$B^0 \to DDX$ for flavour anomalies at LHCb

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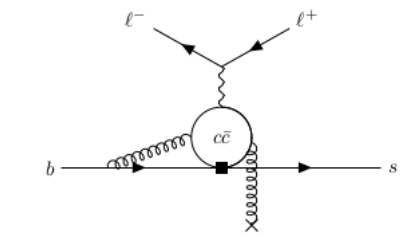
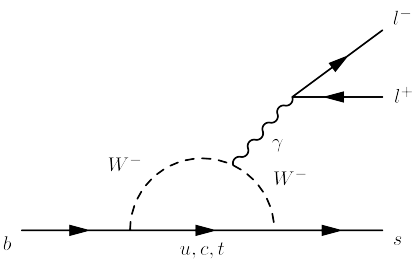
Testing for flavour anomilies with $B^0 \to DDX$





- $D\bar{D}$ systems perfect for studying states above open-charm threshold ($s > 4m_D^2$)
  - 8+ new exotic charm states discovered since 2019
- $b \to sc\bar{c}$ transitions great for studying charm loops
  - Affects FCNCs such as $b \to s\ell^+\ell^-$ (excellent probes of NP)
  - Charm-loops impact discrepancies between measured Wilson coefficeints and the SM.
  - Effects difficult to predict above open charm threshold
- LHCb designed to study c and b decays $\to$ perfect for investigating these flavour anomalies

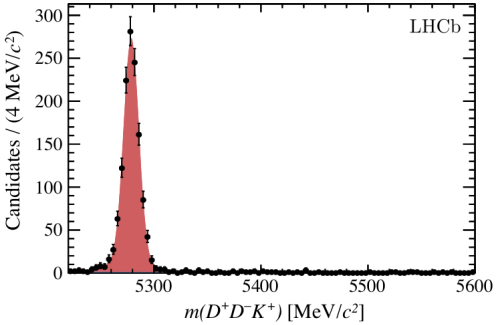
Recent results

Outline

- Amplitude analysis of $B^+ \to D^+ D^- K^+$: Phys. Rev. D 102, 112003 (2020) & Phys. Rev. Lett. 125, 242001 (2020)
- Observation of new excited D_s^+ meson in $B^0 \to D^+ D^- K^+ \pi^-$: Phys. Rev. Lett. 126, 122002 (2021)
- Observation and branching fraction measurement of $B^0 \to D^0 \bar{D}^0 K^+ \pi^-$: Phys. Rev. D 102, 051102 (2020)
- Amplitude analysis of $B^0 \to D^0 \bar{D}^0 K^+ \pi^-$ (in progress)

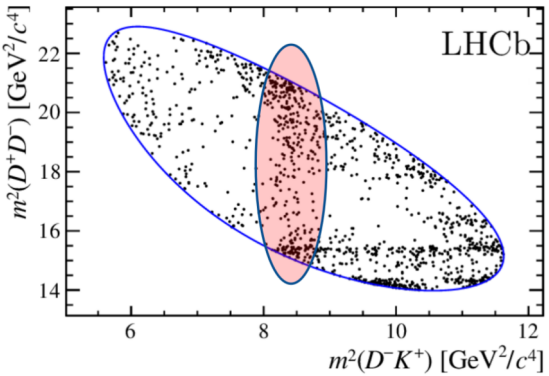
$B^+ \to D^+D^-K^+$: PRD 102, 112003 (2020) & PRL 125, 242001 (2020)

Fitted invariant mass distribution for B candidates



- Amplitude analysis of the $B^+ \to D^+D^-K^+$ decay
- Initially motivated by a search for $D\bar{D}$ resonances and explore $c\bar{s}(c\bar{c})$ structure in $DK(D\bar{D})$ system
- 1260 signal candidates over both LHCb runs ($9fb^{-1}$)
- Purity $> 99.5\%$ in signal region
- Backgrounds removed with vetos & BDT
- Different kinematic refits for mass fits and Dalitz variables

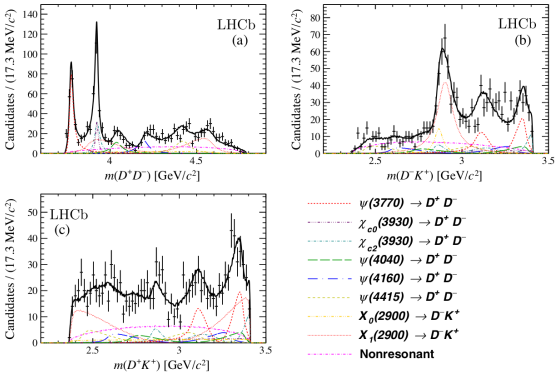
$B^+ \to D^+D^-K^+$: PRD 102, 112003 (2020) & PRL 125, 242001 (2020)



- Surprising structure in D^-K^+ spectrum
- Resonances in D^-K^+ channel must have minimal $\bar{c}d\bar{s}u$ quark content $\to$ exotic.
  - First open-charm tetraquark!

$B^+ \to D^+D^-K^+$: PRD 102, 112003 (2020) & PRL 125, 242001 (2020)

1-D invariant mass projections

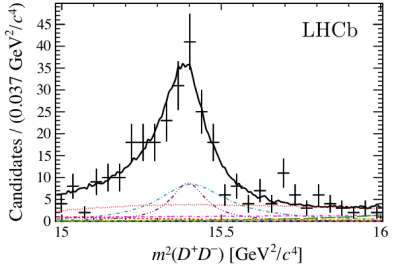


Amplitude model requires new resonances in D^-K^+ channel:

$X_0(2900)$:
$M = 2.866 \pm 0.007 \pm 0.002 GeV/c^2$
$\Gamma = 57 \pm 12 \pm 4 MeV$

$X_1(2900)$:
$M = 2.904 \pm 0.005 \pm 0.001 GeV/c^2$
$\Gamma = 110 \pm 11 \pm 4 MeV$

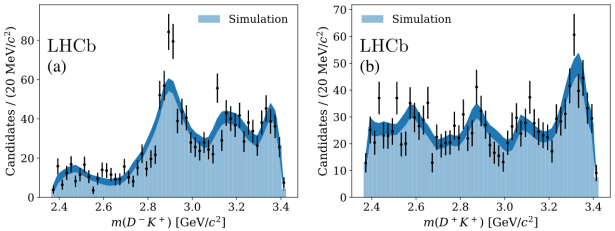
$B^+ \to D^+D^-K^+$: PRD 102, 112003 (2020) & PRL 125, 242001 (2020)



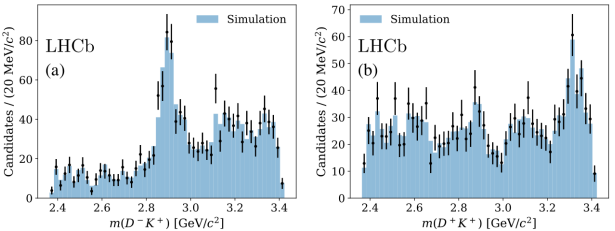
- New spin-0 charm resonance ($\chi_{c0}(3930)$) found in D^+D^- channel, close to $\chi_{c2}(3930)$ state
  - $m = 3.9238 \pm 0.0015 \pm 0.0004 GeV/c^2$
  - $\Gamma = 17.4 \pm 5.1 \pm 0.8 MeV$
  - Consistent with $X(3915)$ state discovered by Belle: JHEP 07 (2019) 035
- $\chi_{c0}(3930)$ narrower than $\chi_{c2}(3930)$, unexpected as decay is S-wave, compared to D-wave decay of $\chi_{c2}(3930)$
- 2-component same-spin models produce unstable fits, so are not included

$B^+ \to D^+D^-K^+$: PRD 102, 112003 (2020) & PRL 125, 242001 (2020)

$J = 2$



$J = 15$



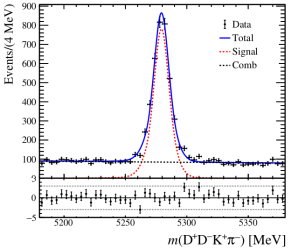
- Results confirmed in model-independent analysis
  - No exotics $\to DK$ structures fully described by D^+D^- resonances up to $J = 2$
- This is not the case, so results cannot be described by $m(D^+D^-)$ resonance reflections $\to$ exotic

$B^0 \to D^+D^-K^+\pi^-$: PRL 126, 122002 (2021)

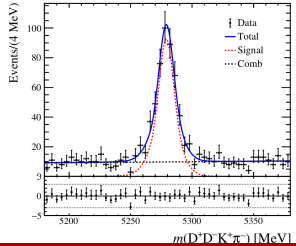
- Amplitude analysis of $B^0 \to D^+D^-K^+\pi^-$ decay in $m(K^+\pi^-) < 0.75 GeV$ region
- Aim is to search for D_s^+ resonances in $D^+K^+\pi^-$ system
  - Previously only seen in DK pairs
- Lays groundwork for amplitude analysis of full phasespace (PHSP)
  - To provide input to $b \to s\ell^+\ell^-$
- 444 ± 27 signal candidates in LHCb Run II data ($5.4 fb^{-1}$)
  - 3420 ± 72 candidates in full PHSP

$B^0 \to D^+D^-K^+\pi^-$: PRL 126, 122002 (2021)

Full PHSP

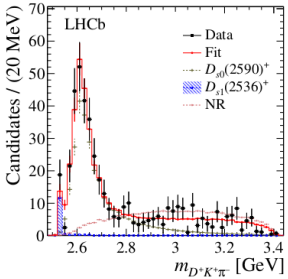


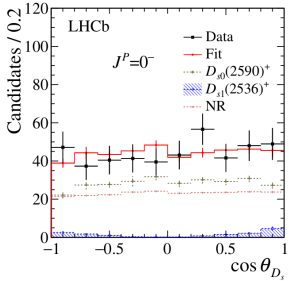
Low $m(K^+\pi^-)$ region



- Only significant background is combinatoric (post-selections)
  - Most backgrounds Cabibbo-supressed or have low BFs
  - Combinatorial subtracted using *sPlot* technique
- Simultaneous unbinned Maximum likelihood fit performed (in low $m(K^+\pi^-)$ region) on 5-D function of $m_{DK\pi}, m_{K\pi}, cos(\theta_{D_s^+}), cos(\theta_{K^*}), \phi_\pi$

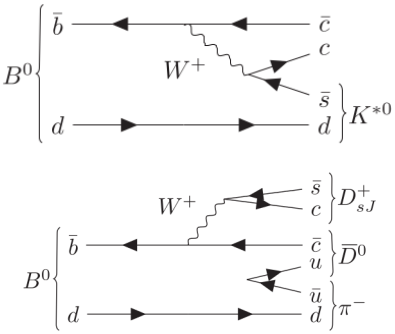
$B^0 \to D^+ D^- K^+ \pi^-$: PRL 126, 122002 (2021)





- New D_s^+ resonance ($D_{s0}(2590)^+$) found in $D^+K^+\pi^-$ system (models without resonance rejected at 10σ level)
- Spin parity determined to be $J^P = 0^-$
  - $m = 2591 \pm 6 \pm 7 MeV/c^2$
  - $\Gamma = 89 \pm 16 \pm 12 MeV$
- Strong candidate for missing $D(2^1s_0)^+$ state
- More data would help confirm this is indeed $D(2^1s_0)^+$, and to more precisely measure width
- Scope to extend these studies to full decay phasespace, providing further results (e.g. D^+D^- resonances)

$B^0 \to D^0 \bar{D}^0 K^+ \pi^-$: PRD 102, 051102 (2020)

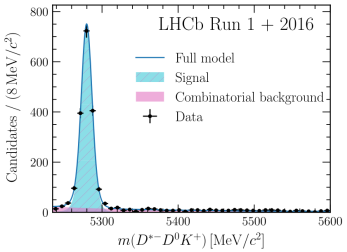


- First observation and branching fraction measurement of this transition
- First step in study of resonant structure
- Excellent candidate for exotic state searches and charm loop studies
- 297 ± 14 signal, 1697 ± 42 control mode decays from LHCb Run I + 2016 data ($4.6 fb^{-1}$)

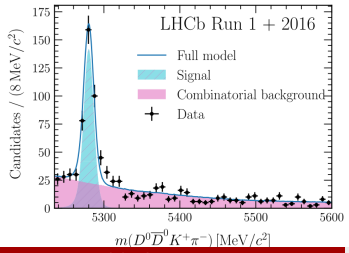
$$\mathcal{R} = \frac{\mathcal{N}(B^0 \to D^0 \bar{D}^0 K^+ \pi^-)}{\mathcal{N}(B^0 \to D^{*-} D^0 K^+)} \times \mathcal{B}(D^{*-} \to D^0 \pi^-) \times \frac{\epsilon^{cont}}{\epsilon^{sig}}$$

$B^0 \to D^0 \bar{D}^0 K^+ \pi^-$: PRD 102, 051102 (2020)

Control mode



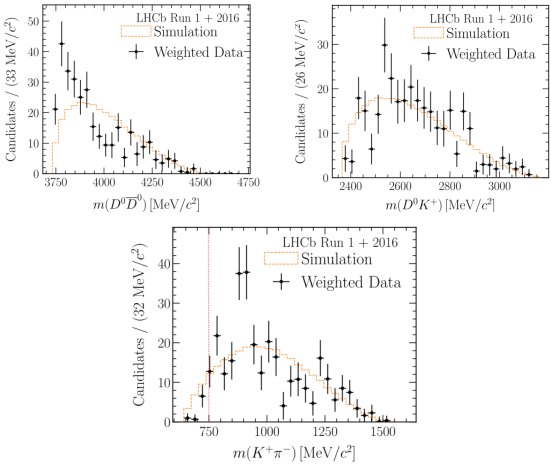
Signal mode



- Backgrounds removed with cuts and veto regions (determined from simulation) + Neural Network (MLP) for combinatorial
- Kinematic refit performed
- Simultaneous unbinned maximum likelihood fit to $m(B^0)$ (across control and signal modes)

$B^0 \to D^0\bar{D}^0K^+\pi^-$: PRD 102, 051102 (2020)

Background-subtracted projections & PHSP MC



- $\mathcal{B}(B^0 \to D^0\bar{D}^0K^+\pi^-) = (3.50 \pm 0.27 \pm 0.26 \pm 0.30)x10^{-4}$
- Hints of resonant structures in $m(D^0\bar{D}^0)$, $m(D^0K^+)$ and $m(K^+\pi^-)$ invariant mass distributions. (could be reflections $\to$ further investigation)
- More events beneficial. Prone to backgrounds. Analytical solutions to 4-body equations are difficult e.g. efficiency modelling.

$B^0 \to D^0 \bar{D}^0 K^+ \pi^-$ amplitude analysis (in progress)

- Follows from $B^0 \to D^0 \bar{D}^0 K^+ \pi^-$ branching fraction measurement
  - Similar selection strategy, extended to include full LHCb dataset ($9 fb^{-1}$) and $D \to K\pi\pi\pi$ sub-decays
- Motivated by search for exotic states and study of charm loops
  - Charmonium contributions in transversity basis $\to$ helicity states separated $\to$ applicable to $b \to s\ell^+\ell^-$
  - Full $K^+\pi^-$ PHSP $\to$ separate S-wave from P-wave states
- Expect a 5-fold increase in signal candidates (roughly 1600)

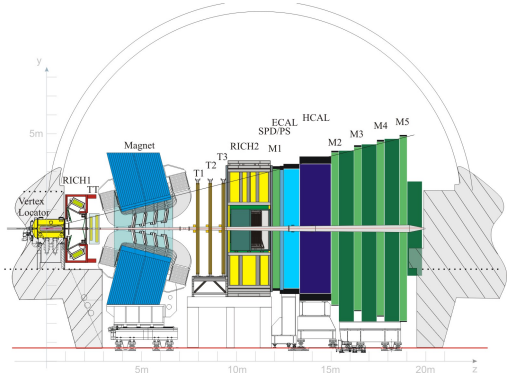
Summary

- $B \to DDX$ decays promising for exotic state searches and charm loop studies (input to $b \to s\ell^+\ell^-$)
- Amplitude analysis of $B^+ \to D^+D^-K^+$ shows resonances in D^-K^+ channel ($X_0(2900)$, $X_1(2900)$) at beyond 5σ level
  - First open-charm tetraquark (previously only $\bar{c}c\bar{q}q'$ seen)
  - New(?) spin-0 charm resonance ($\chi_{c0}(3930)$) also found in D^+D^- channel
- Excited D_s^+ meson ($D_{s0}(2590)^+$) found in $B^0 \to D^-D^+K^+\pi^-$ at $> 10\sigma$ level
- $B^0 \to D^0\bar{D}^0K^+\pi^-$ branching fraction measured, amplitude analysis underway
- More efficient trigger algorithms in LHCb Upgrade I and large integrated luminosity in LHCb Upgrade II will benefit these types of analyses

Thank you for listening

Backup

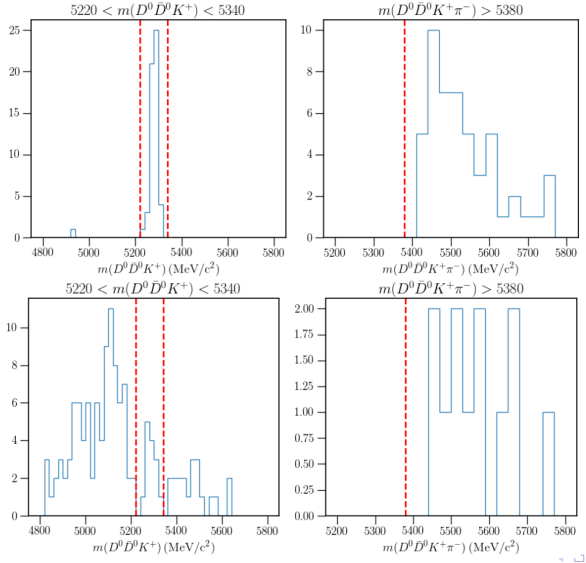
The LHCb Detector



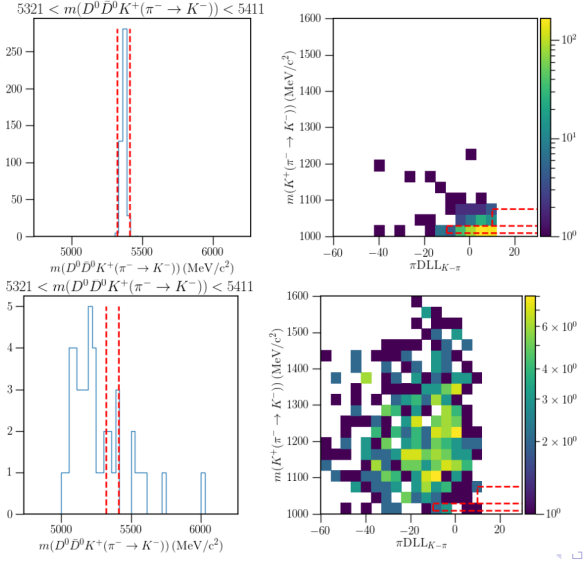
Int. J. Mod. Phys A 30, 1530022 (2015)

- Designed for heavy flavour physics at the LHC
- Single-arm forward spectrometer covering pseudorapidity region $2 < \eta < 5$

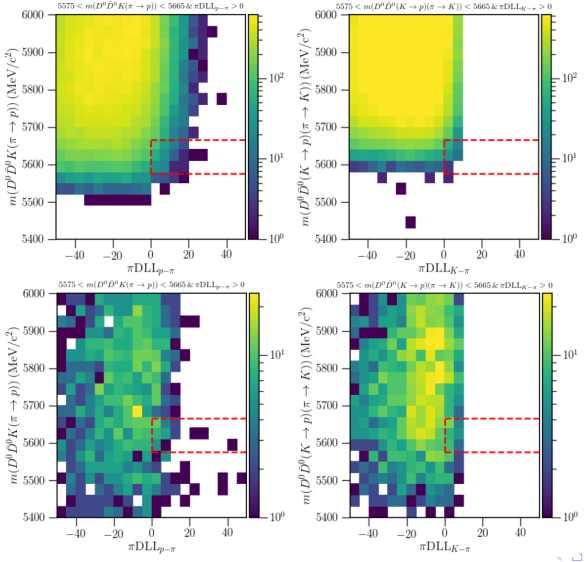
$B^0 \to D^0 \bar{D}^0 K^+ \pi^-$ veto regions 1



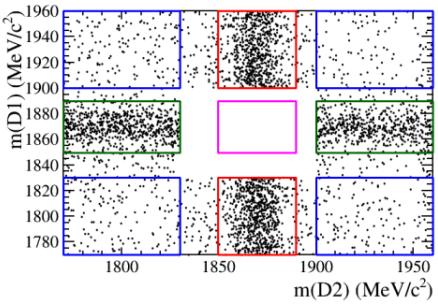
$B^0 \to D^0 \bar{D}^0 K^+ \pi^-$ veto regions 2



$B^0 \to D^0 \bar{D}^0 K^+ \pi^-$ veto regions 3



$B^+ \to D^+D^-K^+$ methods: PRD 102, 112003 (2020)

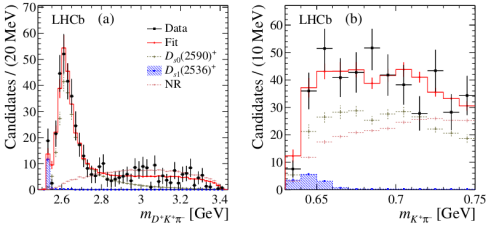


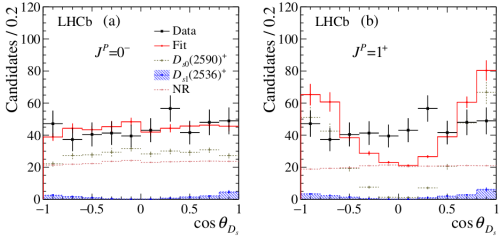
Magenta box $\to$ signal region
Other boxes are charmless or single-charm backgrounds

- BDT used to reduce combinatorial background
- Other backgrounds removed with invariant mass veto regions and flight distance + vertex cuts (plot in D sidebands)
- Two kinematic refits performed:
  - D mass constraint and B from primary vertex (used for mass fits)
  - The above + B mass constraint (used for Dalitz plot variables)
- Maximum likelyhood fit performed on invariant mass distributions

$B^0 \to D^+D^-K^+\pi^-$ full results: PRL 126, 122002 (2021)

Background subtracted, low $m(K^+\pi^-)$ region





Efficiency correction for $B^0 \to D^0 \bar{D}^0 K^+ \pi^-$ amplitude analysis

- In general, the signal PDF for 4-body decays can be expressed as[1]:

$$\mathcal{P}_{Sig}(x;\Theta) = \frac{\varepsilon_{Sig}(x)(|\mathcal{A}_{B^0}(x;\Theta)|^2 + |\mathcal{A}_{\bar{B}^0}(x;\Theta)|^2)\phi_4(x)}{\int \varepsilon_{Sig}(x)(|\mathcal{A}_{B^0}(x;\Theta)|^2 + |\mathcal{A}_{\bar{B}^0}(x;\Theta)|^2)\phi_4(x)dx^5} \quad (1)$$

- From this we can see the $log(\mathcal{L})$ has 2 efficiency terms, one appears as an additive constant, so can be ignored.
- The other efficiency term appears in the normalisation integral, which can be determined numerically with MC intergration of a simulated sample.
  - Allows for inclusion of the efficiency in the amplitude fit without requiring an analytical form.
  - Desirable as such functions are hard to parameterise in 4-body decays.

[1] PRD 85.122002 (2012), JHEP05 143 (2017)