universität freiburg

University of Glasgow

Amplitude Analysis of $B^+ \to D^- K^+ \pi^+$ decays

LHCb-Germany Meeting
Aachen 1-2 October 2026

Aleksandrina Docheva, Mark Whitehead, William Barker, Naomi Cooke, Patrick Spradlin

LHCb

Outline

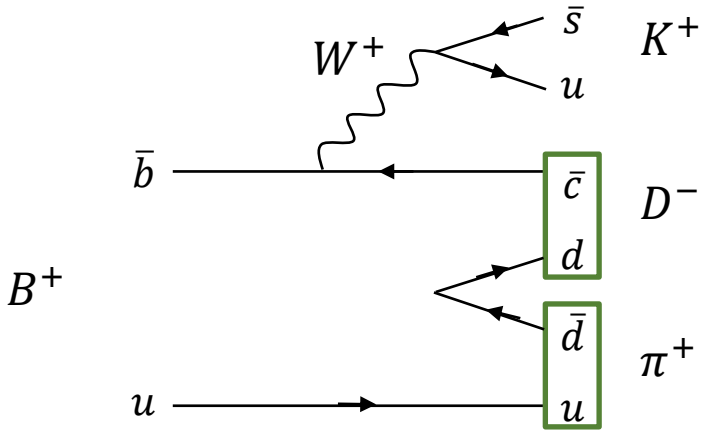
- Motivation for the amplitude analysis of $B^+ \to D^- K^+ \pi^+$ decays
- Analysis strategy
- Amplitude fit
- Results
- Summary and next steps

Motivation

Excited states

Charm meson spectroscopy:

Expect to see excited states of neutral D mesons with natural spin - parity in the $D^-\pi^+$ system

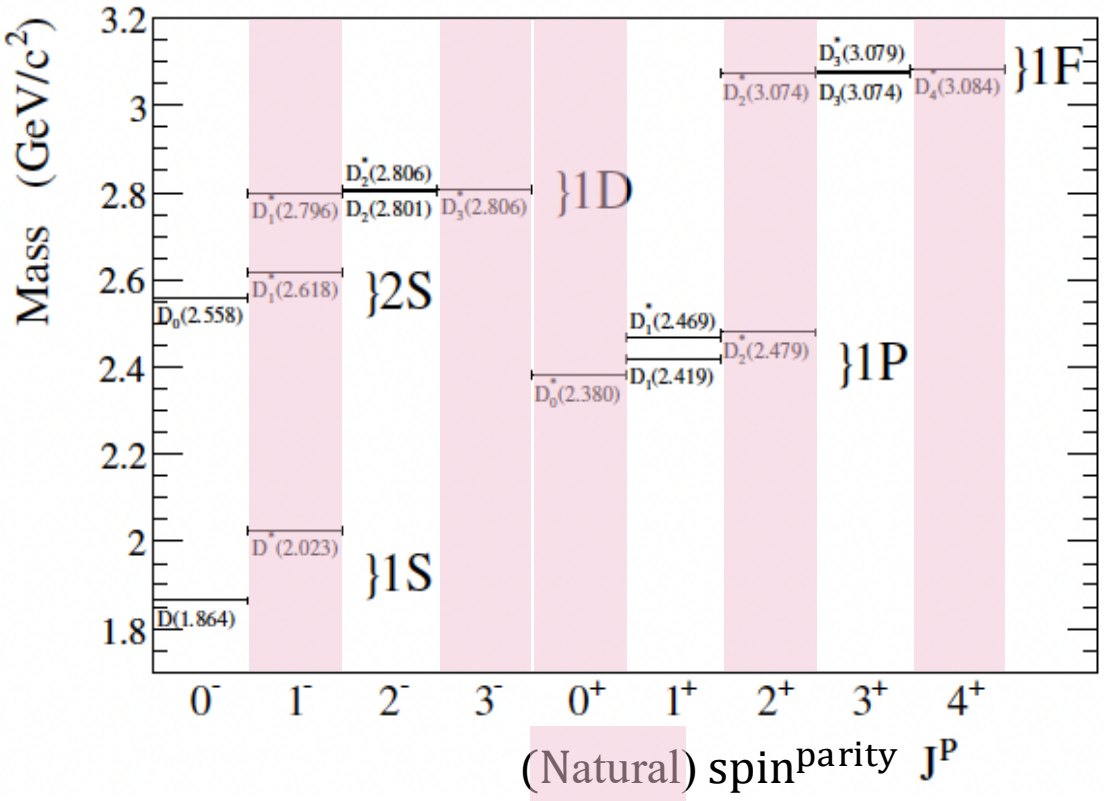


Signal

$B^+ \to D^- K^+ \pi^+$

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

$\hookrightarrow D^- \pi^+$



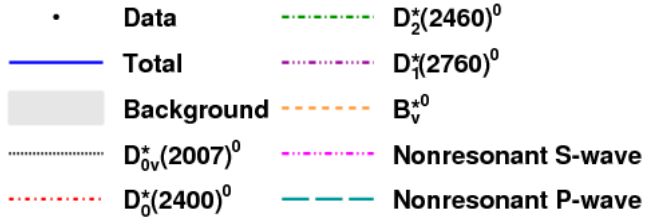
Mass spectrum of the $c\bar{u}$ system. [PhysRevD.32.189]

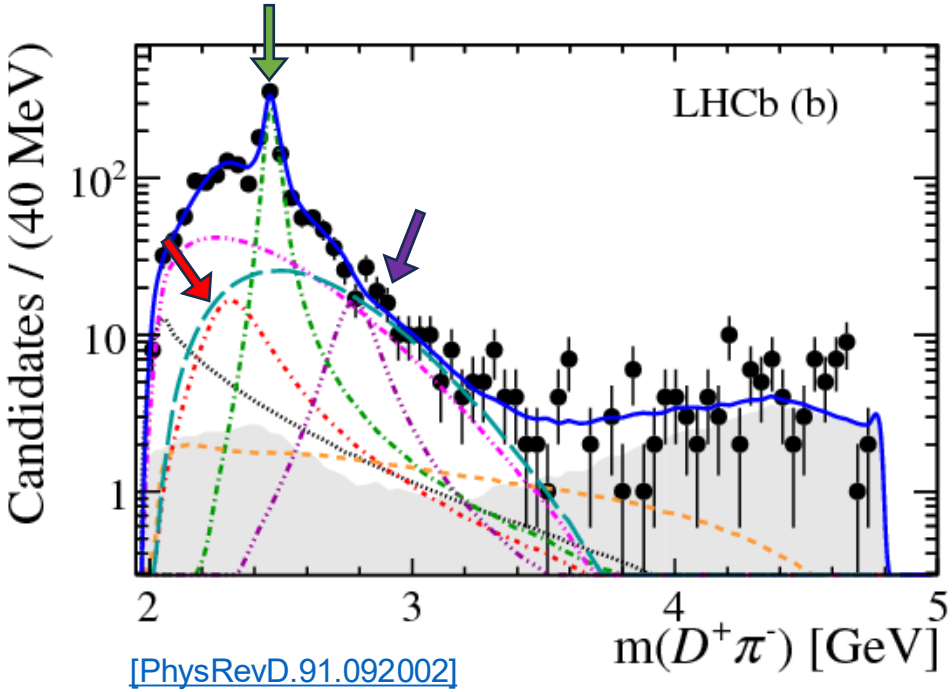
Experimental status

- Same decay mode was studied before using Run 1 data only [PhysRevD.91.092002]

- The study reported the first observation of the decay mode, branching fraction calculation and observation of 3 excited states in the $D^-\pi^+$ system:

  - $D_0^*(2400)^0$ - has been changed to $D_0^*(2300)^0$
  - $D_2^*(2460)^0$
  - $D_1^*(2760)^0$

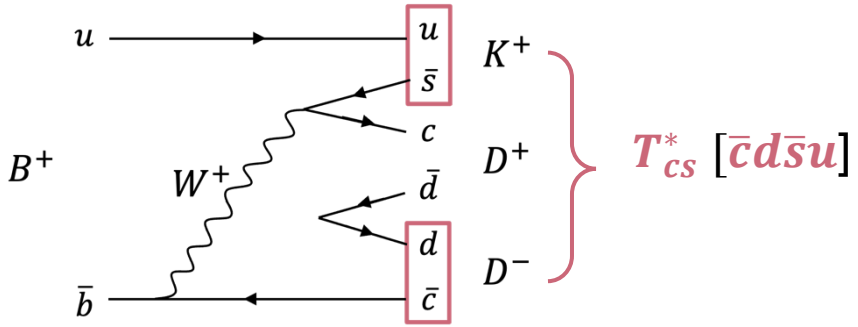




[PhysRevD.91.092002]

Exotic states $T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$

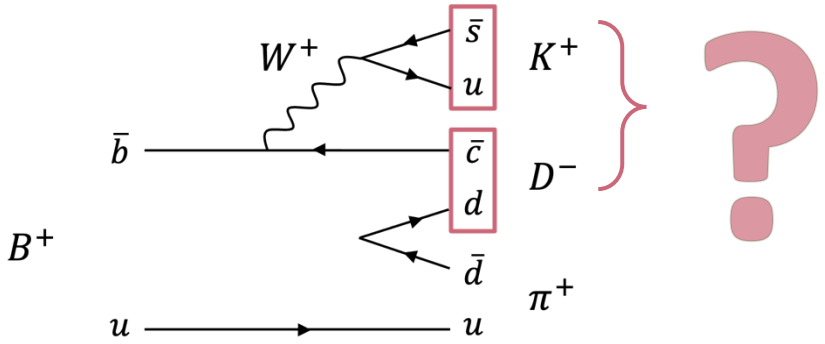
- Tetraquarks $T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ observed in $B^+ \to D^+D^-K^+$ decays in 2020 [PhysRevD.102.112003]



[PhysRevLett.133.131902]

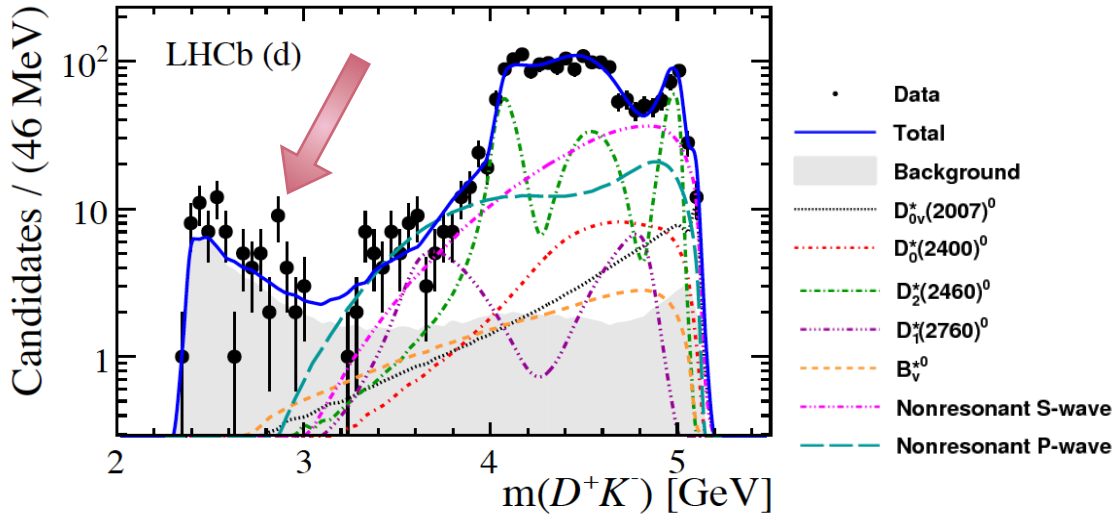
- T^*_{cs0} and T^*_{cs1} also observed in $B^+ \to D^{*+}D^-K^+$ and $B^- \to D^-D^0K^0_S$ decays [PhysRevLett.134.101901]

- Can $T^*_{cs0,1}$ also be observed in $B^+ \to D^-K^+\pi^+$ decays?



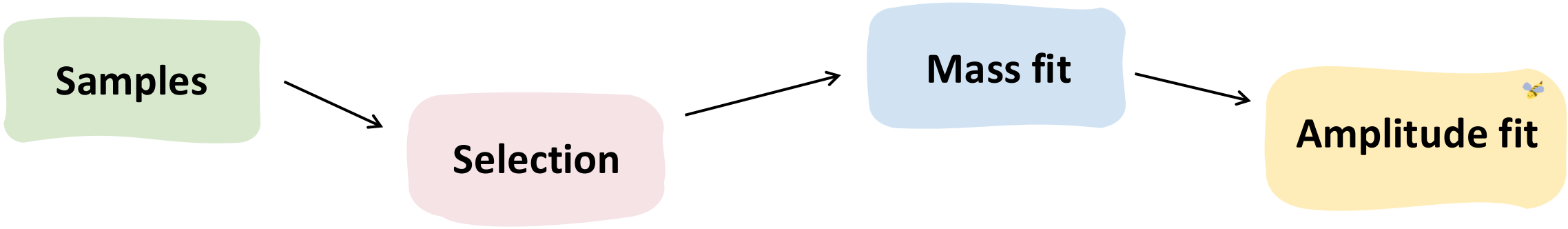
- Interpretations of the T^*_{cs0} and T^*_{cs1} states: Compact tetraquark, molecule, kinematic singularity

A different final state with only one *D* meson may provide complementary information on the nature of the T^*_{cs} states



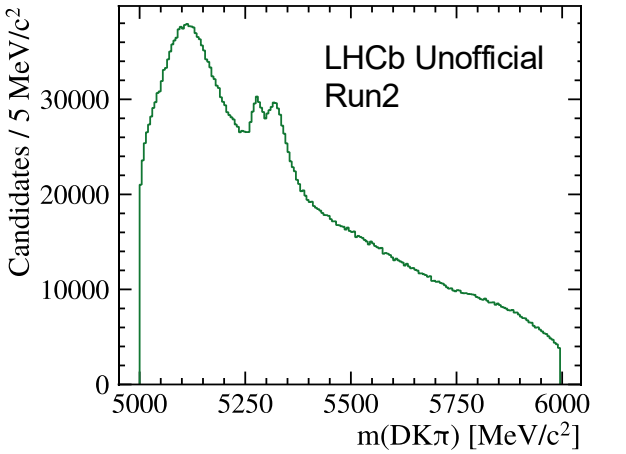
[PhysRevD.91.092002]

Analysis strategy



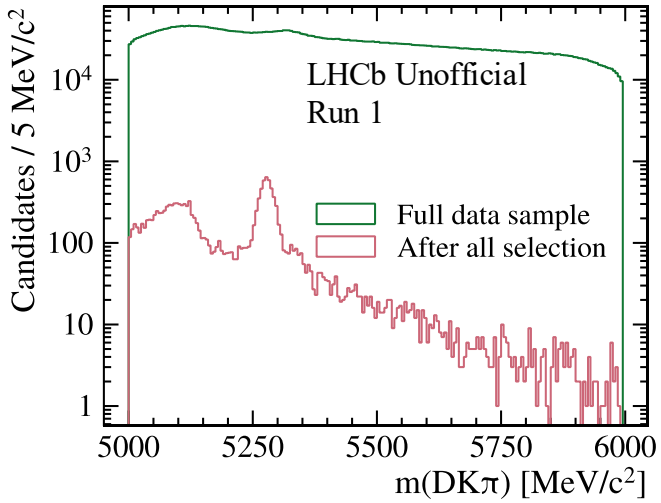
Selection

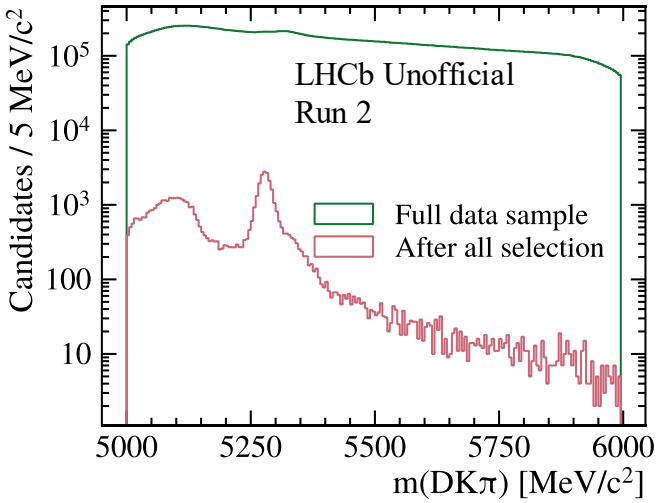
- **Samples:** Full Run 1 and Run 2 data and MC samples
- **Trigger, stripping and initial selection**



B reconstructed mass after initial selection

- **PID requirements -** Reject misidentified backgrounds, such as $B^+ \to D^-\pi^+\pi^+$
- **Simultaneous optimisation of BDT and PID cuts**
- **Vetoes** - Reduce peaking backgrounds





- **Multivariate analysis (MVA) -** Suppress combinatorial backgrounds
  - BDT classifier - XGBoost trained on signal MC and *B* candidate invariant mass distribution sidebands

Backgrounds summary

combinatorial background

D + random tracks
MVA classifier

Significantly reduced – modelled with an exponential function in the mass fit

charmless peaking background

no real D
MVA classifier

Absent after all selections

peaking backgrounds

Real D + misidentified particles
PID cut + vetoes

Model using MC samples

partially reconstructed background

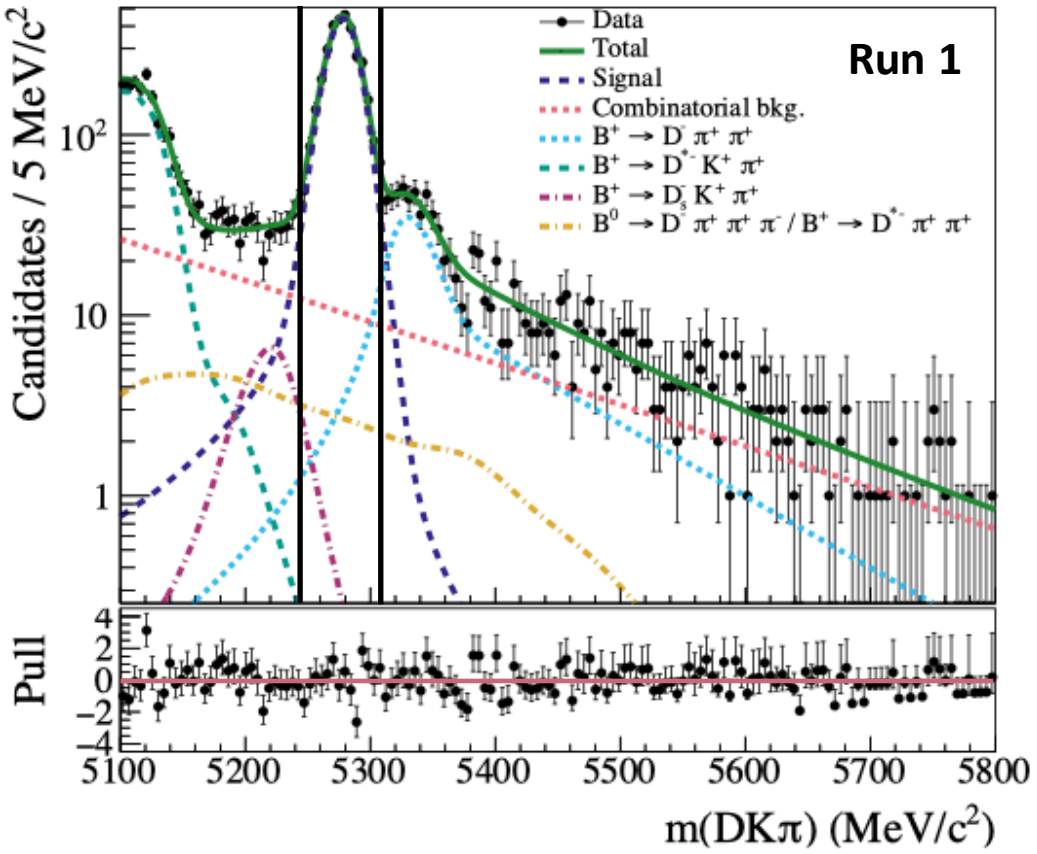
D meson + two other tracks + additional tracks that are not reconstructed

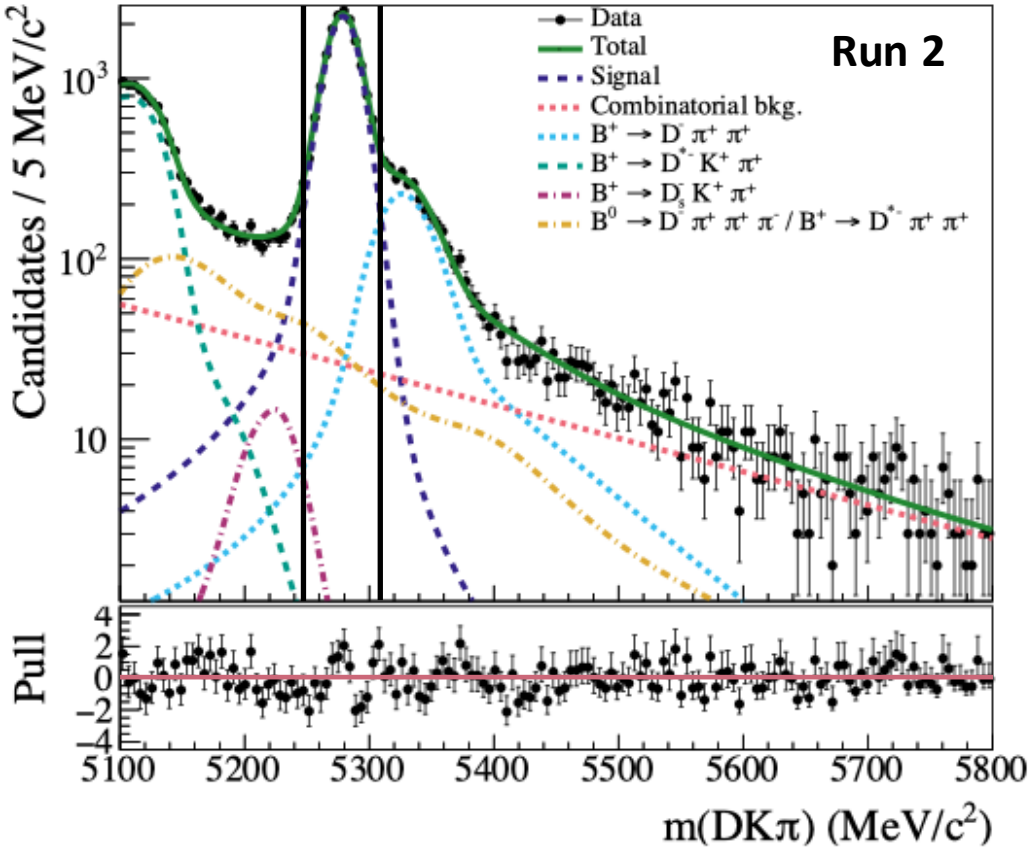
Model using MC samples

Mass fit

Signal region: Mass window 2.5 sigma from the mean of the signal shape:

- **3038 signal decays - 92% purity**
- Previous analysis: 1909 signal decays - 93% purity
- 15216 signal decays - 91% purity

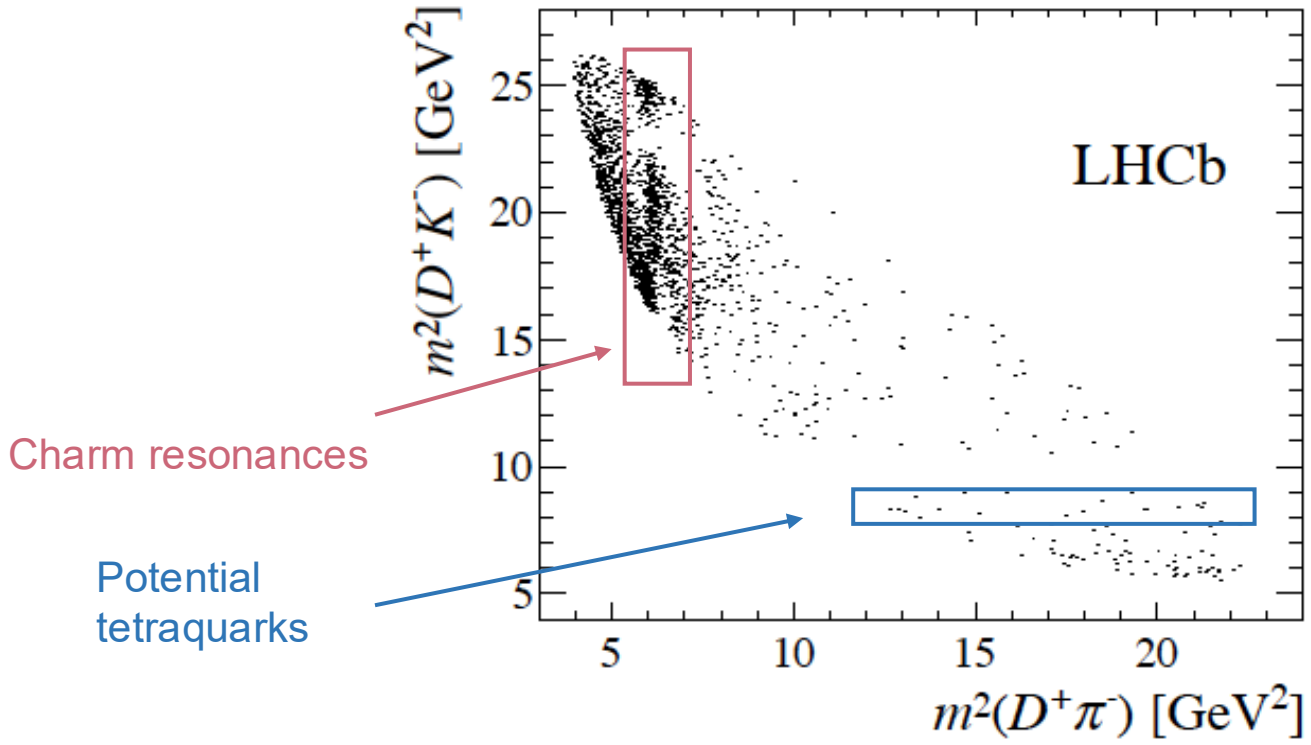




Amplitude fit

The Dalitz plot

- A 2D scatter plot representing a 3-body decay, where the axes are the invariant mass squares of two of the three particles
  - Can infer the mass and spin of a resonance from its shape in the Dalitz plot



Distribution of $B^- \to D^+K^-\pi^-$ candidates over the **Dalitz plot** from the Run 1 analysis [PhysRevD.91.092002]

Dalitz Plot fit strategy

Why amplitude analysis?

- Resonances in the $m(D^-\pi^+)$ and possible exotic contributions in $m(D^-K^+)$ overlap and interfere across the Dalitz Plot

Use LAURA++ to perform an unbinned maximum likelihood fit

- The $m(D^-K^+)$ region around the $T^*_{cs0/1}$ masses is blinded to avoid bias

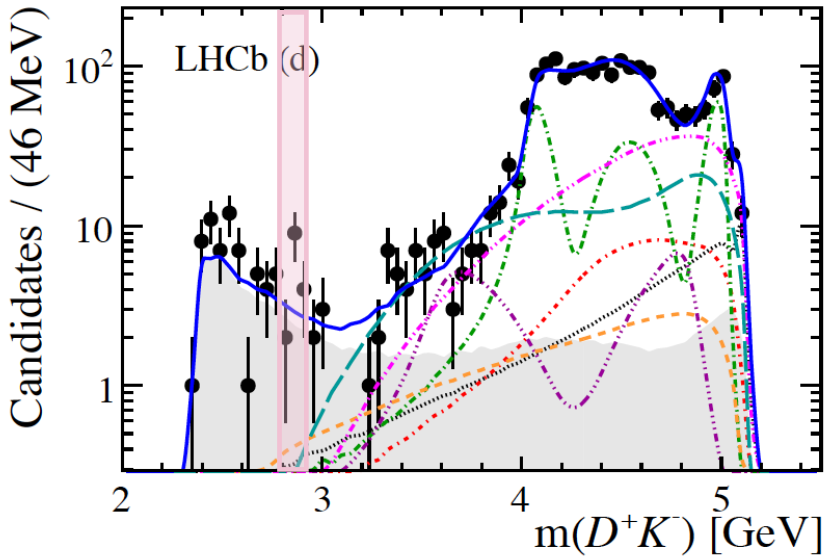
Input

- Signal and background yields determined from the mass fit
- The efficiency variation across the Dalitz plot
- Dalitz plot distributions of the backgrounds

Amplitude model:

[PhysRevD.94.072001]

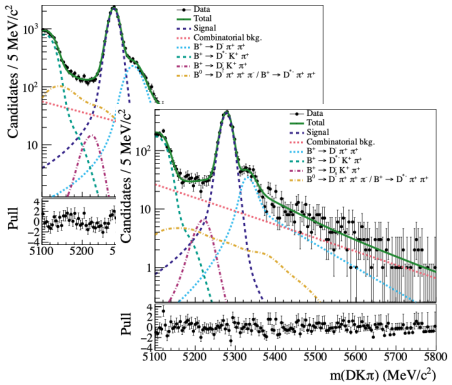
- Baseline model - Adopted from the $B^+ \to D^-\pi^+\pi^+$ analysis
- Extended amplitude model – Baseline model + T^*_{cs0} and/or T^*_{cs1}



[PhysRevD.91.092002]

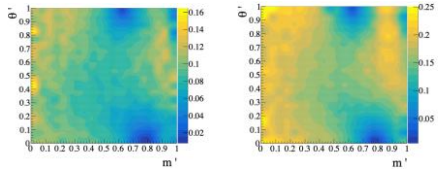
Resonance	System
$D_2^*(2460)^0$	$D\pi$
$D_1^*(2600)^0$	$D\pi$
$D_3^*(2750)^0$	$D\pi$
$D_2^*(3000)^0$	$D\pi$
$D_v^*(2007)^0$	$D\pi$
B_v^{*0}	DK
$D\pi$ S-wave	$D\pi$

Quasi-model independent $D^-\pi^+$ S-wave



Signal and background yields from the mass fit

Efficiency variation across the SDP

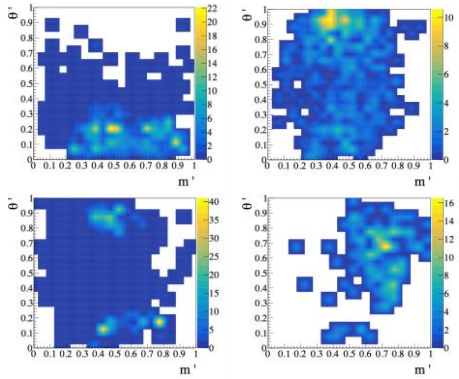


Simultaneous fit

Resonance	System
$D_2^*(2460)^0$	$D\pi$
$D_1^*(2600)^0$	$D\pi$
$D_3^*(2750)^0$	$D\pi$
$D_2^*(3000)^0$	$D\pi$
$D_v^*(2007)^0$	$D\pi$
B_v^{*0}	DK
$D\pi$ S-wave	$D\pi$

Baseline model

Backgrounds SDP distributions



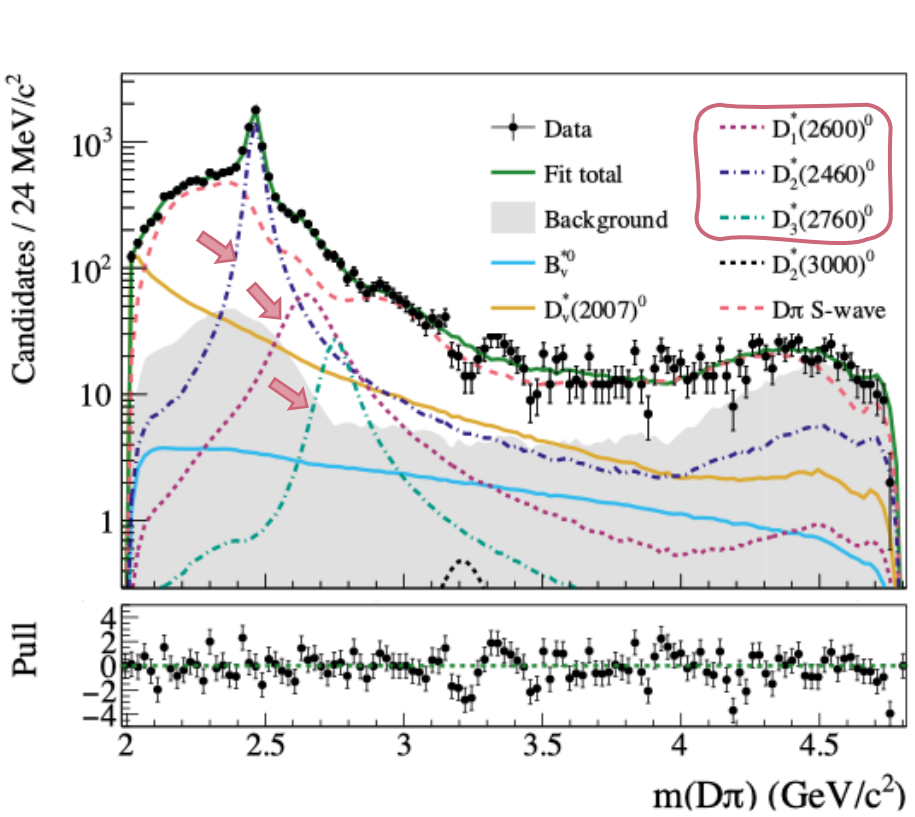
Baseline model fit results

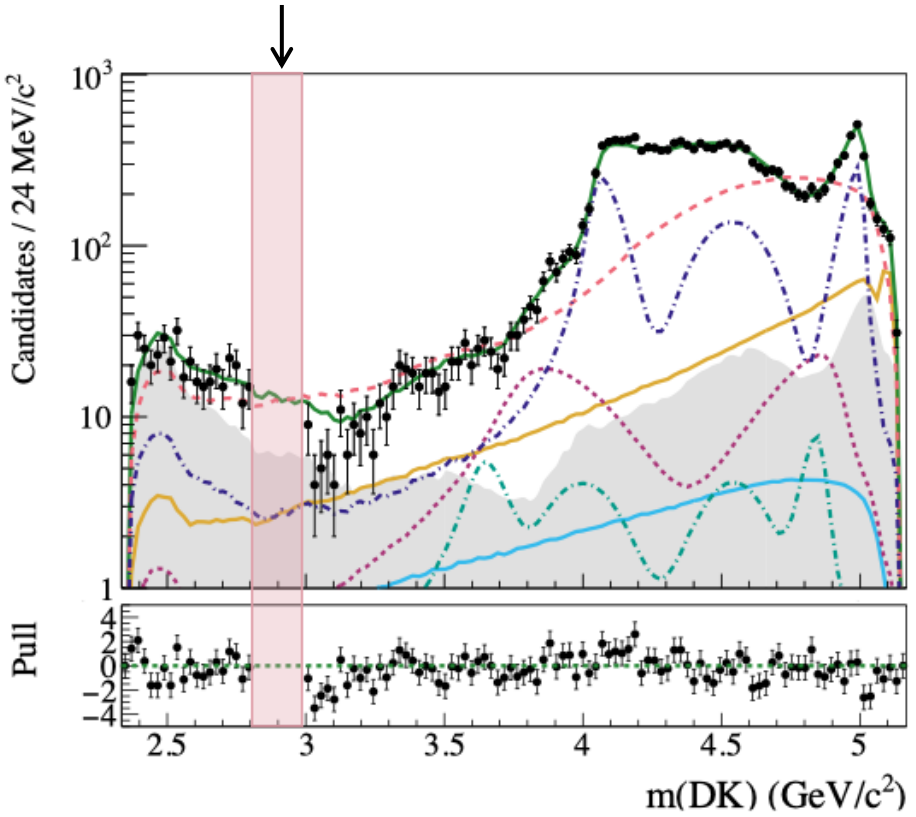
Baseline model fit results

Masses and widths of the three main resonances are floated

Baseline amplitude model describes the data distribution in the $D^-\pi^+$ projection well

We search for the $T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ in D^-K^+ projection





Contribution	Fit fraction (%)
$D^*_2(2460)^0$	31.1
$D^*_1(2680)^0$	4.7
$D^*_3(2760)^0$	1.3
$D^*_2(3000)^0$	0.04
$D^*_v(2007)^0$	10.9
B^{*0}_v	1.4
Total S-wave	57.0
Total fit frac.	106.3

Summary and next steps

Motivation for the Amplitude analysis of $B^+ \to D^- K^+ \pi^+$

- Aiming to study excited neutral D mesons in the $D^-\pi^+$ system
- Search for exotic contributions in the $D^- K^+$ system

What has been achieved?

- Full Run 1 and Run 2 analysis sample with > 18,000 signal decays and purity > 90%
- Simultaneous amplitude fit to Run 1 and Run 2 data using the baseline model
- Established $D^-\pi^+$ resonances and quasi-model-independent $D^-\pi^+$ S-wave describes data well

Status of the analysis and next steps

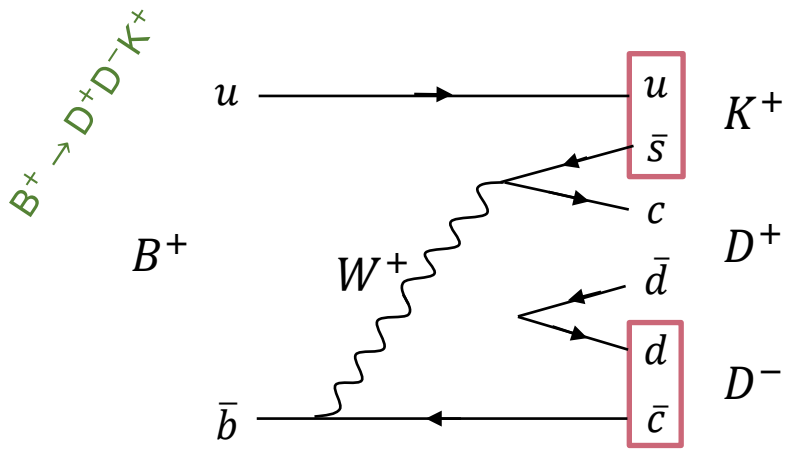
- In WG review
- Finalising systematic uncertainties
- Unblinding – Fit data with an extended amplitude model including $T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ states

Thank you for the attention!

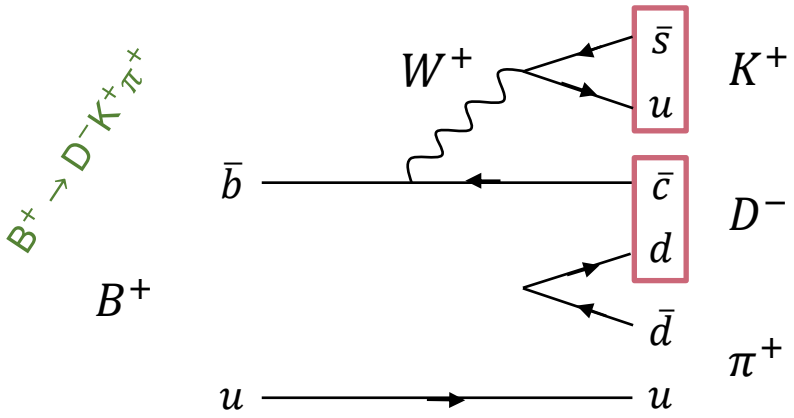
Backup

Exotic states

- Neutral tetraquarks $T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ observed in $B^+ \to D^+D^-K^+$ decays [PhysRevD.102.112003]



D^-K^+ channel:
T^*_{cs} $[\bar{c}d\bar{s}u]$

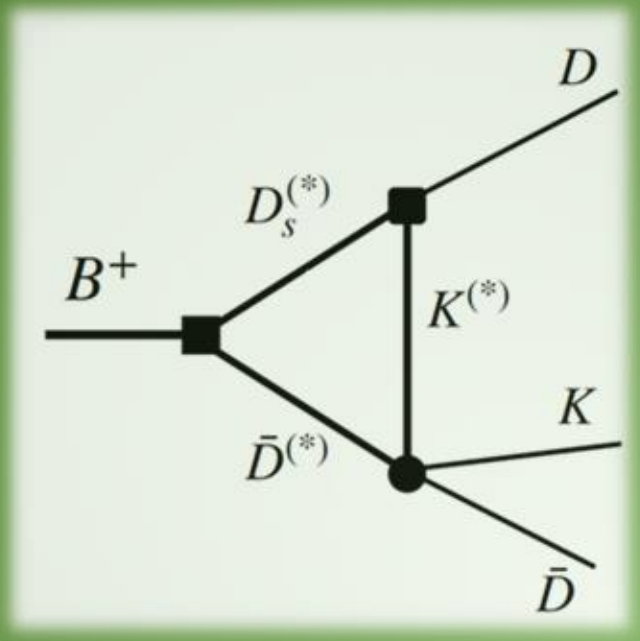


D^-K^+ channel:

?

- $T^*_{cs0,1}$ states – different interpretations:

Tetraquark or molecule or produced through triangle diagrams with two D mesons in the final state [PhysRevD.103.014004]



?

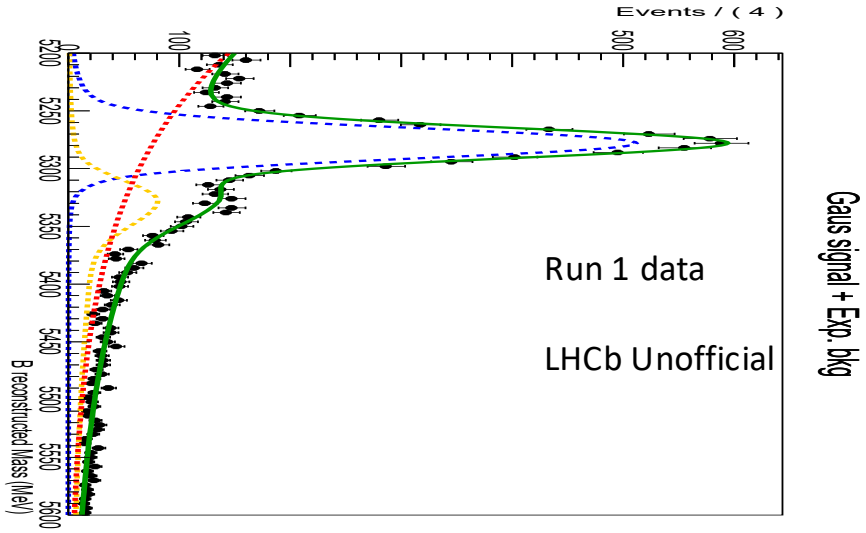
Mode: $B^+ \to D^+T^*_{cs}$, $T^*_{cs} \to D^-K^+$

XGBoost and PID simultaneous optimisation

Figure of merit : $\frac{S}{\sqrt{S+B}} \times \frac{S}{S+B}$

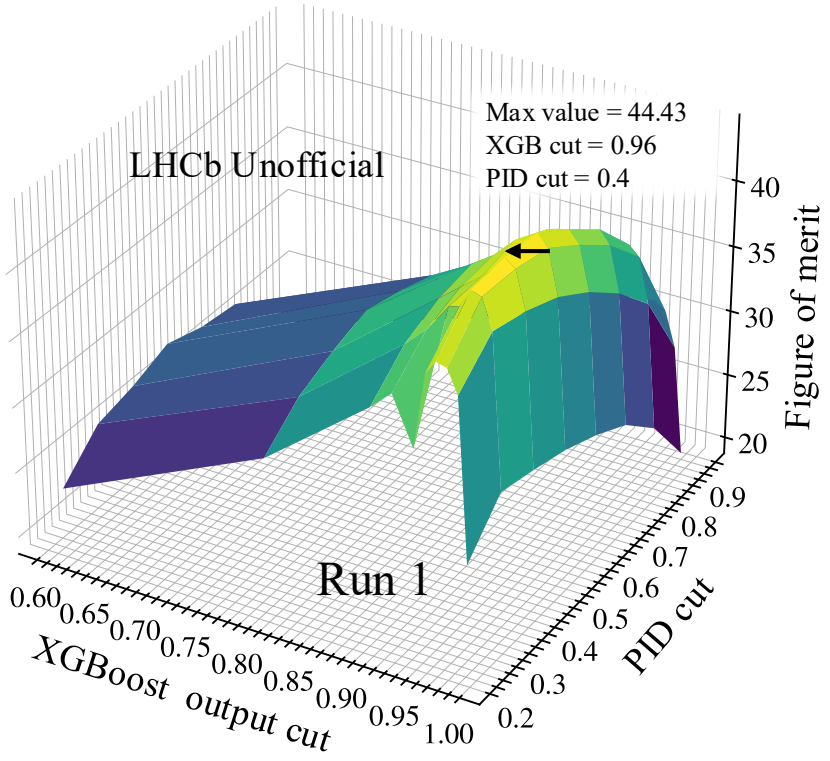
(significance × purity)

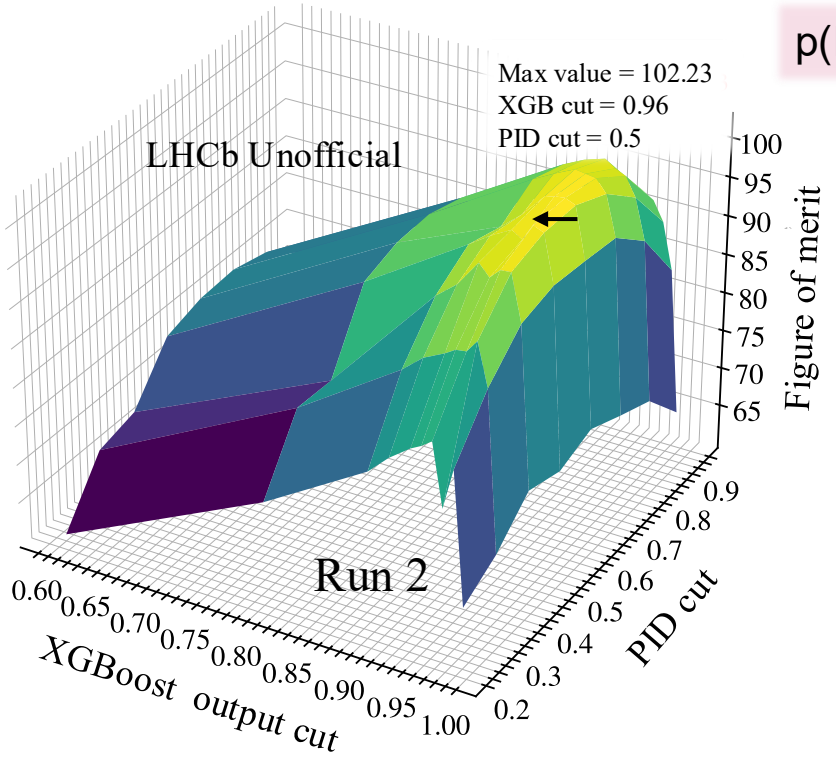
- Signal and $B^+ \to D^-\pi^+\pi^+$ background – Two Crystal Ball
- Other background – exponential



Simple mass fit for estimating the number of signal and background candidates

XGBoost and PID simultaneous optimisation





$p(K) * (1 - p(\pi))$ - PID cut on K from B^+

Figure of merit = $\frac{S}{\sqrt{S+B}} \cdot \frac{S}{S+B}$

After performing the mass fit the XGBoost cut for Run1 is tightened from 0.96 to 0.97 to improve purity

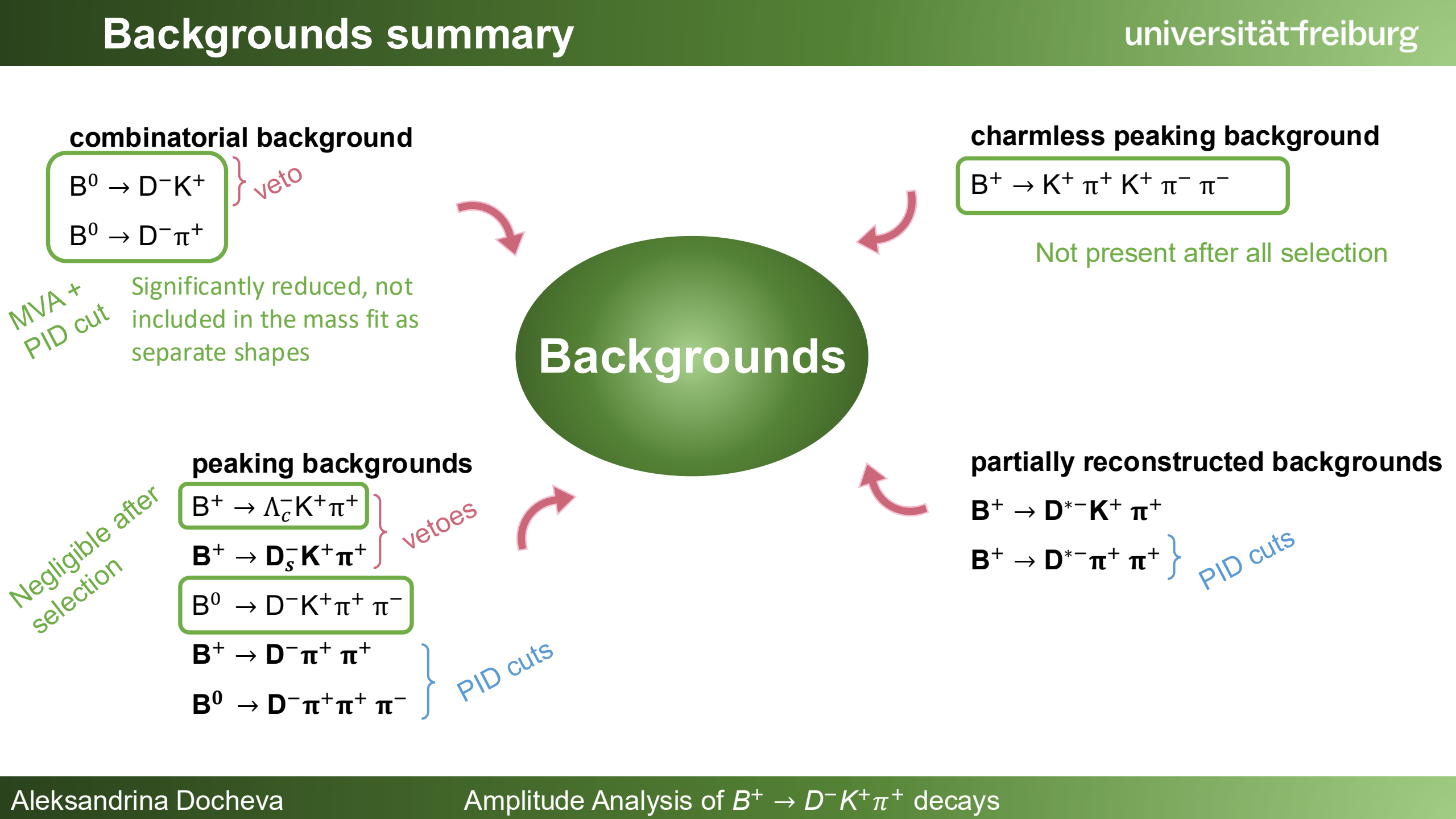
XGBoost output cut

- Run1: signal efficiency = 55%, background rejection = 99%
- Run2: signal efficiency = 60%, background rejection = 99%

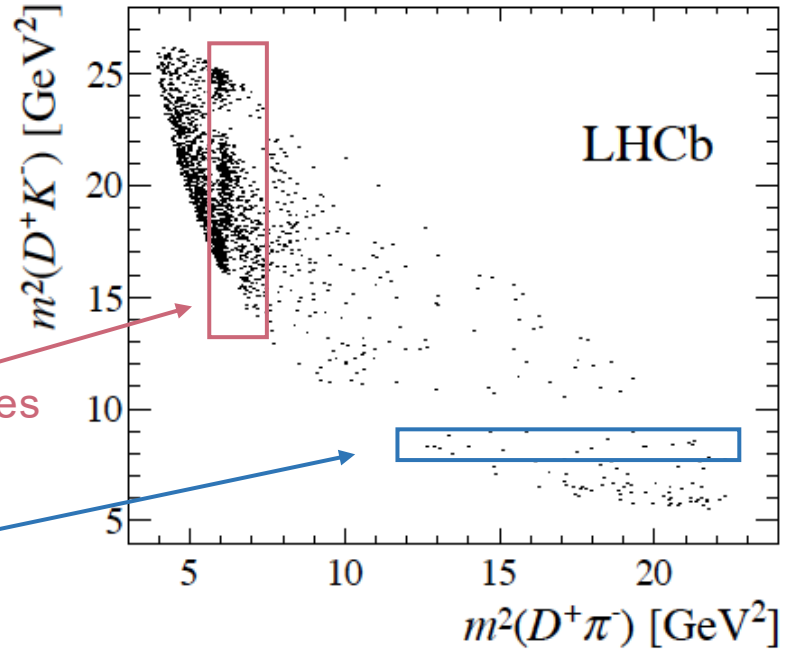
XGBoost output and PID cuts

- Run1: $B^+ \to D^-\pi^+\pi^+$ rejection = 99%
- Run2: $B^+ \to D^-\pi^+\pi^+$ rejection = 97%

Backgrounds summary



The Dalitz plot



Charm resonances

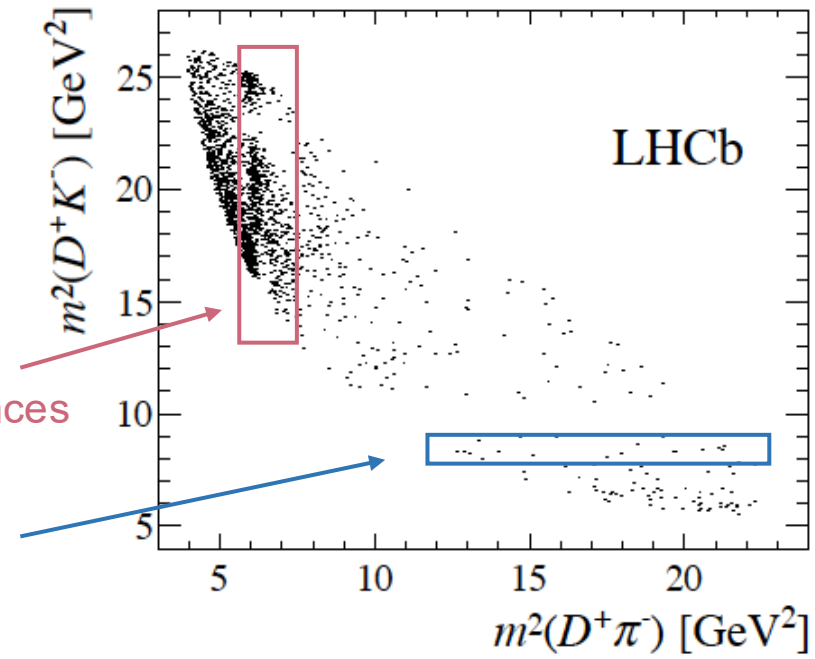
Potential tetraquarks

For $X \to abc$

$$m_X^2 + m_a^2 + m_b^2 + m_c^2 = \underbrace{m_{ab}^2 + m_{ac}^2 + m_{bc}^2}$$

Only two are independent

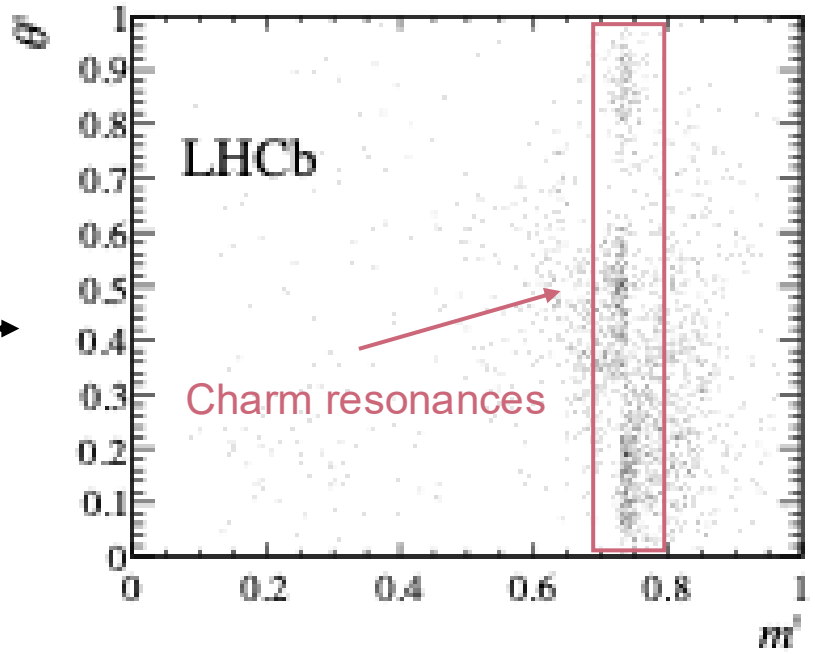
The Dalitz plot



Charm resonances

Potential tetraquarks

Variable transformation

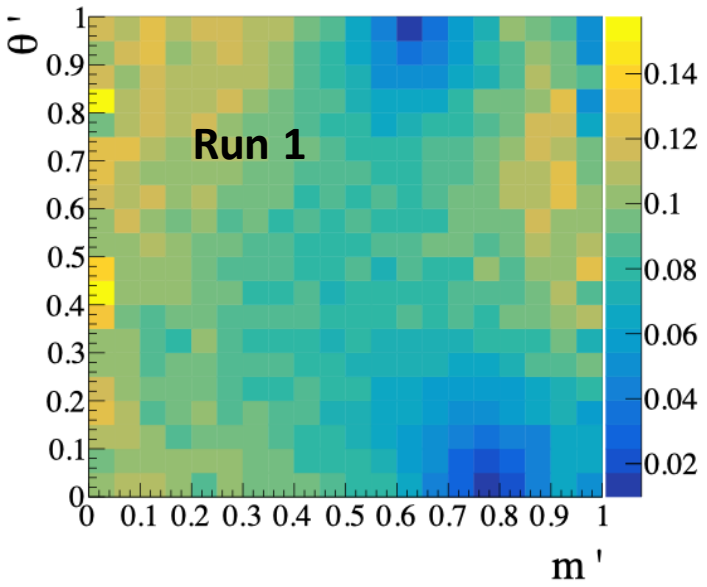


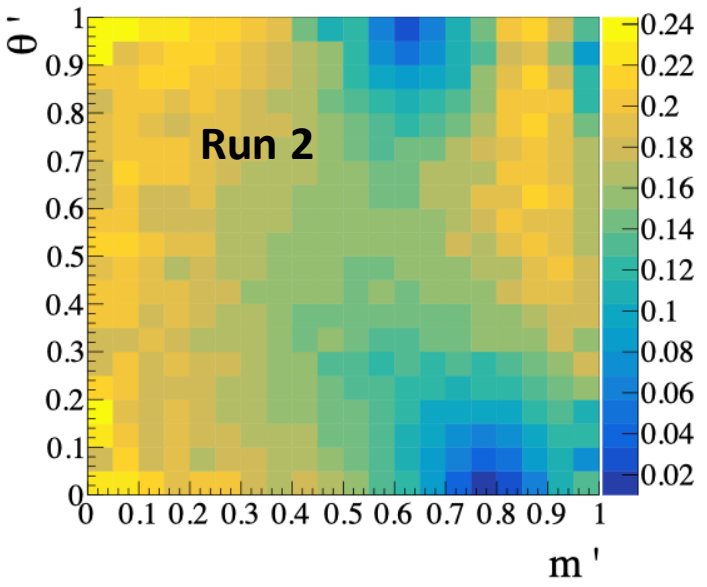
$$m' = \frac{1}{\pi}\cos^{-1}\left(2\frac{m_{ab} - m_{ab}^{\min}}{m_{ab}^{\max} - m_{ab}^{\min}} - 1\right) \text{ and } \theta' = \frac{1}{\pi}\theta_{ab}$$

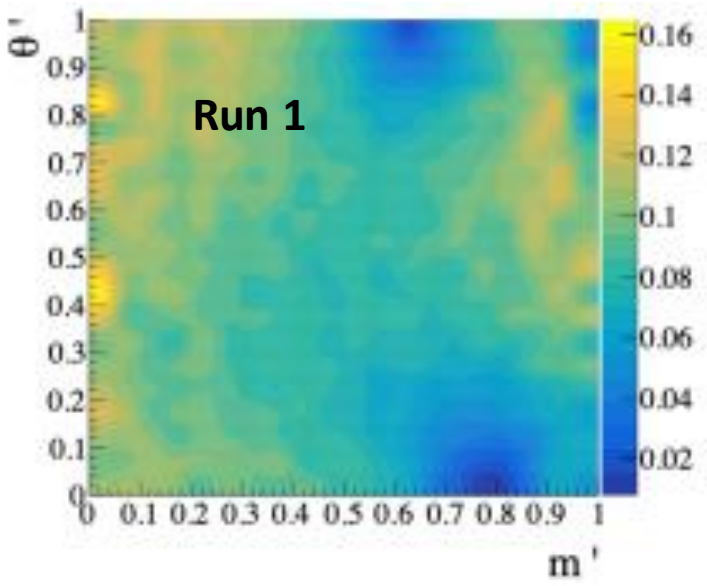
Efficiency

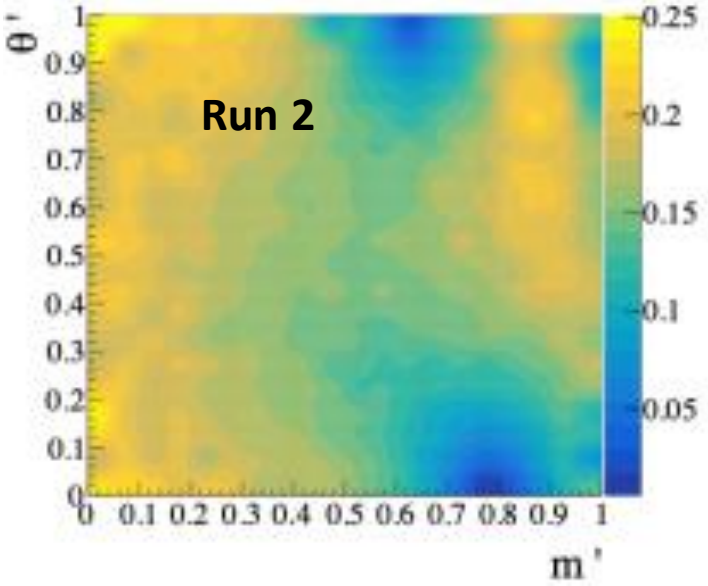
- **Efficiency variation across the SDP phase space is incorporated into the amplitude fit**

Spline interpolation







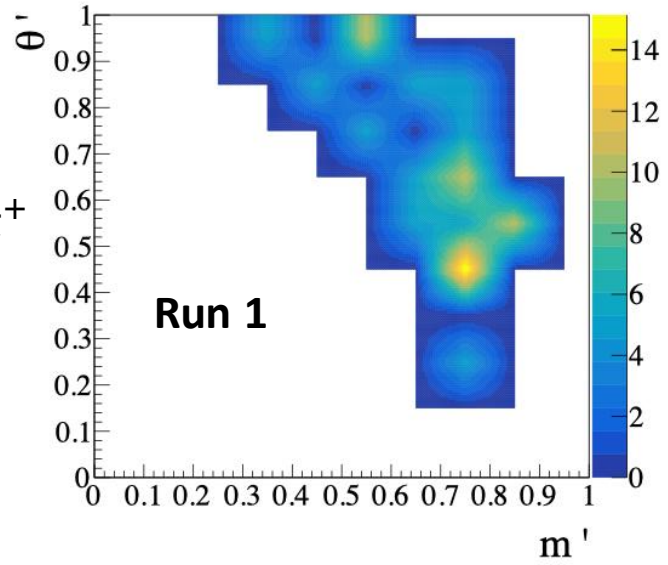


Backgrounds

Background distributions across the SDP phase space

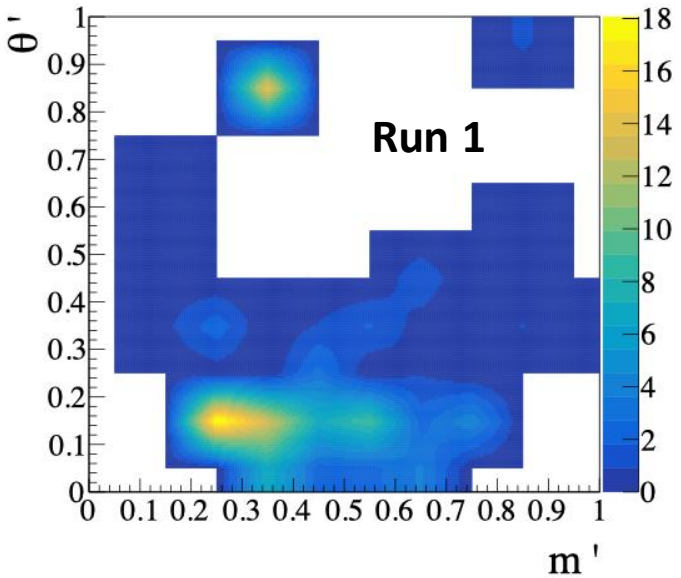
$B^0 \to D^-\pi^-\pi^+\pi^+$

No reweighting

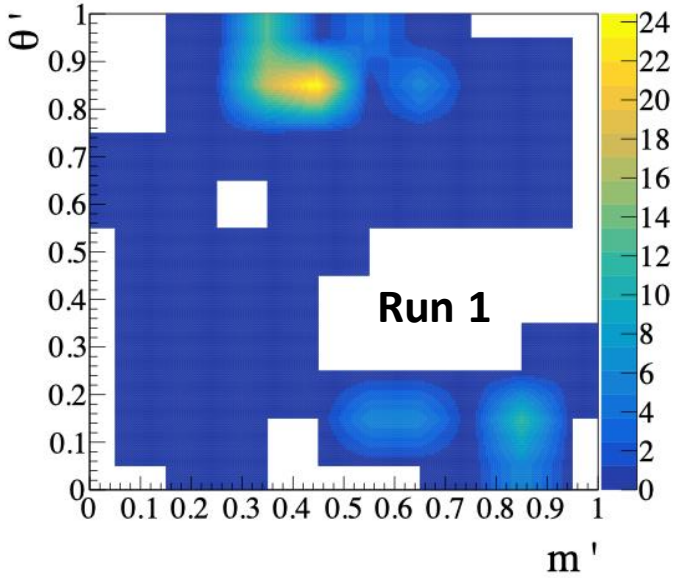


Reweighted to the true distributions

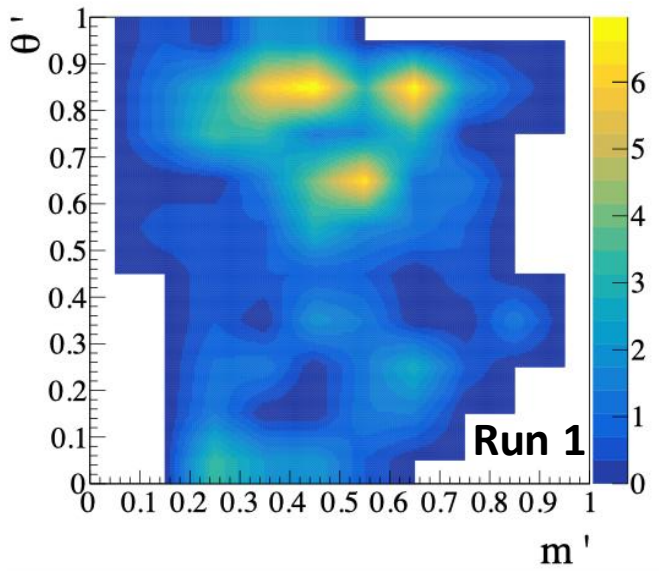
$B^+ \to D^-\pi^+\pi^+$



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



Combinatorial



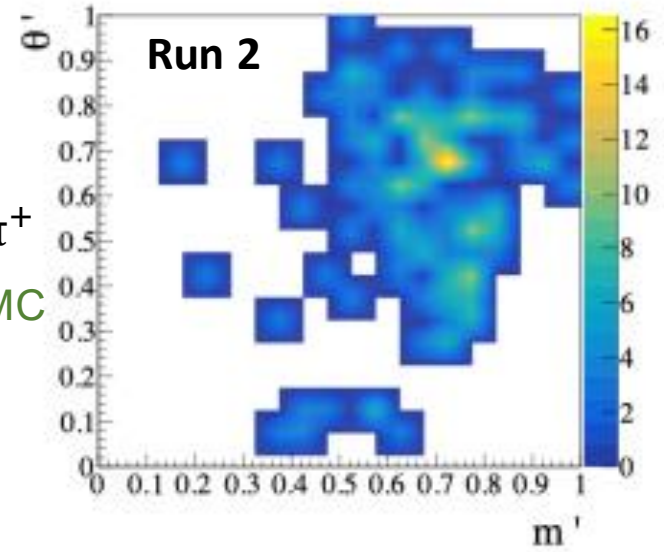
Constructed from data sidebands

Backgrounds

Background distributions across the SDP phase space

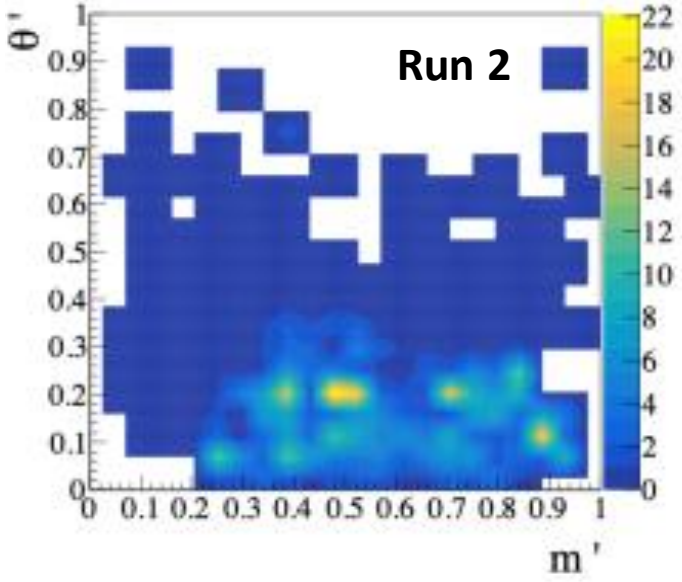
$B^0 \to D^-\pi^-\pi^+\pi^+$

No reweighting MC

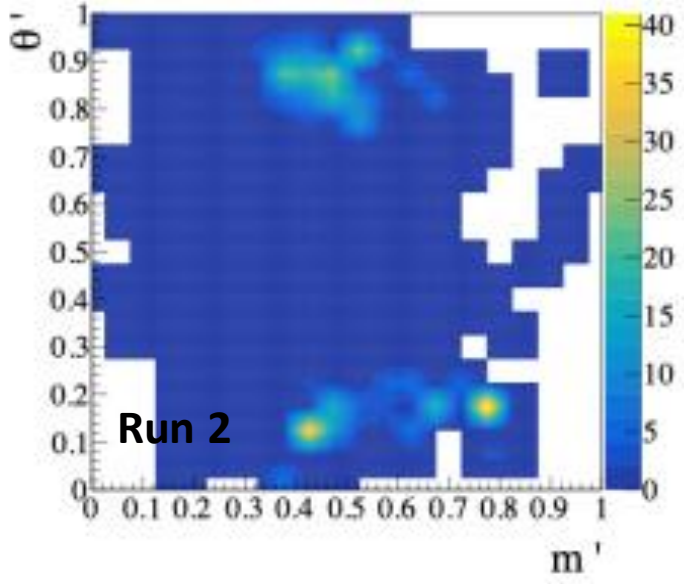


Reweighted MC to the true distributions

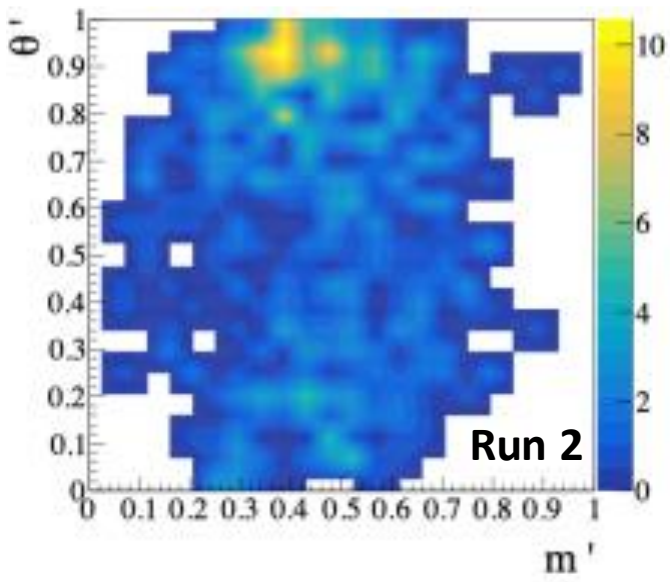
$B^+ \to D^-\pi^+\pi^+$



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



Combinatorial



Constructed from data sidebands

Baseline model fit results

Masses and widths of some of the resonances are floated:

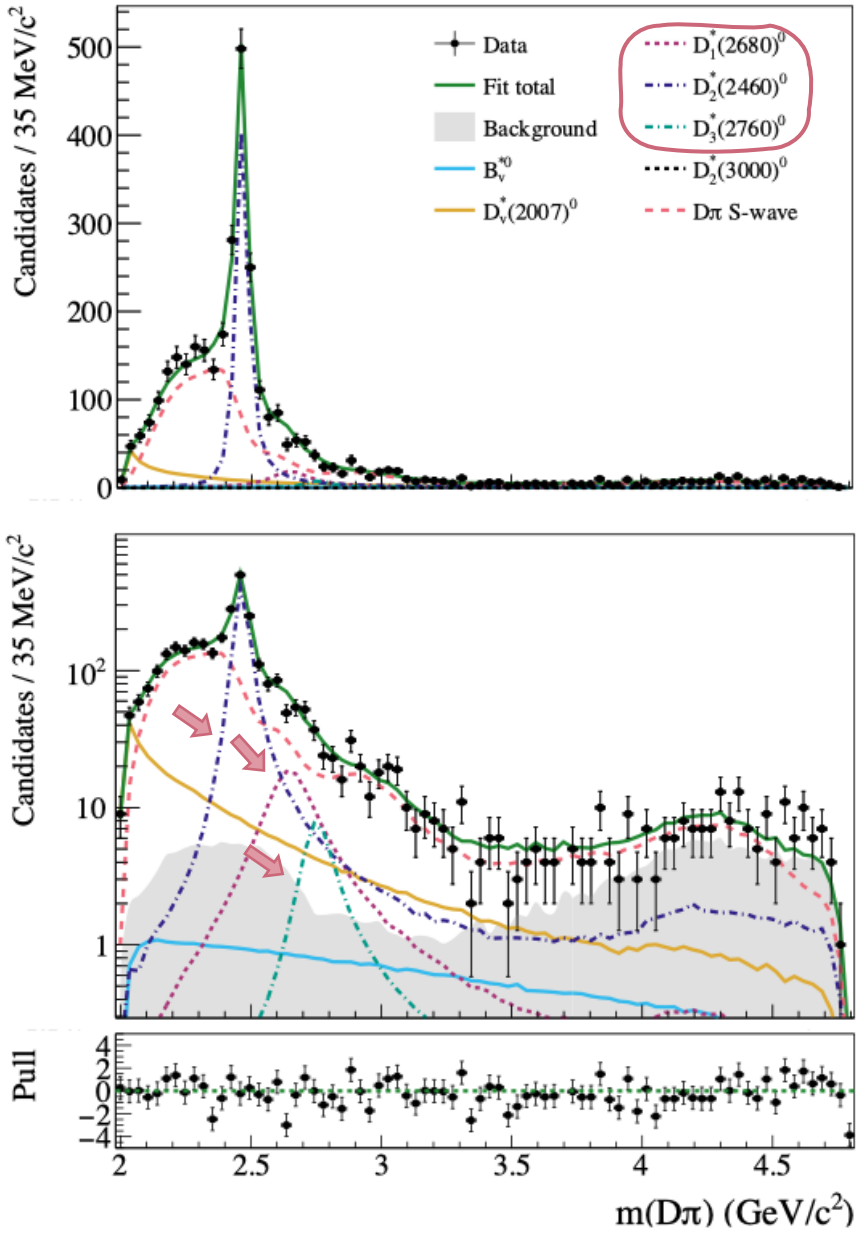
- All floated simultaneously

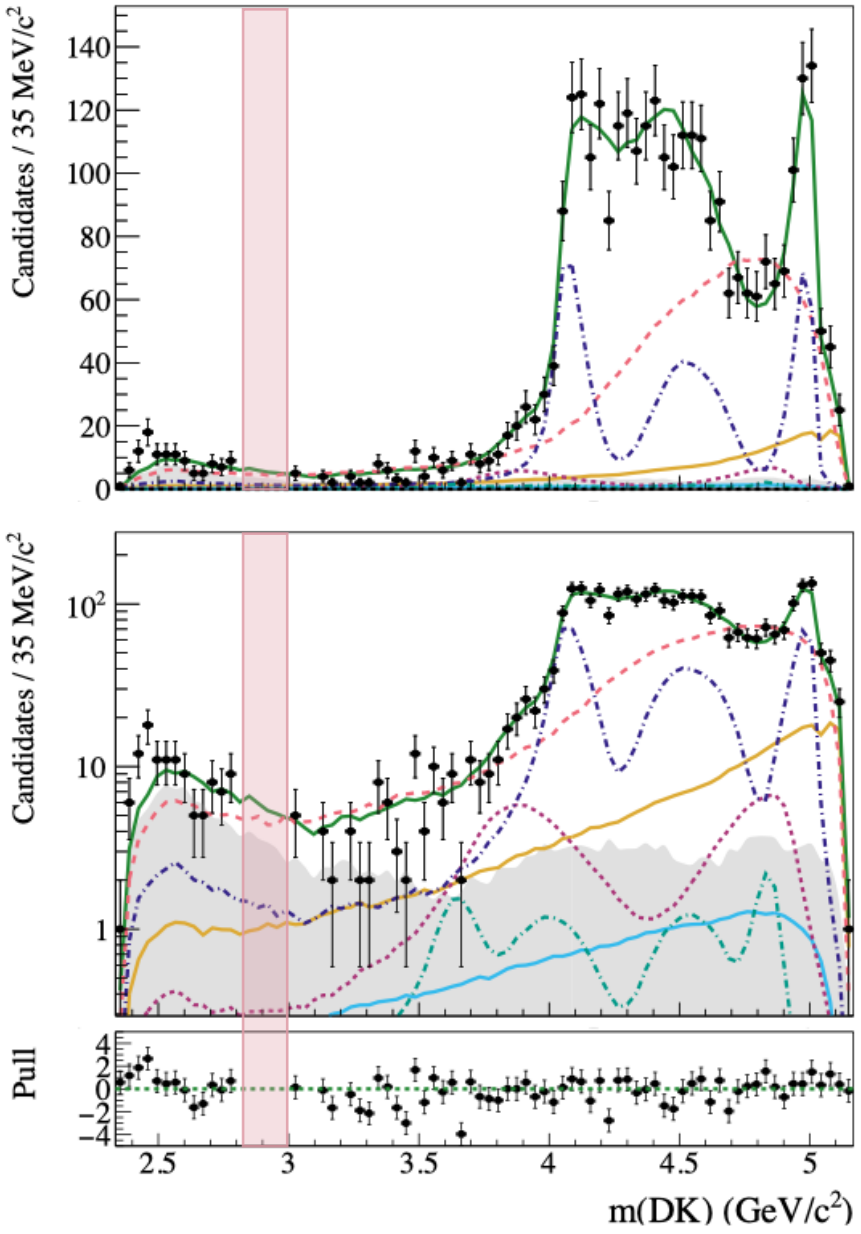
Resonance	System
$D_2^*(2460)^0$	$D\pi$
$D_1^*(2600)^0$	$D\pi$
$D_3^*(2750)^0$	$D\pi$
$D_2^*(3000)^0$	$D\pi$
$D_v^*(2007)^0$	$D\pi$
B_v^{*0}	DK
$D\pi$ S-wave	$D\pi$

Resonance		PDG value	$B^+ \to D^-\pi^+\pi^+$ analysis	$B^+ \to D^-K^+\pi^+$ analysis
$D_2^*(2460)^0$	mass	2461.1 ± 0.7	2463.7 ± 0.4	2463.5 ± 0.5
	width	47.3 ± 0.8	47.0 ± 0.8	44.8 ± 1.0
$D_1^*(2600)^0$	mass	2627 ± 10	2681.1 ± 5.6	2649.7 ± 6.1
	width	141 ± 23	186.7 ± 8.5	165.0 ± 11.7
$D_3^*(2750)^0$	mass	2763.1 ± 3.2	2775 ± 4.5	2755.9 ± 7.0
	width	66 ± 5	95.3 ± 9.6	99.7 ± 12.6

All values in MeV

Baseline model fit results Run 1





Amplitude fit Results

Summary table of fit fractions, magnitudes and phases of the amplitude components

Contribution	Fit fraction (%)	Magnitude	Phase
$D_2^*(2460)^0$	31.1	1	0
$D_1^*(2680)^0$	4.7	0.39 ± 0.01	8.63 ± 0.07
$D_3^*(2760)^0$	1.3	0.20 ± 0.01	-0.35 ± 0.10
$D_2^*(3000)^0$	0.04	0.03 ± 0.02	-4.29 ± 0.47
$D_v^*(2007)^0$	10.9	0.59 ± 0.02	-0.32 ± 0.11
B_v^{*0}	1.4	0.21 ± 0.03	-6.32 ± 0.28
Total S-wave	57.0	1.35 ± 0.02	-6.42 ± 0.05
Total fit fraction	106.3		

Model including tetraquarks

- $T_{cs0}^*(2870)^0$, m = 2872 $\mathrm{MeV/c^2}$, Γ = 67 MeV
- $T_{cs1}^*(2900)^0$, m = 2904 $\mathrm{MeV/c^2}$, Γ = 106 MeV