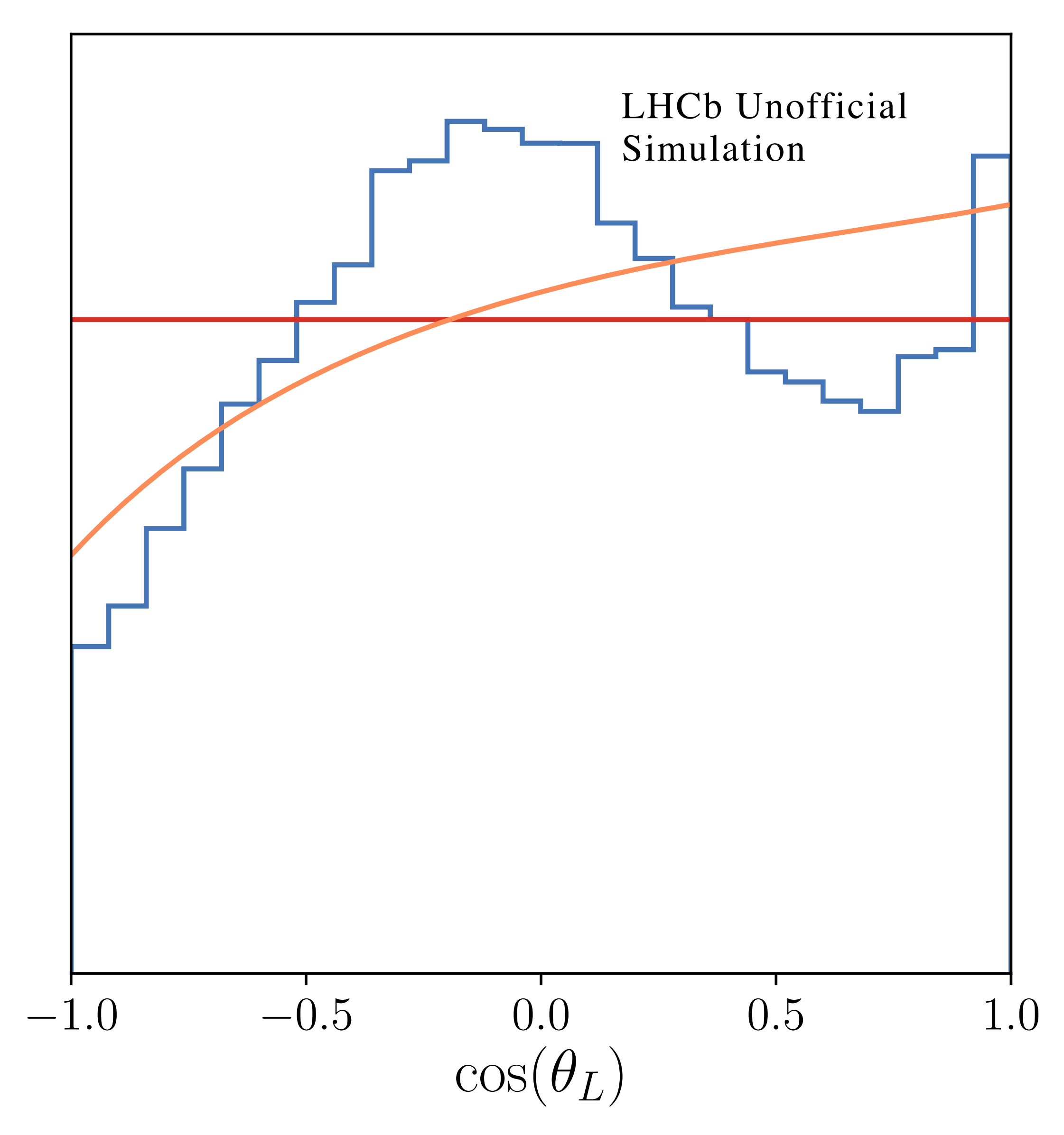
- In traditional $\mathscr{R}(D^*)$ analyses, the signal and background PDFs use SM simulation as the templates
  - Assumes SM and a form factor model

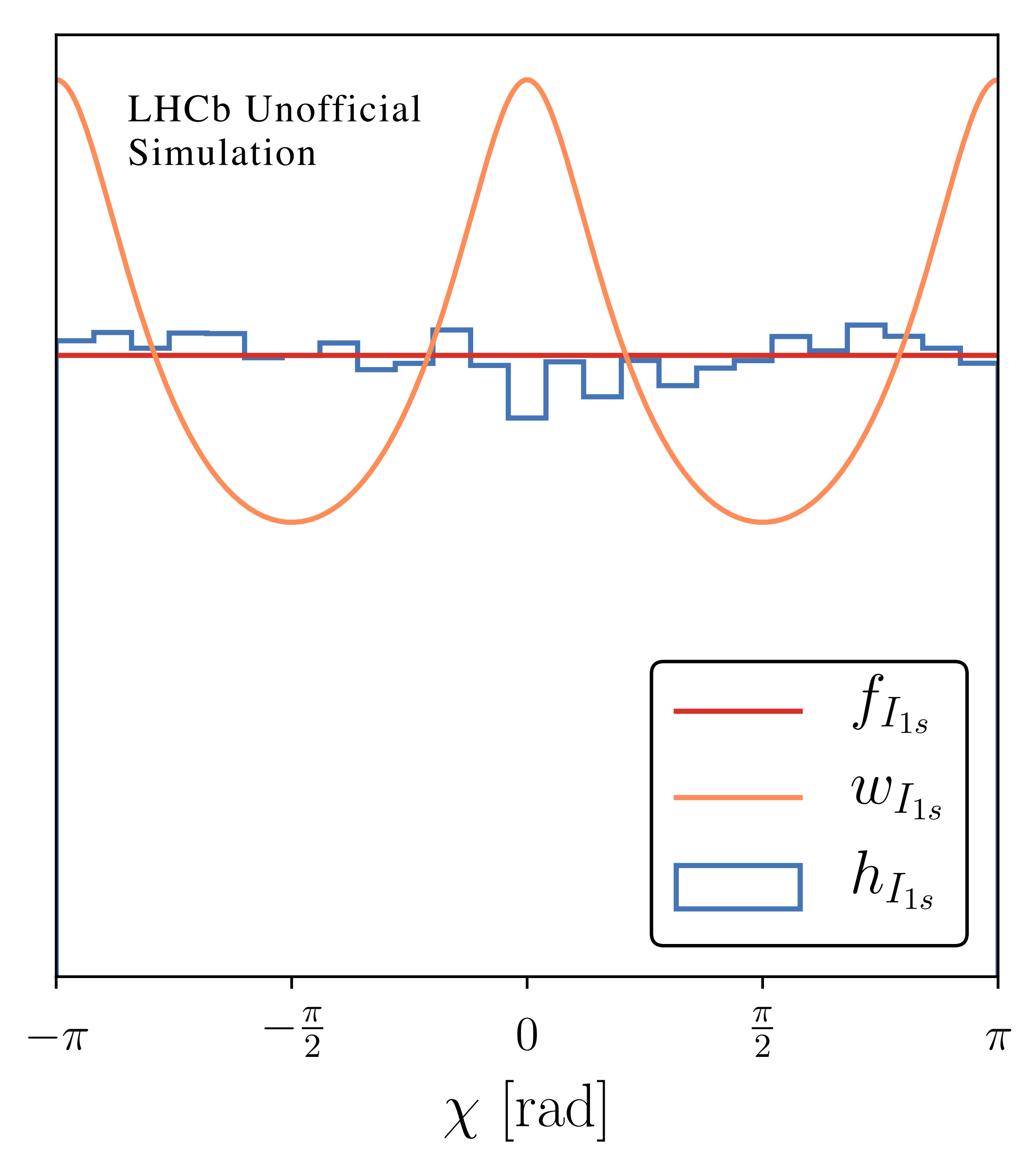
- In this analysis, background templates are still SM shapes taken from simulation
- The signal simulation is divided into 12 model independent angular templates, h_{I_x}
  - Signal template is the sum of these angular templates
    - Each h_{I_x} is normalised by their I_x coefficient which floats in the fit:

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

SIGNAL PDF CREATION







- Take angular function for a particular I_x ,

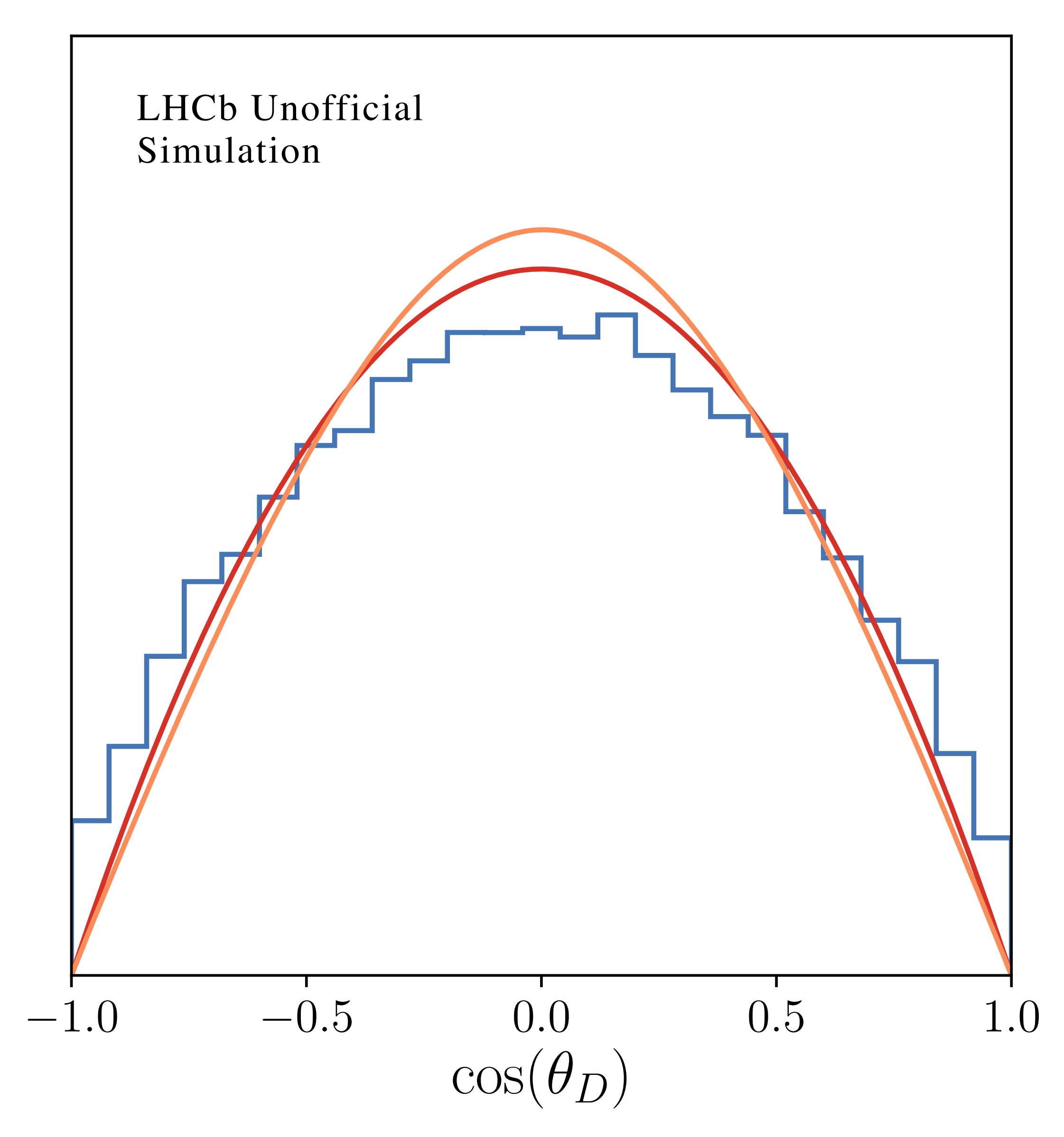
  f_{I_x}: $I_{1s}\sin^2\theta_D$

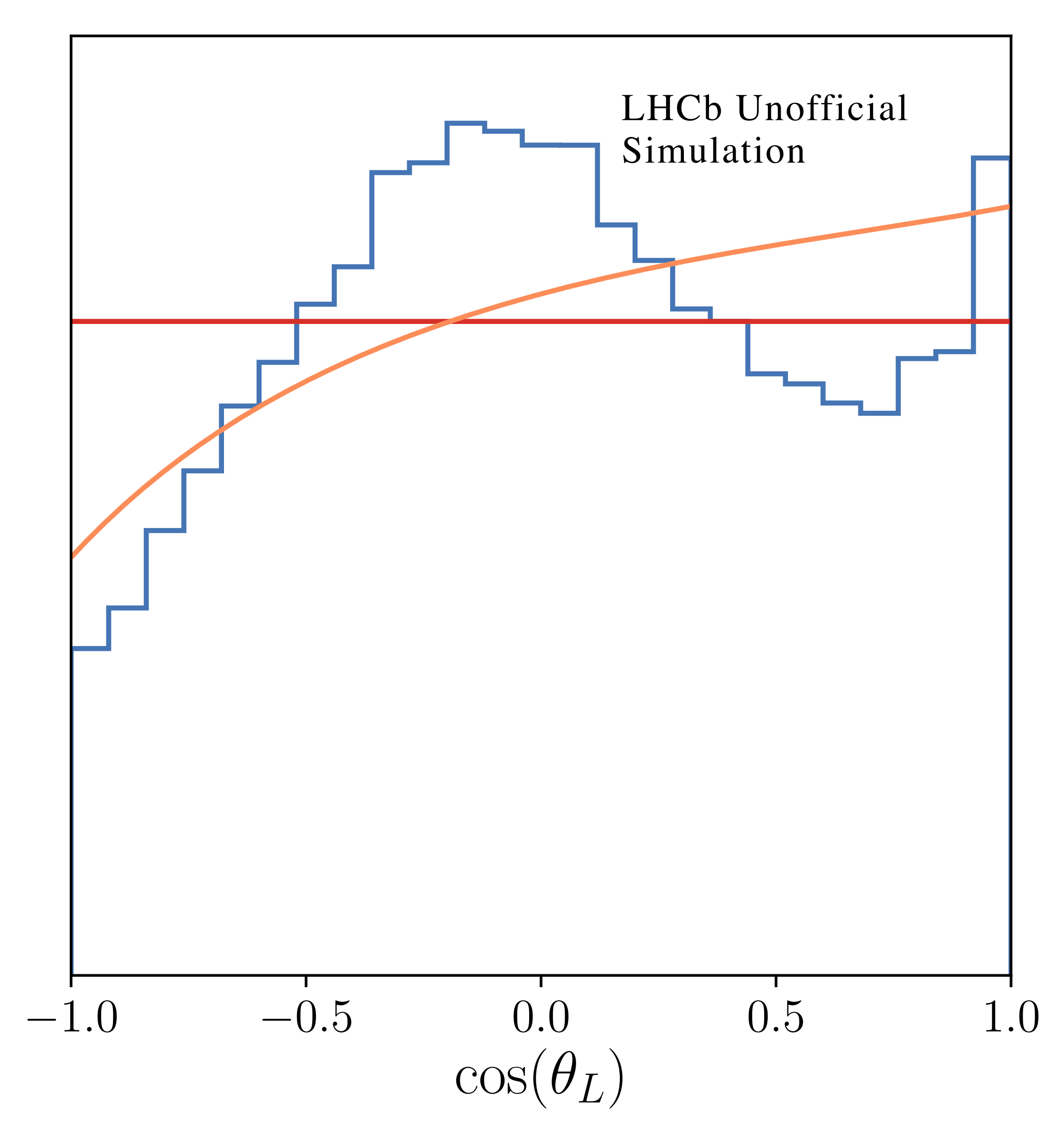
- Divide by the total model M to obtain weight function, w_{I_x} $\quad M = \frac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_L d\chi}$

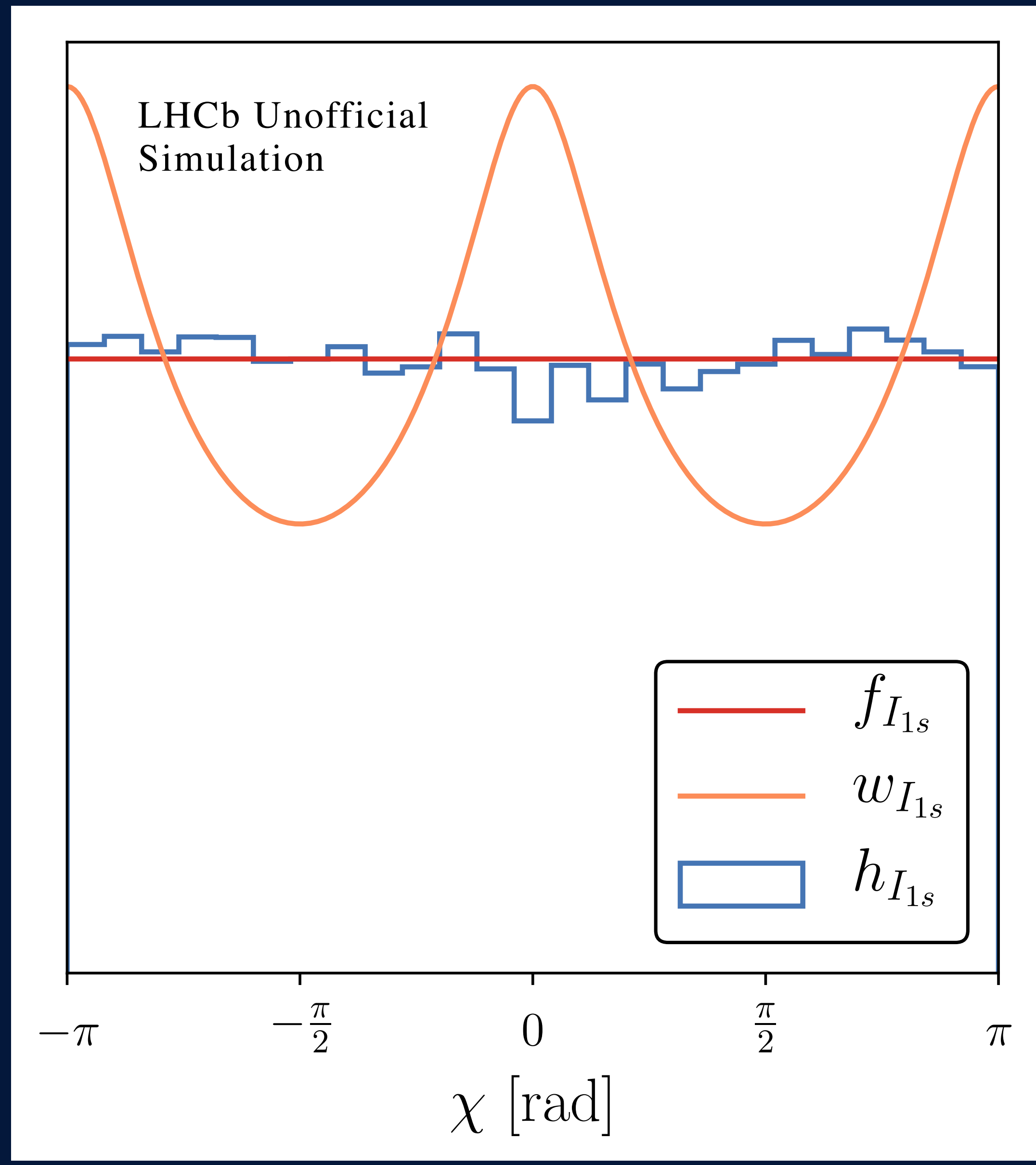
- Calculate the value of the weight function for signal simulation (using truth variables)

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

SIGNAL PDF CREATION







- Take angular function for a particular I_x ,

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

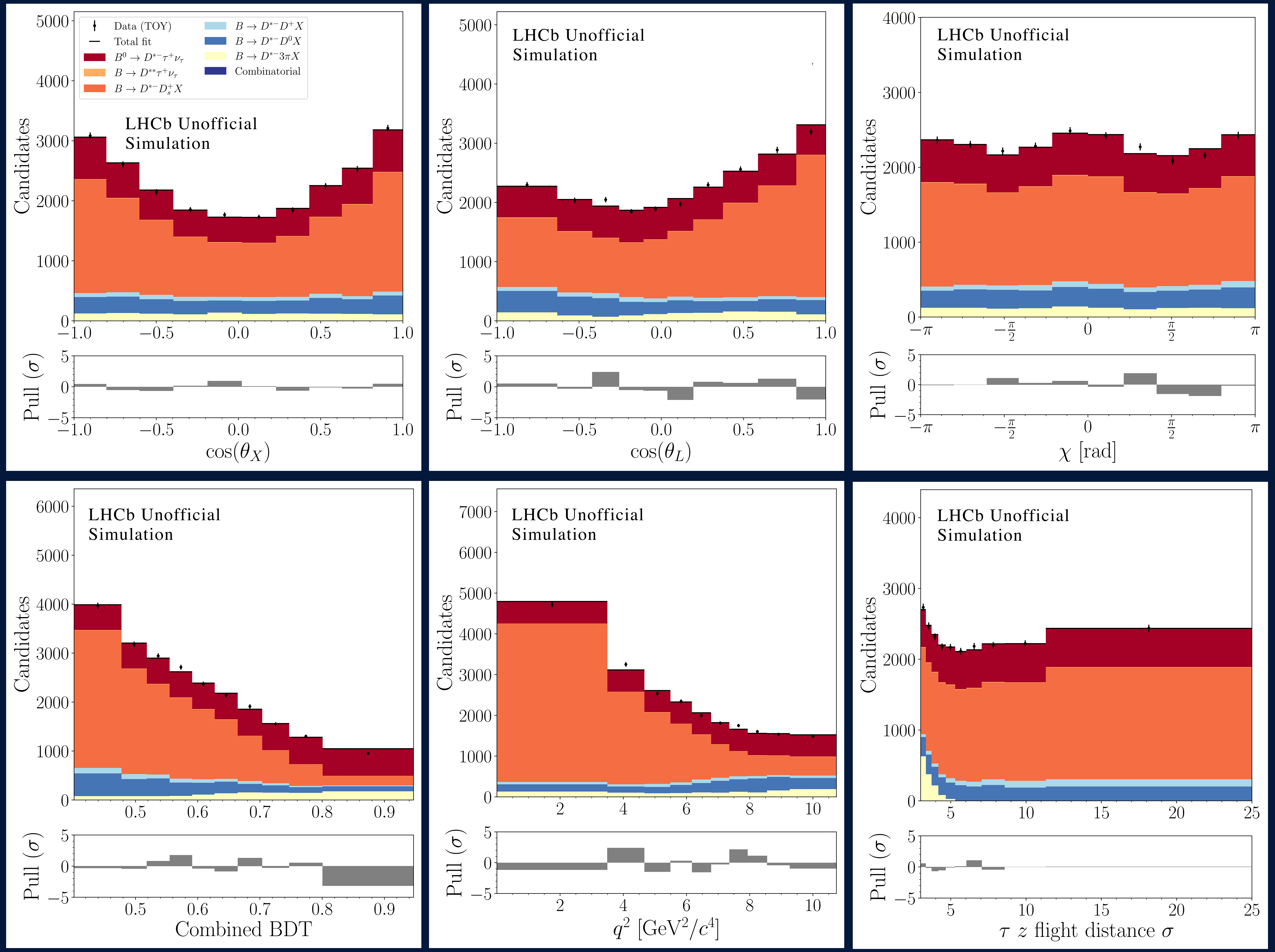
- Divide by the total model M to obtain weight function, w_{I_x}

$$M = \frac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_L d\chi}$$

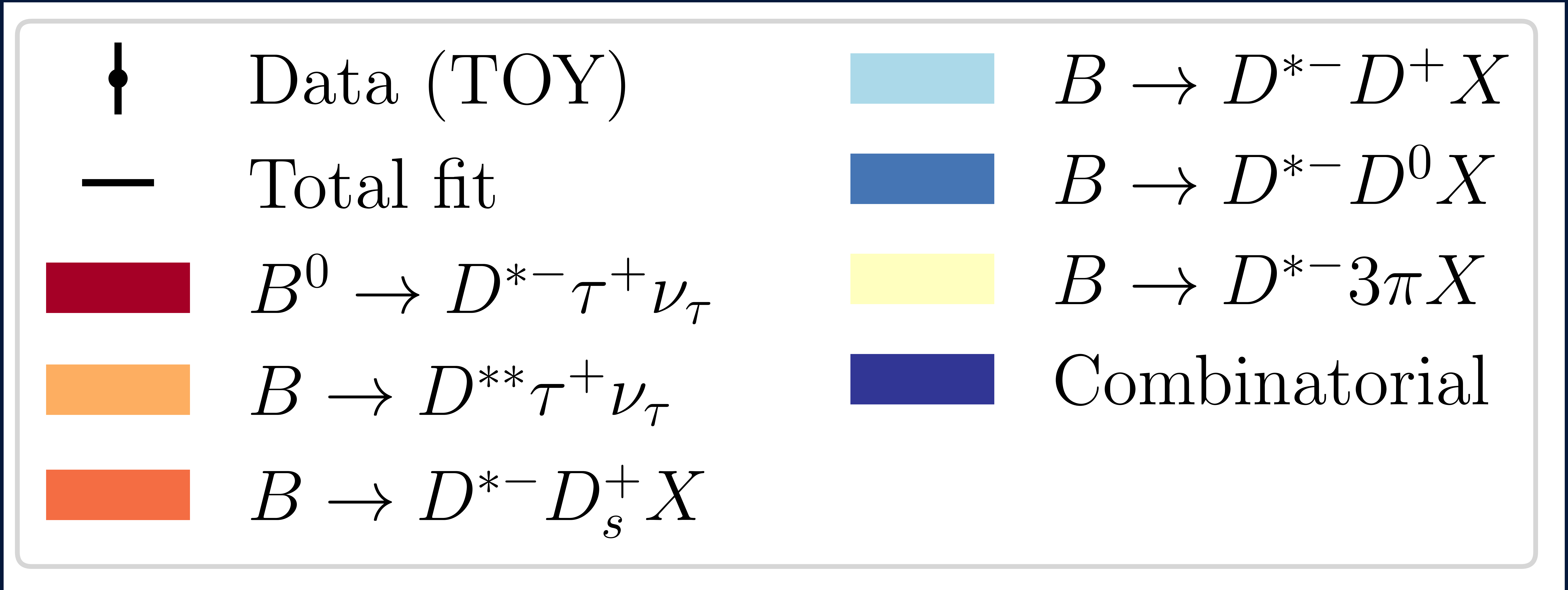
- Calculate the value of the weight function for signal simulation (using truth variables)
- Apply weights to signal simulation to create I_x template, h_{I_x} (in reconstructed space)
- h_{I_x} and f_{I_x} deviate due
  - Selection effects
  - Missing ν
  - Angular resolution

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 $\mathscr{R}(D^*)$ (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



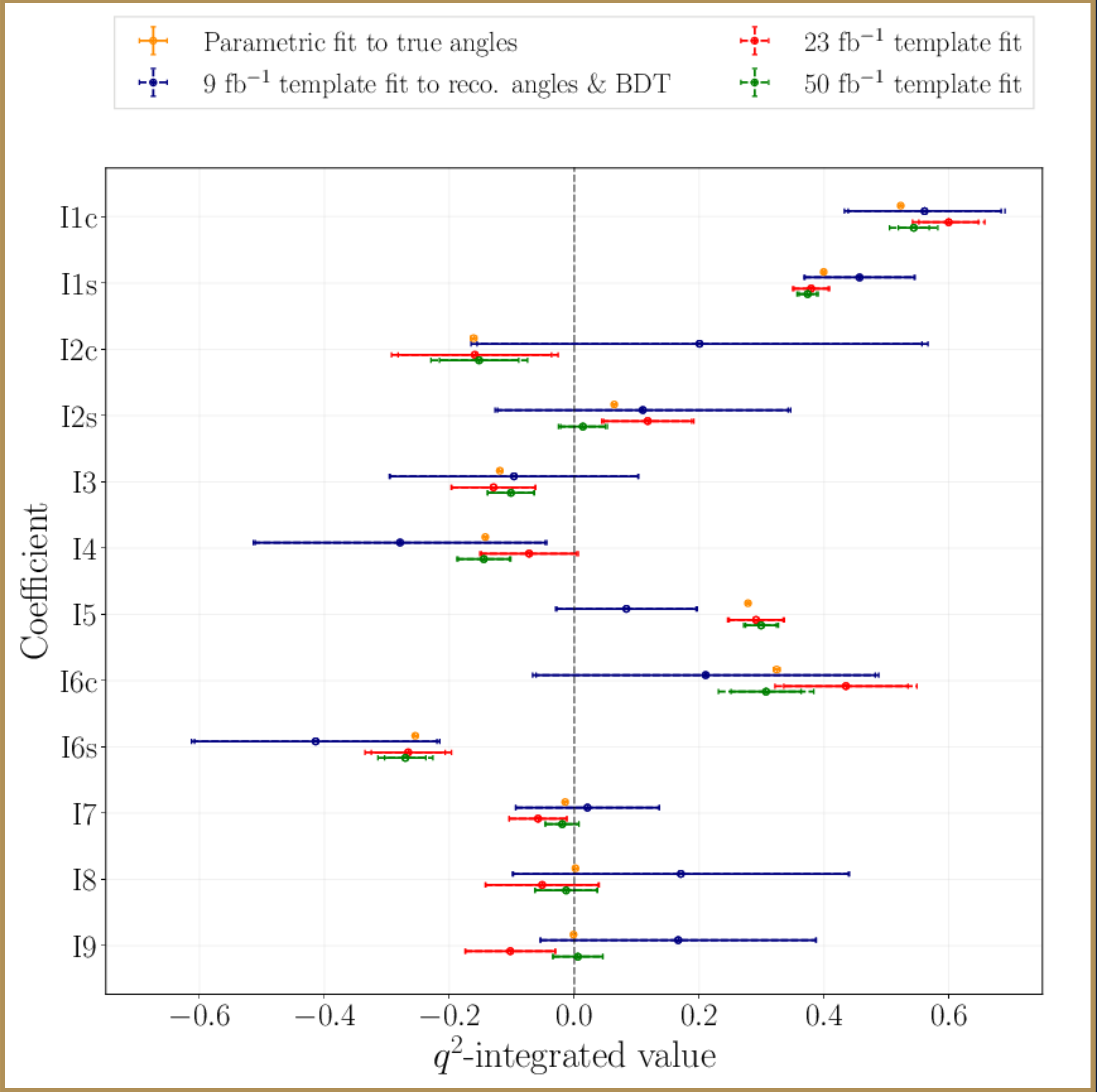
ANGULAR FIT - TOY COMPONENTS



ANGULAR FIT - TOY

ANGULAR ANALYSIS: ANGULAR COEFFICIENTS

- Expected performance of angular coefficient measurements for different dataset sizes:
- 9fb^{-1}: Run 1 + 2 (blue)
- 23fb^{-1}: Run 1 + 2 + 3 (red)
- 50fb^{-1}: Run 1 + 2 + 3 + 4 (green)



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