First observation of the decay $B^0 \to D^0 \bar{D}^0 K^+ \pi^-$

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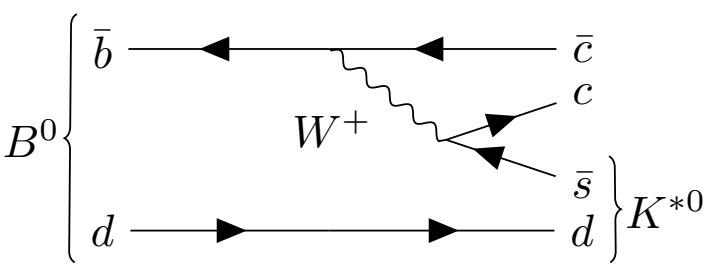
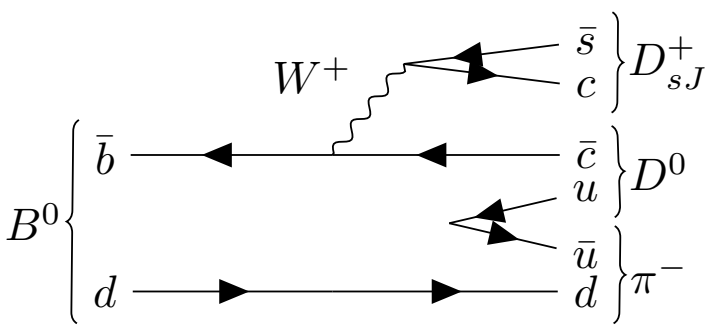
Introduction

- First observation and branching fraction measurement of $B^0 \to D^0 \overline{D}^0 K^+ \pi^-$ [LHCb-PAPER-2020-015 Preliminary]
  - Full kinematically allowed range, outside D^{*-} resonance
- Proceeds via CKM-favoured $b \to c\overline{c}s$ transition
- Opportunity to search for new $c\overline{s}$ or $c\overline{c}$ states, and measure structure of $D\overline{D}$ system
- Pre-cursor to amplitude analysis with full LHCb Run 1 + 2 data



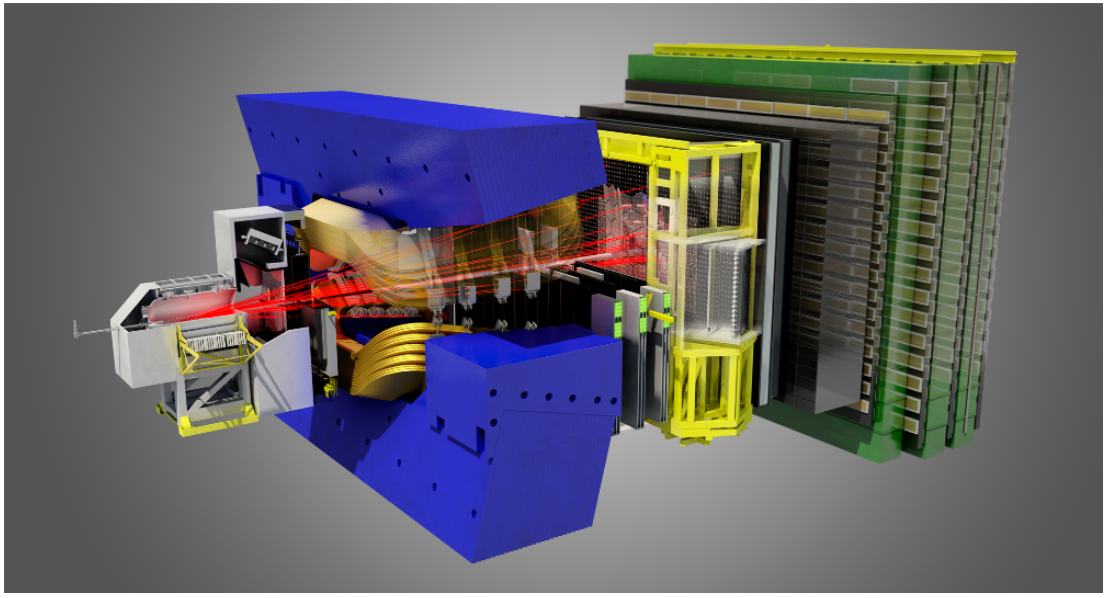


Experimental status

- Existing measurements of $B \to D^{(*)}\overline{D}^{(*)}K$ decays have been performed by the ALEPH, BaBar, Belle and LHCb collaborations [EPJ C 4 (1998) 387-407, BABAR-PUB-03/010, BABAR-PUB-10/018, PRL 97 (2006) 162002, PRL 100 (2008) 092001, LHCb-PAPER-2020-006]

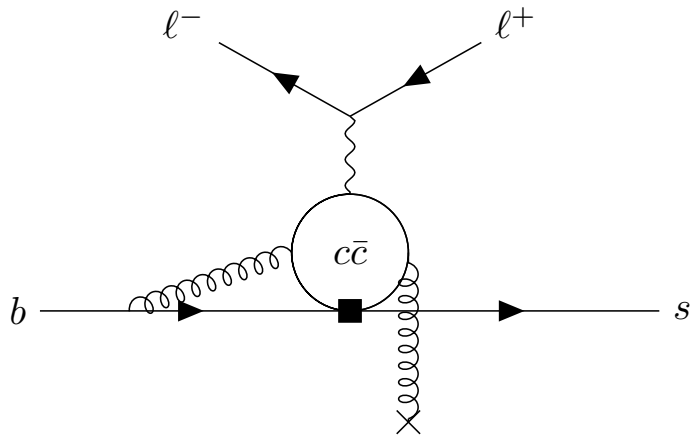
- Expect $B^0 \to D^0\overline{D}^0K^+\pi^-$ branching fraction to be $\mathcal{O}(10^{-4})$, and including $D^0 \to K\pi$ BF, $\mathcal{O}(10^{-7})$.

- First observation made possible with data from LHCb



Motivation: Charm Loops

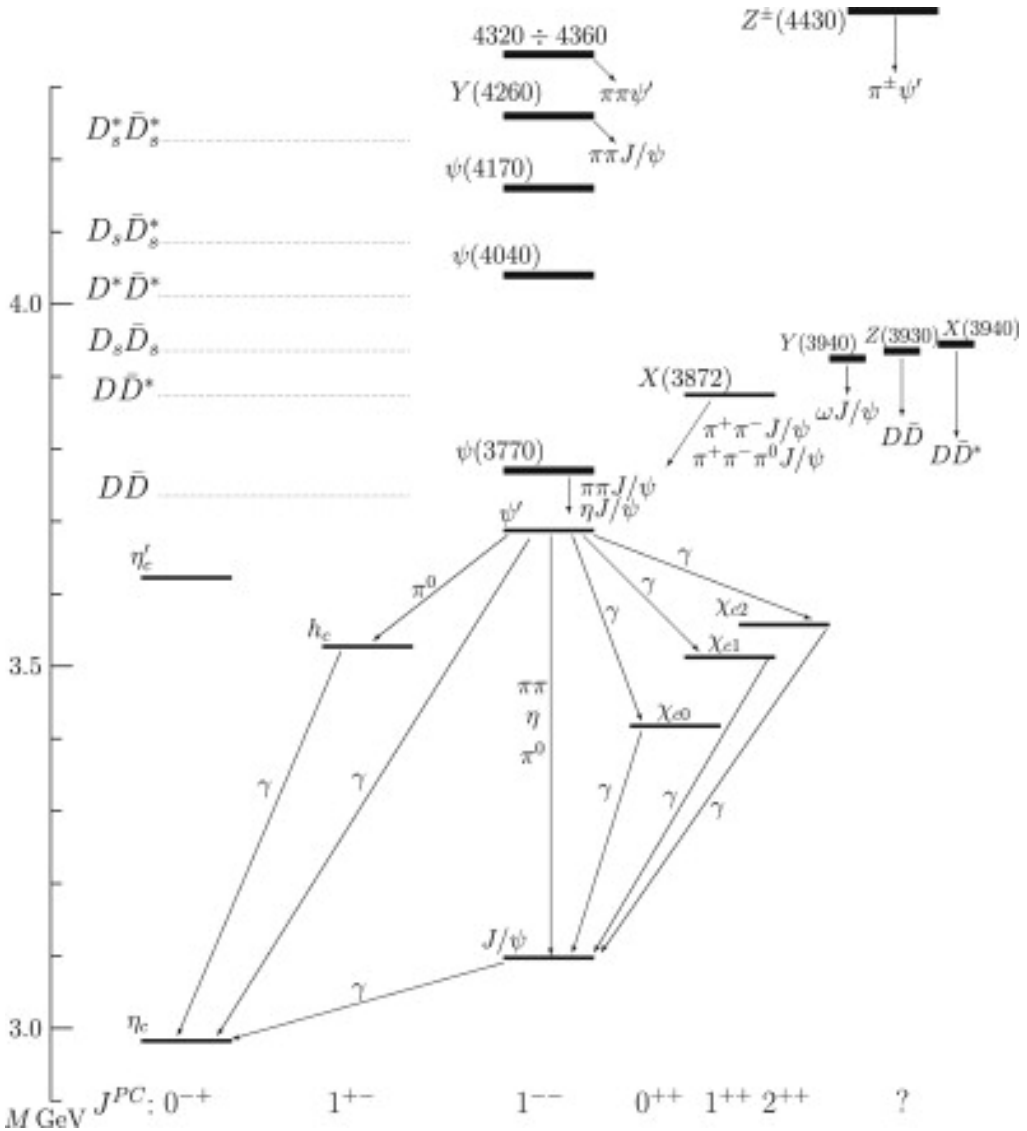
- $b \to s\ell^+\ell^-$ processes such as $B^0 \to K^{*0}\mu^+\mu^-$ are sensitive to New Physics



- Intermediate charm loop mimics a q^2-dependent contribution to the Wilson coefficient $\mathcal{C}_9$
- Spectral density $\rho(s)$ describes ψ-resonances and continuum $c\bar{c}$-states for $s > 4m_D^2$ [Khodjamirian et al.]
- $B^0 \to D^0\bar{D}^0K^{*0}$ is a start, to experimentally constrain $\rho(s)$

$$\mathcal{H}(q^2) = \mathcal{H}(0) + q^2\left[\underbrace{\sum_{J/\Psi,\Psi(2S),\ldots}(A_{res})}_{\text{Resonant states}} + \overbrace{\int_{4m_D^2}^{\infty}\frac{\rho(s)}{s(s-q^2-i\epsilon)}ds}^{\text{Density above threshold}}\right]$$

Motivation: Charmonium spectroscopy



- Look for non-conventional $q\bar{q}$ states above the charm threshold
- Searches for $\Psi(4260) \to D\bar{D}$ [PRD 80 (2009) 072001]
- $Z_c(4430)^-$ minimal $c\bar{c}d\bar{u}$ content [LHCb-PAPER-2014-014], look in $D^{*-}D$, or look for the isospin partner Z_c^0
- Look for higher $D^*(\to D\pi)$ or $D_s^*(\to DK^{(*)})$ states

Branching fraction ratio measurement

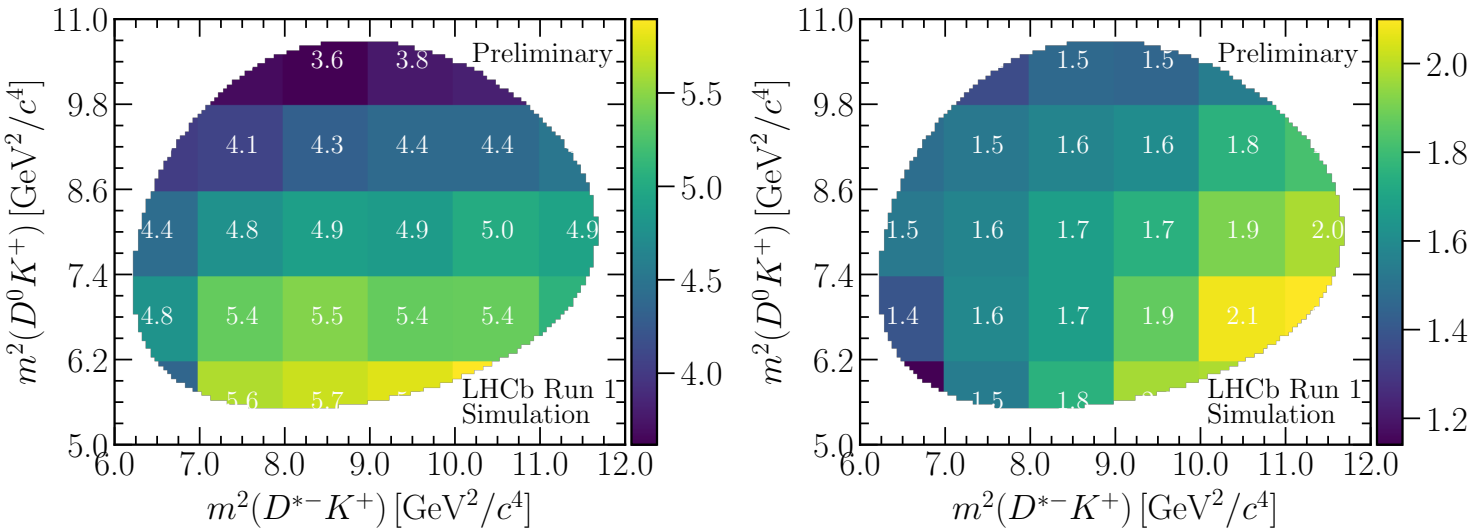
- Measure branching fraction of $B^0 \to D^0 \bar{D}^0 K^+ \pi^-$ with respect to control mode $B^0 \to D^{*-} D^0 K^+$
- Signal and control modes present the same final-state particles, $D^0 \bar{D}^0 K^+ \pi^-$, with control decay $B^0 \to D^{*-}(\to \bar{D}^0 \pi^-) D^0 K^+$
- $\mathcal{R} = \frac{\mathcal{B}(B^0 \to D^0 \bar{D}^0 K \pi)}{\mathcal{B}(B^0 \to D^{*-} D^0 K^+)}$
  - $\mathcal{B}(B^0 \to D^{*-} D^0 K^+) = (2.47 \pm 0.21) \times 10^{-3}$ [PRD 83 (2011) 032004] used in this analysis
  - New measurement by LHCb using ratio $\frac{\mathcal{B}(B^0 \to D^{*-} D^0 K^+)}{\mathcal{B}(B^0 \to D^- D^0 K^+)}$ [LHCb-PAPER-2020-006]
- $\mathcal{R} = \frac{\mathcal{N}(B^0 \to D^0 \bar{D}^0 K \pi)}{\mathcal{N}(B^0 \to D^{*-} D^0 K^+)} \times \mathcal{B}(D^{*-} \to D^0 \pi^-) \times \frac{\epsilon_{DP}^{\text{cont}}}{\epsilon^{\text{sig}}}$

Data sample

- Data from Run 1 (3.0fb^{-1}) and 2016 (1.6fb^{-1})
- Require the $\overline{D}^0\pi^-$ system to be well separated from the D^{*-} resonance for the signal mode, and the opposite requirement for the control mode
- Split into two exclusive categories
  - TOS: triggered by particles in the signal decay
  - TIS: triggered by other particles in the event
- Selections include
  - Loose particle identification (PID) cuts
  - Cut on flight distance of D^0 mesons to reduce charmless backgrounds
  - Neural network classifiers to reduce combinatorial backgrounds

Selection efficiencies

- Efficiencies extracted from simulation
- Dalitz-dependent efficiency correction in control mode, $\epsilon_{DP}^{\text{cont}}$



Efficiency variation in arbitrary units, Run 1 (left) TOS and (right) TIS. 2016 in Backup.

- Single global efficiency ϵ^{sig}, for signal mode
  - Consider systematic uncertainty using efficiency as a function of $(m_{D^0K^+}, m_{\bar{D}^0K^+}, m_{K^+\pi^-})$

Backgrounds

- Partially reconstructed backgrounds
  - $B^0 \to D^{(*)}\overline{D}^{(*)}K\pi$
  - Negligible in considered fit range $[5235, 5600]\,\mathrm{MeV}/c^2$
- Charmless backgrounds
  - Contamination in signal region of events with one or both D^0 mesons fulfilling $40 <\mid m(D) - m_{\mathrm{PDG}}(D) \mid < 100\mathrm{MeV}/c^2$
  - $\mathcal{O}(10)$ events subtracted from signal yield in fit
- Peaking backgrounds
  - $B^+ \to D^0\overline{D}^0K^+$, $B^+ \to D^0D^{*0}K^+$, $B_s^0 \to D^0\overline{D}^0\phi$ and $\overline{\Lambda}_b^0 \to D^0\overline{D}^0\overline{p}K^+$ found to be potentially significant
  - Vetoed with requirements on the three- or four-body invariant masses, and in some cases tighter PID selections

Fit to Data

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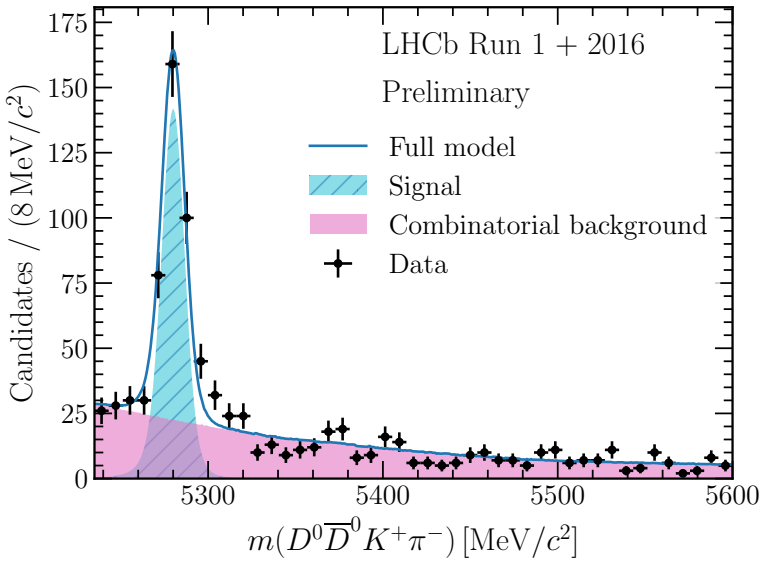
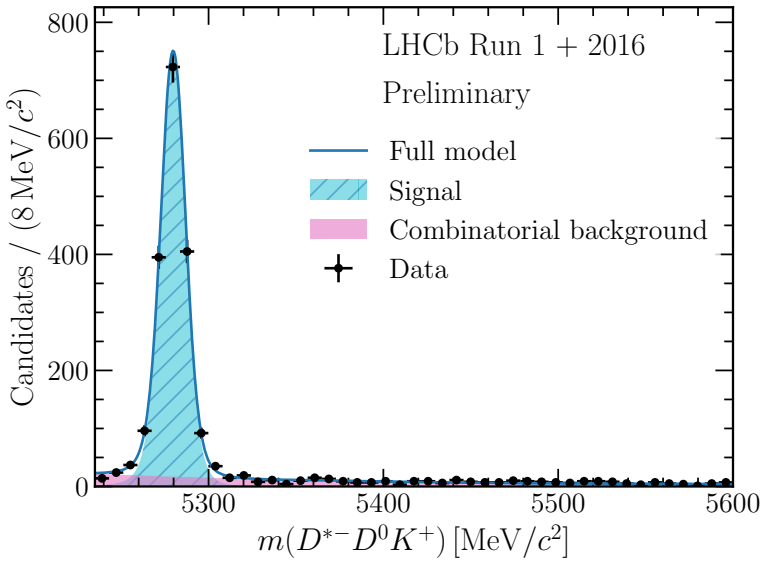


(a) $B^0 \to D^0\overline{D}^0K^+\pi^-$



(b) $B^0 \to D^{*-}D^0K^+$

- 297 ± 14 signal and 1697 ± 42 control mode candidates found
  - Simultaneous fit across run periods and trigger categories
  - Separate fits in Backup
- $\mathcal{R} = (14.2 \pm 1.1(\text{stat}) \pm 1.0(\text{syst}))\%$ (preliminary)
- Summary of systematic uncertainties in Backup

Branching Fraction Measurement

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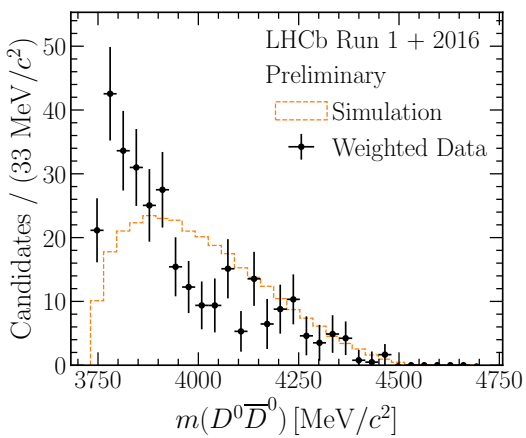
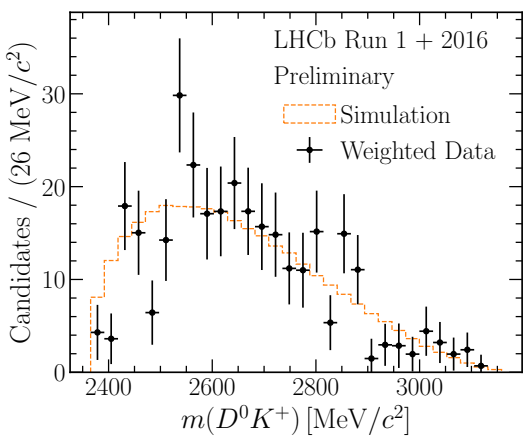
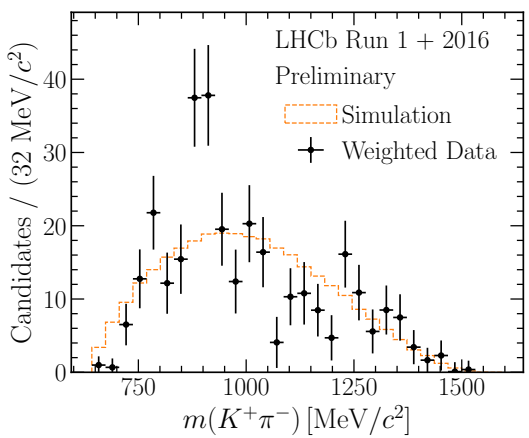
- $\mathcal{B}(B^0 \to D^0 \overline{D}^0 K^+ \pi^-) = (3.50 \pm 0.27 \pm 0.26 \pm 0.30(\mathcal{B})) \times 10^{-4}$ (preliminary)
  - Third uncertainty from control mode BF
- Hints of structures in $m(D^0 \overline{D}^0)$, $m(D^0 K^+)$ and $m(K^+ \pi^-)$
- Motivates further amplitude analysis







Projections of *s*Weighted[1] data (black points) with the phase-space only distribution (orange dashed line) superimposed for reference.

[1] [arXiv:1011.3929]

Conclusion

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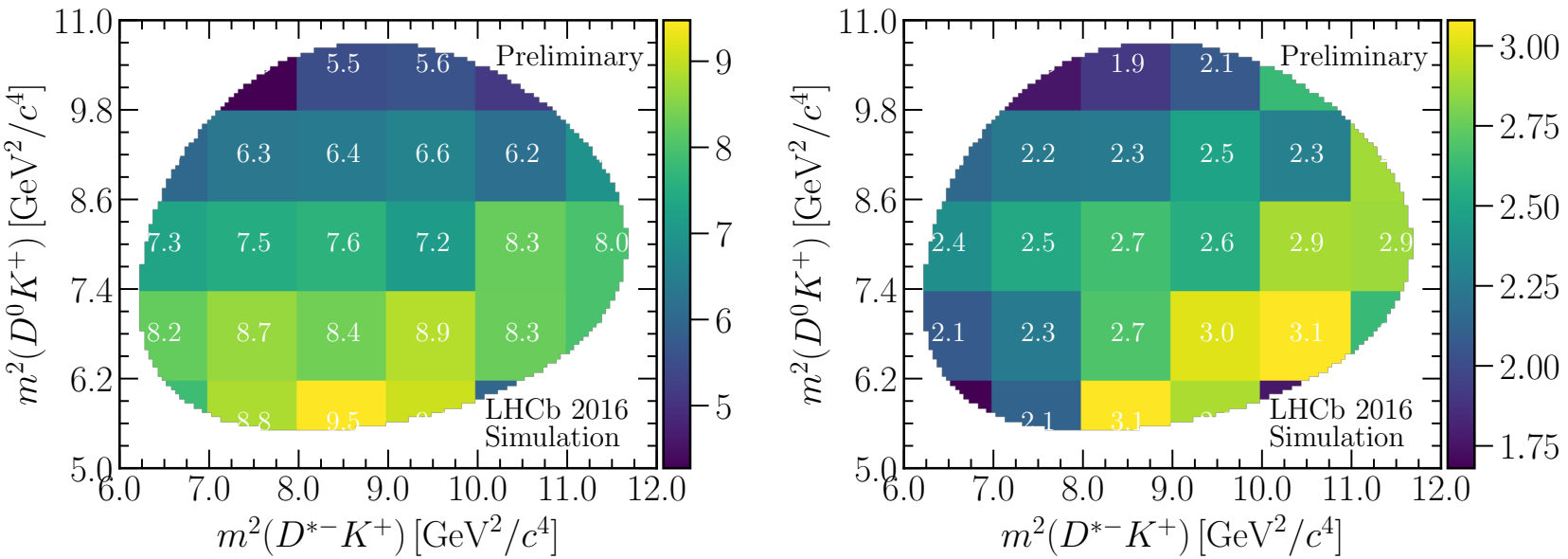
- First observation of $B^0 \to D^0 \overline{D}^0 K^+ \pi^-$
- Branching fraction measured with respect to known control mode $B^0 \to D^{*-} D^0 K^+$
- $\mathcal{B}(B^0 \to D^0 \overline{D}^0 K^+ \pi^-) = (3.50 \pm 0.27 \pm 0.26 \pm 0.30(\mathcal{B})) \times 10^{-4}$ (preliminary)
- Important implications for spectroscopy and charm loop contributions in $b \to s\ell^+\ell^-$ decays
- Next step is amplitude analysis with full Run 1 + 2

Thank you for your attention!

Backup

Selection efficiencies



Efficiency variation in arbitrary units, 2016 (left) TOS and (right) TIS.

Systematic uncertainties

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Systematic uncertainties expressed as a percentage of the branching fraction ratio $\mathcal{R}$. The statistical uncertainty is included for comparison.

Source	Uncertainty
Signal model	5.0
Background model	2.0
Fixed fit parameters	2.0
Simulation sample size	2.5
Simulation reweighting	2.0
PID reweighting	1.2
Charmless backgrounds	2.0
Classifier modelling	2.0
Selection efficiency	0.6
Sum in quadrature	7.3
Statistical	7.7

Fit Model

- Signal modelled by double-sided Crystal Ball function, background modelled by exponential function

$$N_S f_{\mathrm{DSCB}}(m) + N_B(\lambda e^{-\lambda m} c(m)),$$

- $c(m)$ represents a smooth empirical correction to account for shaping of the combinatorial by peaking background vetoes, derived from simulation

- Fit to control mode data separately for each category (run period and trigger)

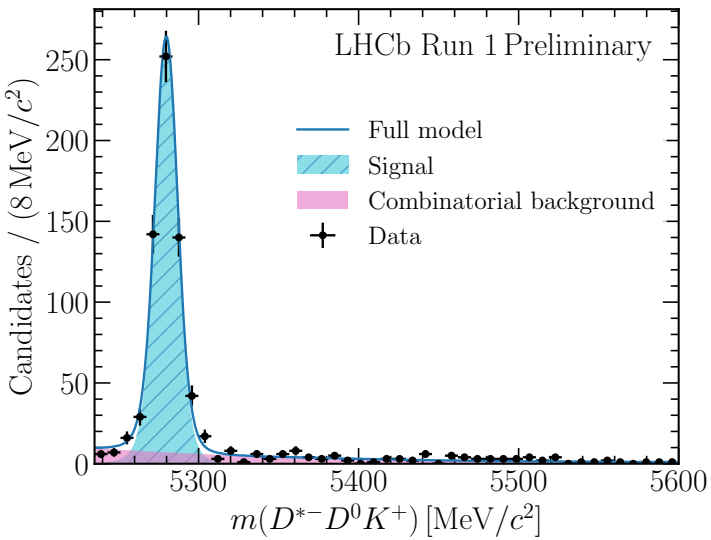
- Parameterise signal yield in terms of branching ratio as

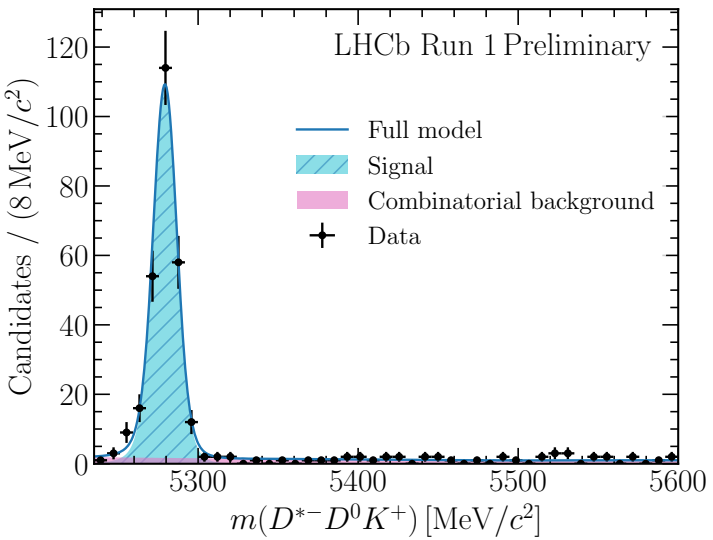
$$\mathcal{N}_S^{\mathrm{sig},i} = \mathcal{R} \times \frac{\mathcal{N}_S^{\mathrm{cont},i}}{\mathcal{B}(D^{*-} \to D^0 \pi^-)} \times \frac{\epsilon^{\mathrm{sig},i}}{\epsilon_{DP}^{\mathrm{cont},i}}$$

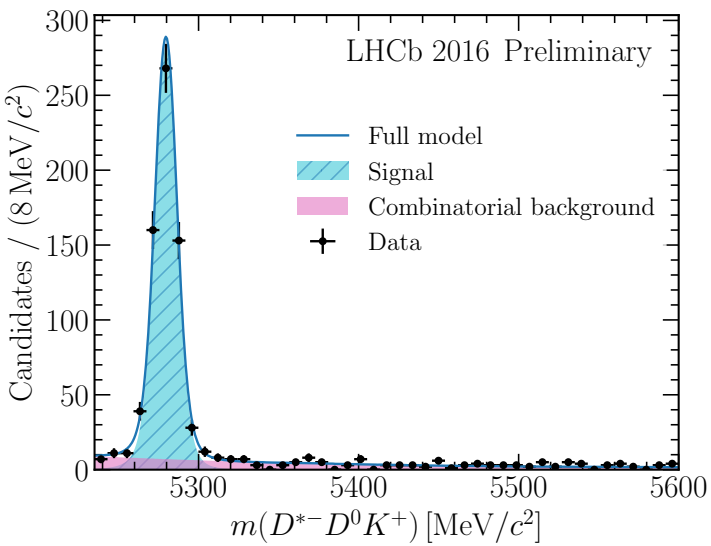
and fit for $\mathcal{R}$ simultaneously across categories of signal mode

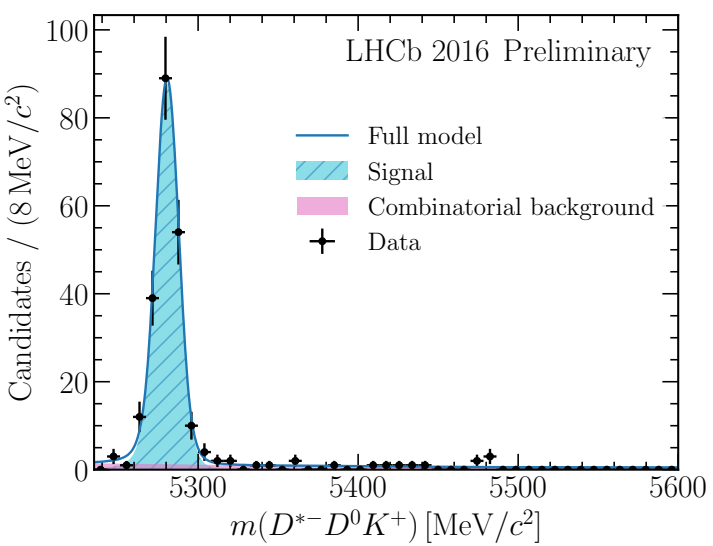
Fits to Data

Control mode $B^0 \to D^{*-} D^0 K^+$



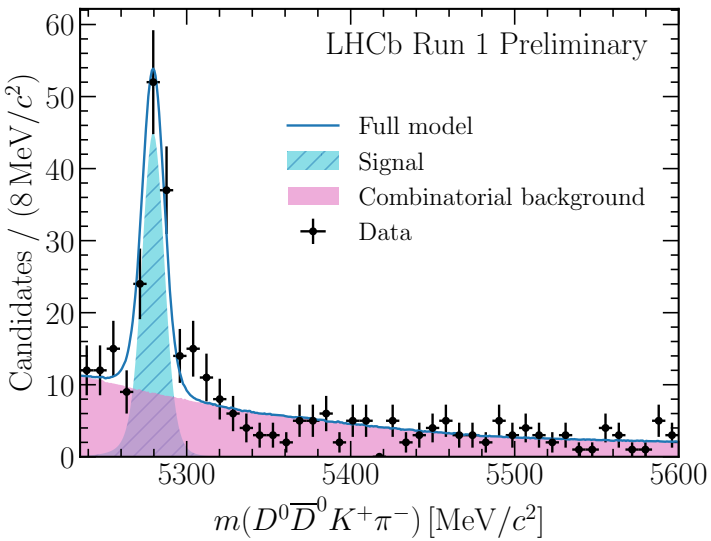


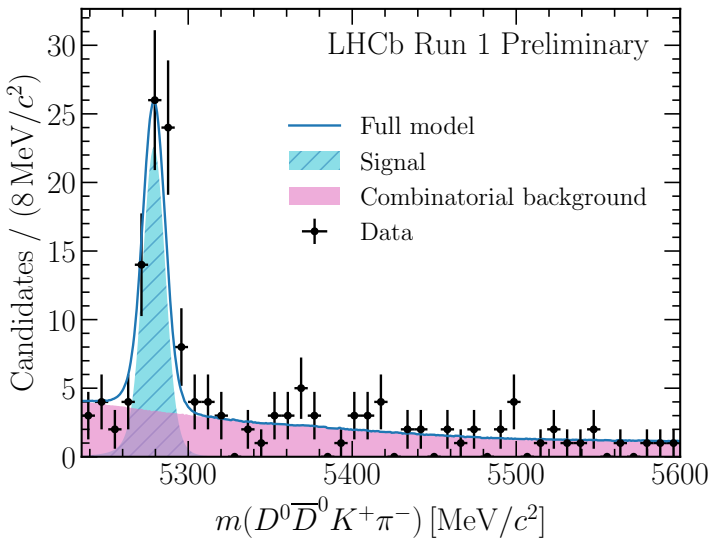


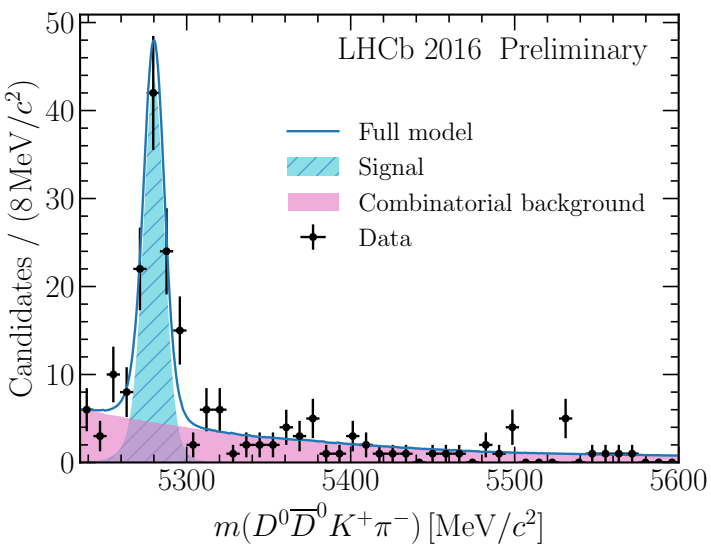


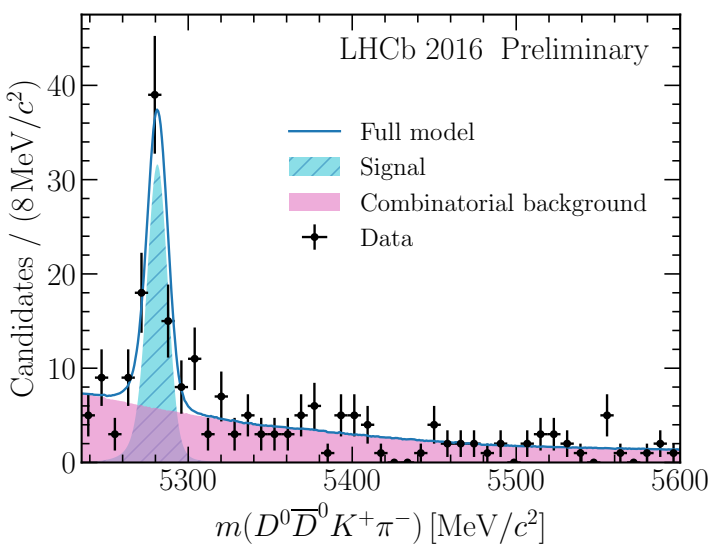
Simultaneous fit

Signal mode $B^0 \to D^0 \overline{D}^0 K^+ \pi^-$









Simultaneous fit

Signal mode in an extended range showing partially reconstructed peaks, to illustrate they are negligible in the nominal fit range $(5235, 5600)\,\mathrm{MeV}/\mathrm{c}^2$.