Amplitude Analysis of $B^0 \to D^0 \bar{D}^0 K^+ \pi^-$

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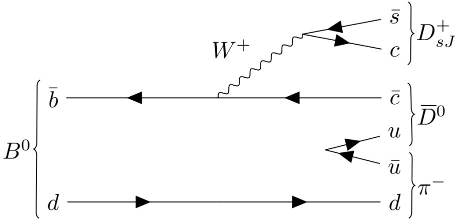
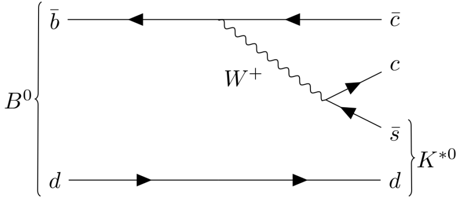
The $B^0 \to D^0 \bar{D}^0 K^+ \pi^-$ decay

- It is a favoured $b \to cW^-(\to \bar{c}s)$ transition due to V_{cb} being relatively large.
- Either 'external' or 'internal' W emission.
- Rare charm-strange states can appear in external case.
- "Charm loops" can be studied in internal case and charmonium exotics may also be present.

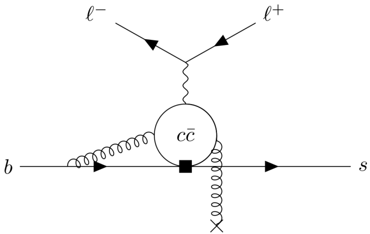




Motivations: exotics and charm loops

- Studying the amplitudes in the $D^0\bar{D}^0$ system can help us understand exotic states (non-$q\bar{q}$, qqq) above the open-charm threshold ($s > 4m_D^2$).
  - e.g. tetraquarks ($q\bar{q}q\bar{q}$) like $Z_c(4430)^-$, may be present in $D^0\bar{D}^0\pi$ system[1].
- Can also study rare Charmonium ($c\bar{c}$) and charm-strange states ($c\bar{s}$) e.g. $\chi_{c(0,2)}(3930) \rightarrow D^0\bar{D}^0$.

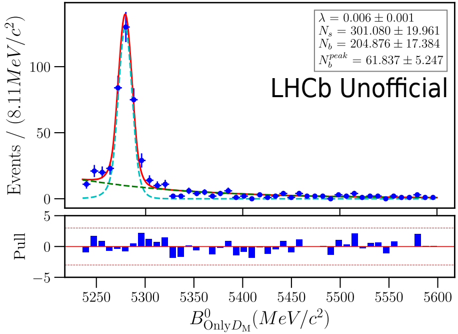
- Studying the $D^0\bar{D}^0$ system can provide information on charm contibutions mimicking new physics in $b \rightarrow s\ell\ell$ measurements.



[1] arXiv:1404.1903

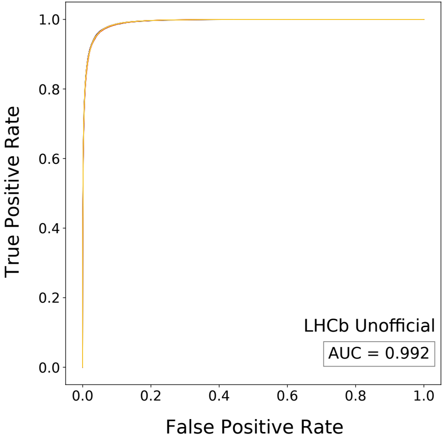
Selections - overview

- D^0 candidates reconstructed from either $K\pi$ or $K\pi\pi\pi$.
- Cut-based selections on particle identification, kinematic, and mass variables to remove combinatorial and peaking backgrounds.
  - Kinematic refit performed on final state particles to improve B^0 mass resolution.
    - D^0 candidates constrained to their known mass and originate from the B^0 candidate decay vertex.
  - MVA used to suppress combinatorial backgrounds.
  - Resulting yield: roughly 1400 signal and 300 background candidates within 35 MeV of the B^0 known mass.



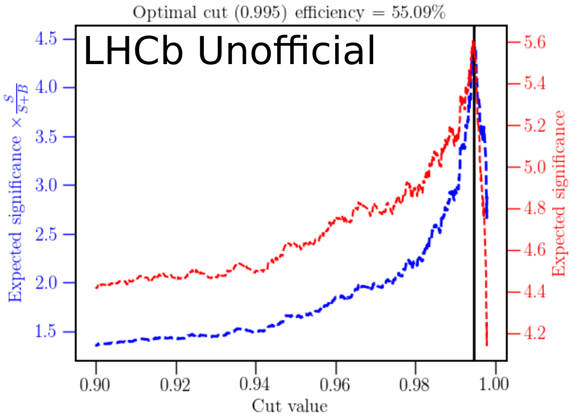
Selections - MVA

- Two-stage fully connected feed-forward NN, first stage feeds into second.
- First stage: trained on kinematic and topological variables related to D^0 candidates and their child particles.
- Second stage: trained on previous stage output and kinematic and topological variables independent of $m(K\pi)$.



Selections - MVA optimisation

- Cuts are placed on NN output, position of cut optimised by maximising a combination of expected signal purity and significance.
- Purity estimated from fits to a control mode $B^0 \to D^{*-} D^0 K^+$ peak and extrapolating an exponential background fit to the signal upper mass sideband.



Amplitude analysis - model

- This decay is 4-body, so phasespace is 5-dimensional. We are free to choose from invariant mass or angular distributions.
- Using Isobar model, full amplitude written as coherent sum of components:

$$\mathcal{P}(x) = |\mathcal{M}|^2 = \left| \sum_r c_r \mathcal{A}_r(x) \right|^2 \tag{1}$$

- Using helicity formalism, and considering our initial and final state particles are spin-0, the amplitude for a given $B^0 \to (R \to ab)(R' \to cd)$ decay is:

$$\mathcal{A}_B \propto \sum_{\lambda=-J_{R'}}^{J_{R'}} \mathcal{H}_{\lambda_R \lambda_{R'}} \times F_R(x) D^{J_R}_{\lambda,0}(\Omega_R) \times F_{R'}(x) D^{J_{R'}}_{\lambda,0}(\Omega_{R'}) \tag{2}$$

- here $\mathcal{H}_{\lambda_R \lambda_{R'}}$ is the helicity coupling, $F_R(x)$ describes the lineshape, and $D^{J_R}_{\lambda,0}(\Omega_R)$ is the relevant Wigner-D function for a contribution with spin J_R and decay product helicities λ. Ω_R contains angular information.

Amplitude analysis - likelihood

- Our total likelihood is:

$$\mathcal{L} = \prod_{x_i} \frac{\varepsilon(x_i)\phi(x_i)\mathcal{P}(x_i)}{\int \varepsilon(x)\phi(x)\mathcal{P}(x)dx} \quad (3)$$

- where $\varepsilon(x_i)$ is the efficiency and $\phi(x_i)$ is the phasespace density, since we deal with the log-likelihood, these terms in the numerator factorise out.
- For integration events generated using a signal model $\mathcal{P}'(x)$ and selected using the same criteria as the data, we can approximate:

$$\int \varepsilon(x)\phi(x)\mathcal{P}(x)dx \approx \frac{1}{N}\sum_{i=0}^{N} \frac{\mathcal{P}(x_i)}{\mathcal{P}'(x_i)} \pm \mathcal{O}(N^{-0.5}) \quad (4)$$

- So we can include the efficiency in the normalisation sample for the fit.

Amplitude analysis - background term

- We model background by incoherent addition of a background term to the likelihood, such that the likelihood becomes:

$$\mathcal{L} = \prod_{x_i} f_s \frac{\varepsilon(x_i)\phi(x_i)\mathcal{P}(x_i)}{\int \varepsilon(x)\phi(x)\mathcal{P}(x)dx} + (1 - f_s)\varepsilon(x_i)\phi(x_i)b(x_i) \tag{5}$$

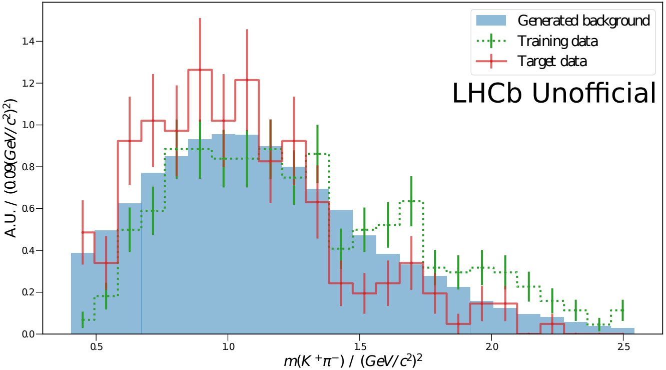
- as before, $\varepsilon(x_i)\phi(x_i)$ factorise out, and $b(x_i)$ is defined as:

$$b(x_i) = w(x_i)\mathcal{P}'(x_i) \tag{6}$$

- where $w(x_i)$ is calculated using a BDT to weight the normalisation sample to a background sample generated with a NN

Background modelling

- Background sample generated by training a NN on the B^0 candidate mass and five invariant mass projections from the upper mass sideband[1].
- The model learns the background shape and extrapolates it into the signal region.



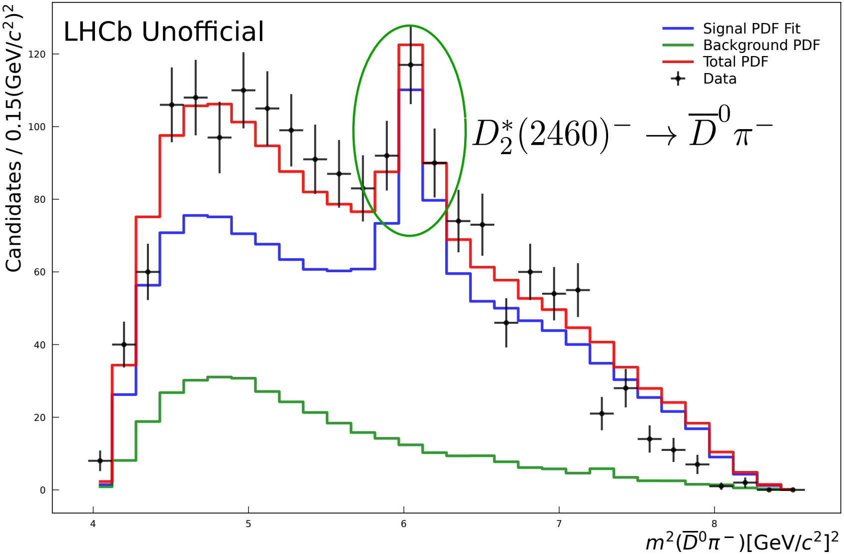
[1] arXiv:1902.01452v2

Amplitude fit and baseline model

Perform simultaneous unbinned maximum-likelihood fit across 12 data categories, including full Run I and Run II dataset. Construct baseline model and build on it by sequentially adding resonances and assessing the likelihood plus some penalty term to penalise complex models:

Nonresonant S-wave $\to D^0\overline{D}^0$	$K^*(892) \to K^+\pi^-$
$\psi(3770) \to D^0\overline{D}^0$	S-wave $\to K^+\pi^-$
$\psi(3770) \to D^0\overline{D}^0$	$K^*(892) \to K^+\pi^-$
$\psi(4040) \to D^0\overline{D}^0$	$K^*(892) \to K^+\pi^-$
$\psi(4160) \to D^0\overline{D}^0$	$K^*(892) \to K^+\pi^-$
$\psi(4230) \to D^0\overline{D}^0$	$K^*(892) \to K^+\pi^-$
$\psi(4360) \to D^0\overline{D}^0$	$K^*(892) \to K^+\pi^-$
$\psi(4415) \to D^0\overline{D}^0$	$K^*(892) \to K^+\pi^-$
$\chi_{c2}(2P) \to D^0\overline{D}^0$	S-wave $\to K^+\pi^-$
$\chi_{c2}(2P) \to D^0\overline{D}^0$	$K^*(892) \to K^+\pi^-$
$\chi_{c0}(3860) \to D^0\overline{D}^0$	$K^*(892) \to K^+\pi^-$
$D_2^*(2460)^- \to \overline{D}^0\pi^-$	$D_{s2}(2573)^+ \to D^0K^+$

Initial fit to data



Summary

- An amplitude analysis of $B^0 \to D^0 \bar{D}^0 K^+ \pi^-$ is being performed, to study charm-loop contributions and exotic states.
- Currently at the stage of refining the amplitude model.
- Fit results of amplitude parameters, particularly for the nonresonant S-wave $\to D^0 \overline{D}^0$ & $K^*(892) \to K^+ \pi^-$, and resonance parameters such as width or mass for lesser-known resonances, will be final results.
- Statistically limited measurement, improved further by Run 3 datasets and beyond.
- We expect the dominant systematic to be the background model - in the process of evaluating

Backup

Motivations - detailed

- Can investigate exotic states above the open-charm threshold ($s > 4m_D^2$) using $D^0\bar{D}^0$
    - Such as $Z_c(4430)^-$ (or $T^b_{\psi 1}(4430)$)[1], determined to have a minimal $c\bar{c}d\bar{u}$ quark content (tetraquark)[2]
- Could also study charmonium or charm-strange states such as:
    - $\chi_{c(0,2)}(3930) \rightarrow D^0\bar{D}^0$
    - $D_s^{**+} \rightarrow D^0K^+$
- Charm loops mimic a q^2-dependent contribution to Wilson coefficient c_9 with large theoretical uncertainties at high q^2
    - Uncertainties due to non-perturbative effects
    - Can put constraints on such charm loop effects by direct study of charm resonances in $b \rightarrow sc\bar{c}$[3]

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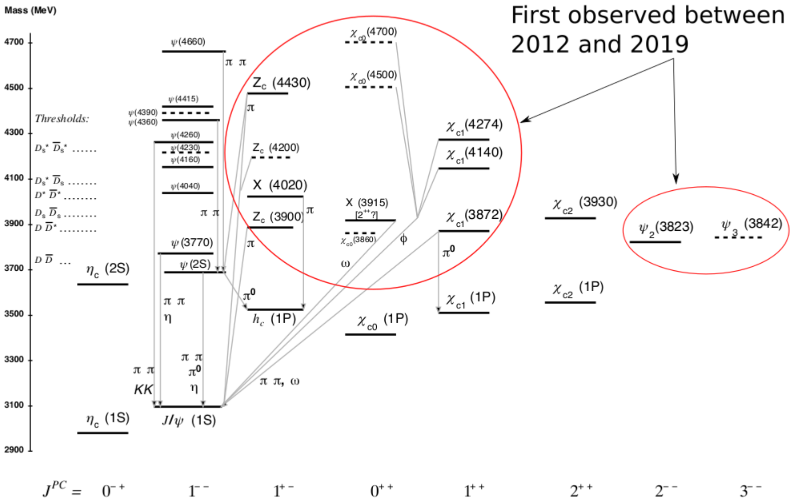
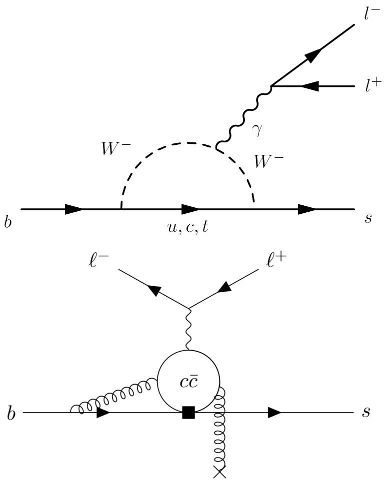
[1] arXiv:2206.15233
[2] arXiv:1404.1903
[3] arXiv:1006.4945

Charm exotics



[1]PhysRevD.98.030001

Charm loops



- $b \to s\ell^+\ell^-$ transitions are important examples of highly supressed FCNC processes.
  - For example, $B^0 \to K_0^* \mu^+\mu^-$ considered a 'golden mode'(rigourous test of SM predictions)
- These can be described by an effective field theory: $\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} \mathcal{C}_i \mathcal{O}_i$
- Charm loops contribute to $b \to s\ell^+\ell^-$
  - Mimic q^2 dependent contribution to $\mathcal{C}_9$ (γ coupling to $\ell^+\ell^-$)
  - Non-factorisable $\to$ non-perturbative effects $\to$ theoretical uncertainties at high q^2

An input to these contributions

- The matrix element describing non-local charm contributions can be expressed as:

$$\mathcal{M} = \mathcal{H}(0) + q^2 \left[\sum_{J/\psi,\psi(2S),\ldots} (BW) + \int_{4m_D^2}^{\infty} \frac{\rho(s)}{s(s-q^2-i\epsilon)}\, ds \right]$$

  - 1^{st} term is the isolated loop, 2^{nd} term is sum of resonant states, final term is broad charm resonances & continuum states (dispersion relation)
- In the final term, the spectral density ($\rho(s)$) is unconstrained.
- Direct measurement of charm resonances in $b \to sc\bar{c}$ can put constraints on $\rho(s)$ e.g. through amplitude analysis of $B^0 \to D^0 \bar{D}^0 K\pi$

Analysis Strategy Overview

- $B^0 \to D^{*-} D^0 K^+$ utilised as a control mode (like in branching fraction measurement).
- For signal mode, D^0 candidates are reconstructed from either $K^+\pi^-$ or $K^+\pi^-\pi^-\pi^+$ (excluding cases where both D^0 mesons decay into $K^+\pi^-\pi^-\pi^+$).
  - K^+ and π^- candidates from K^{*0} meson, with $m(K^{*0}) < 1600 \mathrm{MeV}$
- Kinematic refit performed with DecayTreeFitter.
- Neural Network utilised to reduce combinatorial background.
- Use Run I (11-12) and Run II samples (16-18)
  - $K\pi$ MC - 11196099, 11196011
  - $K3\pi$ MC - 11198099, 11198012 (redecay, no 2011 sample)

Stripping and Trigger Selections

- Stripping 21r1, 21, 28r2, 29r2, 34 (`BHADRON` stream):
  - Both D^0 mesons decay to $K\pi$: `B02D0D0KstD02HHD02HHBeauty2CharmLine`
  - One D^0 meson decays to $K3\pi$: `B02D0D0KstD02HHD02K3PiBeauty2CharmLine`
- Triggers:
  - L0:
    - TOS: `L0HadronDecision TOS`(K_{D^0}) & `L0HadronDecision TOS`(π_{D^0}) & `L0HadronDecision TOS`$(K_{\bar{D}^0})$ & `L0HadronDecision TOS`$(\pi_{\bar{D}^0})$ & `L0HadronDecision TOS`$(K_{K^{*0}})$
    - TIS: (`L0HadronDecision TIS`(B^0) || `L0MuonDecision TIS`(B^0)) & !`L0HadronDecision TOS`(B^0)
  - HLT1:
    - Run I: `Hlt1TrackAllL0Decision TOS`(B^0)
    - RunII: `Hlt1TrackMVADecision TOS`(B^0) & `Hlt1TwoTrackMVADecision TOS`(B^0)
  - HLT2:
    - Run I: `Hlt2Topo{2,3,4}BodyBBDTDecision TOS`(B^0)
    - Run II: `Hlt2Topo{2,3,4}BodyDecision TOS`(B^0)

Preselections

	Offline Selection cuts
Offline cuts carried over from BF analysis	B0_OnlyD_M & B0_BandDs_M > 0 Kst0_M < 1600 B0_D0_decayLength/B0_D0_decayLengthErr > 0 B0_D0bar_decayLength/B0_D0bar_decayLengthErr > 0 $\|\|$D0_M$-m_{PDG}(D^0)\|\| < 30$ $\|\|$D0bar_M$-m_{PDG}(D^0)\|\| < 30$
Tighter cuts for combinatorial background	Pi_Kst0_PIDK < 10 K_Kst0_PIDK $>$ -10 B0_ENDVERTEX_Z $<$ D0_ENDVERTEX_Z B0_ENDVERTEX_Z $<$ D0bar_ENDVERTEX_Z K_Kst0_ProbNNK > 0.2 K_D0_ProbNNK > 0.2 K_D0bar_ProbNNK > 0.2

- Signal and control mode separated by selection (based on fitted D^{*-} reconstructed mass peak width):
$|m(D^0_{fromD^*}\pi^-) - m(D^0_{fromD^*}) - [m_{PDG}(D^{*-}) - m_{PDG}(D^0)]| < (4 \times 0.724) MeV/c^2$

Kinematic refit

- DecayTreeFitter used to improve the B^0 mass resolution
  - Constrains the B^0 meson to originate from the associated PV (denoted `DTF`)
  - Constrains D^0 candidates to the nominal D^0 mass
  - Both constraints applied simultaneously (denoted `OnlyD`)
  - Additional constraint on B^0 mass applied (denoted `BandDs`)
- Fits required to have converged

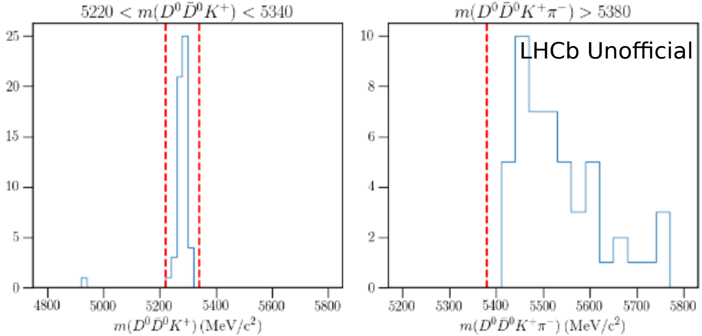
MC Preselections/Corrections

- MC samples Truth matched using selections on `TRUE_ID` and `TRUE_MOTHER_ID` variables
- PID variable transformation performed using PIDCorr from PIDGen package
  - Unbinned correction, function of P_T, η and `nTracks`, correlations preserved.
- 2D reweighting of MC performed to match sWeighted control mode data
  - MC reweighted in $nTracks$ and $B^0_{IP\chi^2_{OWNPV}}$

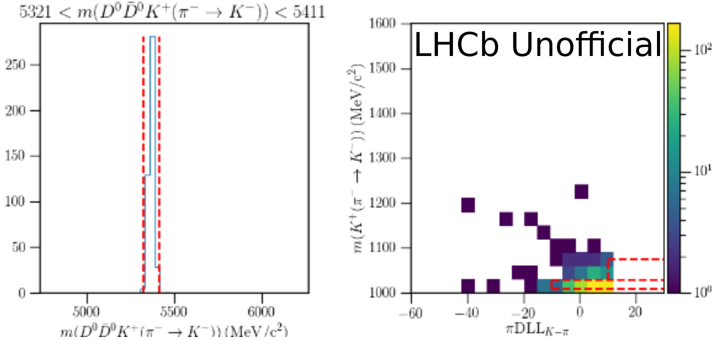
Preselections for peaking backgrounds

- Backgrounds from $B^+ \to D^0\bar{D}^0K^+$ removed with the veto: $(5220 < m(D^0\bar{D}^0K^+) < 5340)$ & $m(D^0\bar{D}^0K\pi) > 5380$ (99.99 % eff.)
- Backgrounds from $B^+ \to D^0\bar{D}^{*0}K^+$ removed with the veto: $(5050 < m(D^0\bar{D}^0K^+) < 5200)$ (92.73 % eff.)
- Background from $B_s^0 \to D^0\bar{D}^0\phi$ removed with the vetoes: $(5321 < m(D^0\bar{D}^0K^+(\pi^- \to K^-)) < 5411)$ and either $(1010 < m(K^+(\pi^- \to K^-)) < 1030)\&(\pi DLL_{K\pi} > -10)$ or $(1030 < m(K^+(\pi^- \to K^-)) < 1075)\&(\pi DLL_{K\pi} > 10)$ (99.97 % eff.)
- Background from $\Lambda_b^0 \to D^0\bar{D}^0pK$ removed with the vetoes: $(5575 < m(D^0\bar{D}^0K(\pi \to p)) < 5665)\&\pi DLL_{p\pi} > 0$ and $(5575 < m(D^0\bar{D}^0(\pi \to K)(K \to p)) < 5665)\&\pi DLL_{K\pi} > 0$ (99.7 % eff.)

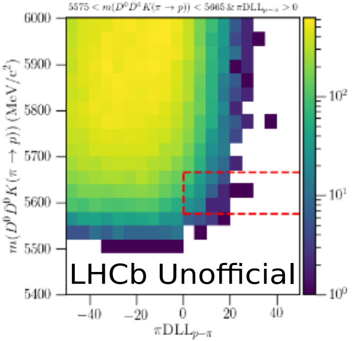
Veto region to remove background from $B^+ \to D^0 \bar{D}^0 K^+$ (background MC)

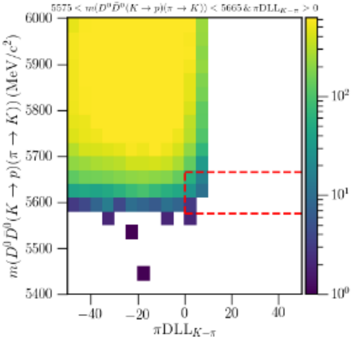


Veto region to remove background from $B_s^0 \to D^0 \bar{D}^0 \phi$ (swapped-mass hypothesis MC)



Veto region to remove background from $\Lambda_b^0 \to D^0 \bar{D}^0 pK$ (swapped-mass hypothesis MC)





Neural network classifier

- Use fully connected feed-forward neural network to further reduce combinatorial background (trained per tis/tos, D^0 decay and run period, different hyperparams)
- NN classifier trained in two stages, with the first feeding into the second:
  - 1. D_{fromB} selects D^0 candidates originating from the B^0 meson
  - 2. $B_{selection}$ selects B^0 candidates
- D_{fromB} uses kinematic and topological variables related to D^0 candidates and their child particles ($K\pi$ or $K3\pi$)
  - $D \to K3\pi$ modes use additional variables for each extra pion
  - Signal sample from MC
  - Background sample from data in D^0 mass sidebands (in signal region for B^0 and $\bar{D}^0$)
- $B_{selection}$ uses kinematic and topological variables independent of $m(K\pi)$, as well as the results from the D_{fromB} classifier
  - Signal sample from MC
  - Background sample from data in the B^0 mass sidebands, no cuts on D meson masses

Mass fits

- Signal fitted with DSCB function, background with exponential
  - DSCB tail parameters fixed to MC fit
  - Background parameters floated
  - Control mode Gaussian mean and sigma floated
  - Signal mode Gaussian mean and sigma fixed to value derived from fits to control mode and MC:

$$\mu_{sig}^{Data} = \mu_{sig}^{MC} + (\mu_{ref}^{Data} - \mu_{ref}^{MC}) + (\mu_{sig}^{MC} - \mu_{ref}^{MC})$$

$$\sigma_{sig}^{Data} = \sigma_{ref}^{Data} \times \frac{\sigma_{sig}^{MC}}{\sigma_{ref}^{MC}}$$

- Seperate fits for Run I and each year in Run II, as well as TIS TOS categories and D^0 decay modes

Background PDF NN - procedure (arXiv:1902.01452v2)

- An ANN estimates the background density as a function of the B^0 mass and five invariant mass projections.
- Heavily regularised in B^0 mass - continuity as a function of m_{B^0}.
- Trained on data in upper mass sideband, extrapolates into signal region.
- Accept/reject of a uniform sample covering the full B^0 mass range used to generate the background distribution under the signal peak.
- A GBReweighter is then trained to weight the normalisation MC to look like generated background.
- Procedure implemented in Search for CP violation in $\Xi_b^- \to pK^-K^-$ decays. - Tim Gershon, Thomas Latham, Anton Poluektov, Abhijit Mathad.

Model builder methodology - arXiv:1505.05133v2

- Start with baseline model - Add resonances one at a time, evaluate likelihood ratio, then decide whether to keep it or not based on comparison with previous models.
- We modify the likelihood using LASSO when considering what resonances to keep:

$$-2log\mathcal{L} + \lambda(\sum \sqrt{FitFraction})$$

- Here λ is determined using the data sample, by minimising either the Akaike or Bayesian information criteria:

$$AIC(\lambda) = -2log\mathcal{L} + 2r, BIC(\lambda) = -2log\mathcal{L} + r \log n.$$

- $-2log\mathcal{L}$ is from minimising the modified -2LL for a set of models evaluated with a given λ value.