γ measurements in LHCb and the first observation of $B^0_{(s)} \to \overline{D}^*(2007)^0 K^\pm \pi^\mp$ decays

Warwick EPP seminar

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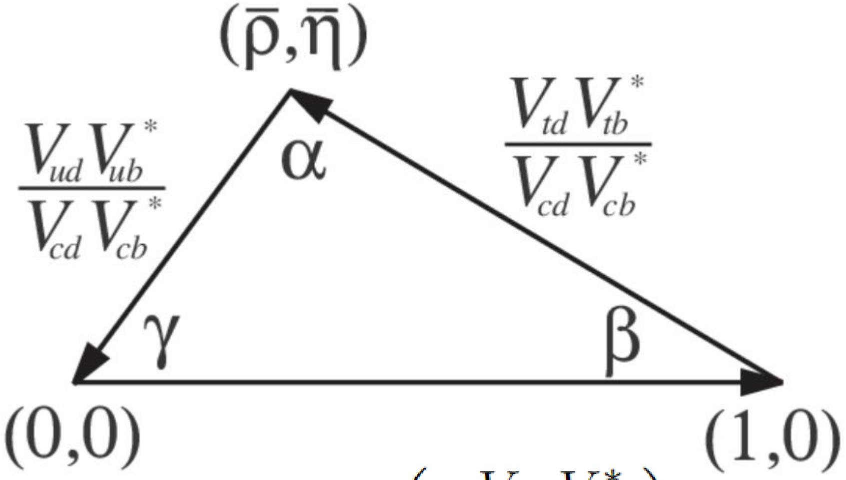
Outline:

- γ measurements in LHCb
  - The maths
  - The methods
  - The results
- First observation of $B_{(s)}^{0} \rightarrow \overline{D}^{*}(2007)^{0}K^{\pm}\pi^{\mp}$
  - Motivation
  - Analysis strategy
  - Interesting features
  - Systematic uncertainties
  - Results
  - Future prospects

The γ angle and the CKM matrix

CKM matrix controls flavour changing transitions in the SM

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$



It satisfies unitarity: $\sum_{k=1}^{3} V_{ki}^* V_{kj} = \delta_{ij}$

$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

Described by 3 rotation angles in the flavour space and a complex phase δ

$$\boxed{\gamma = \delta + \mathcal{O}(\lambda^4)}$$

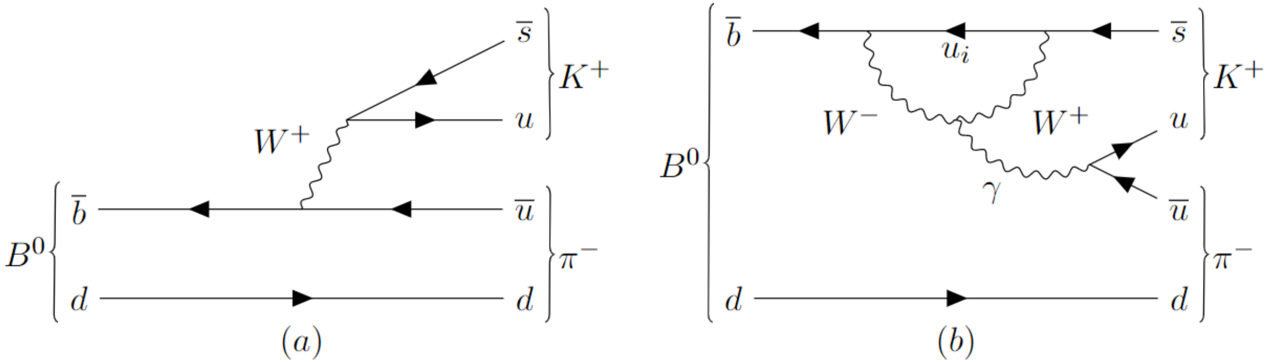
Measuring γ

How to access the amplitude complex phase?

Consider a decay to a final state f under the presence of CP violation

$A_f = |A_f|e^{i\alpha_1}$, $\overline{A}_{\overline{f}} = |A_f|e^{i\alpha_2}$. Here, even when γ relates to $\alpha_1 - \alpha_2$ only $|A_f|$ is observable.

Same decay with two different channels (for example, through a tree-level transition (a) and a 1-loop/penguin diagram (b))



Now the amplitude will look like.

$$A_f = |A_T|e^{i\alpha_{1T}} + |A_P|e^{i\alpha_{1P}}, \quad \overline{A}_{\overline{f}} = |A_T|e^{i\alpha_{2T}} + |A_P|e^{i\alpha_{2P}}$$

Measuring γ

Introduce strong (δ) and weak (ϕ) phases: $\alpha_1 = \delta + \phi, \quad \alpha_2 = \delta - \phi$

$$A_f = |A_T|e^{i(\delta_T+\phi_T)} + |A_P|e^{i(\delta_P+\phi_P)}, \quad \overline{A}_{\overline{f}} = |A_T|e^{i(\delta_T-\phi_T)} + |A_P|e^{i(\delta_P-\phi_P)}.$$

And the squared amplitude is:

$$A_f^2 = |A_T|^2 + |A_P|^2 + 2|A_T||A_P|\cos(\delta_T - \delta_P + \phi_T - \phi_P) = |A_T|^2 + |A_P|^2 + 2|A_T||A_P|\cos(\delta_B + \gamma)$$

$$\overline{A}_{\overline{f}}^2 = |A_T|^2 + |A_P|^2 + 2|A_T||A_P|\cos(\delta_T - \delta_P - \phi_T + \phi_P) = |A_T|^2 + |A_P|^2 + 2|A_T||A_P|\cos(\delta_B - \gamma)$$

Finally, we can write the CP asymmetry

$$\mathcal{A}_{CP} = \frac{\left|\overline{A}_{\overline{f}}\right|^2 - \left|A_f\right|^2}{\left|\overline{A}_{\overline{f}}\right|^2 + \left|A_f\right|^2} = \frac{2r\sin(\delta_T - \delta_P)\sin(\phi_T - \phi_P)}{1 + r^2 + 2r\cos(\delta_T - \delta_P)\cos(\phi_T - \phi_P)}$$

CP asymmetry only non-zero if:

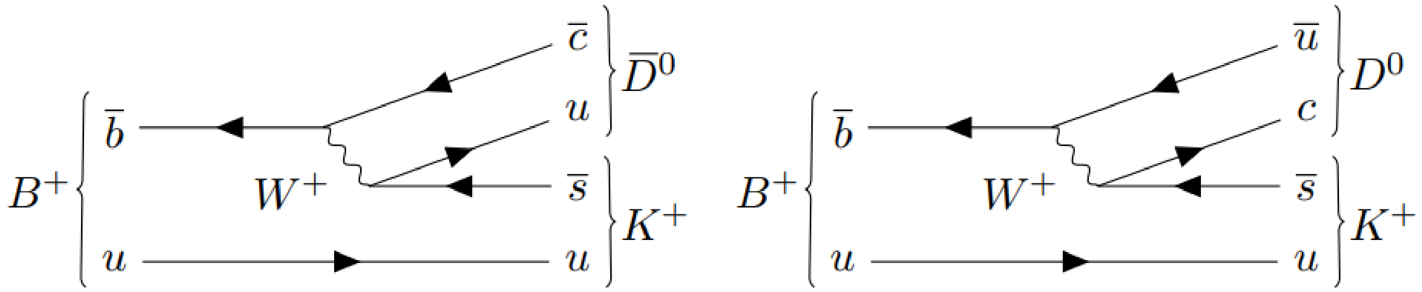
- $r \neq 0$
- $\delta_T - \delta_P \neq 0$
- $\phi_T - \phi_P \neq 0$

With $r = |A_T|/|A_P|$

Although we assumed a tree and penguin diagrams, this is valid for any decay with two possible paths

Measuring γ

Lets consider now $B^+ \to DK^+$ decays, with D^0 and $\overline{D}^0$ decaying to the same final state f



Now, in this case we can directly associate the weak phase difference between both channels with γ, due to the interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ interactions.

However, we need to also consider the amplitude from the $D \to f$ decay

$$A_1 = |A_{B1}|e^{i(\delta_{B1}+\phi_{B1})}|A_{D1}|e^{i(\delta_{D1}+\phi_{D1})}$$

$$A_2 = |A_{B2}|e^{i(\delta_{B2}+\phi_{B2})}|A_{D2}|e^{i(\delta_{D2}+\phi_{D2})}$$

$$\mathcal{A}_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2r_D r_B \sin(\delta_B + \delta_D)\sin(\gamma)}{r_D^2 + r_B^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma)}$$

Where in this case we have considered : $\phi_{D1} - \phi_{D2} \approx 0$

Measuring γ

$$\mathcal{A}_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2r_D r_B \sin(\delta_B + \delta_D)\sin(\gamma)}{r_D^2 + r_B^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma)}$$

In order to measure γ, we need inputs for r_B, r_D, δ_B and δ_D

Or we can use some tricks:

- **The Gronau-London-Wyler (GLW) method:**
  - Use CP invariant final states so $r_D = 1$ and $\delta_D = 0, \pi$
  - $D \to KK, D \to \pi\pi$ ...

$$\mathcal{A}_{CP}^{GLW} = \frac{\pm 2r_B \sin(\delta_B)\sin(\gamma)}{1 + r_B^2 \pm 2r_B \cos(\delta_B)\cos(\gamma)}$$

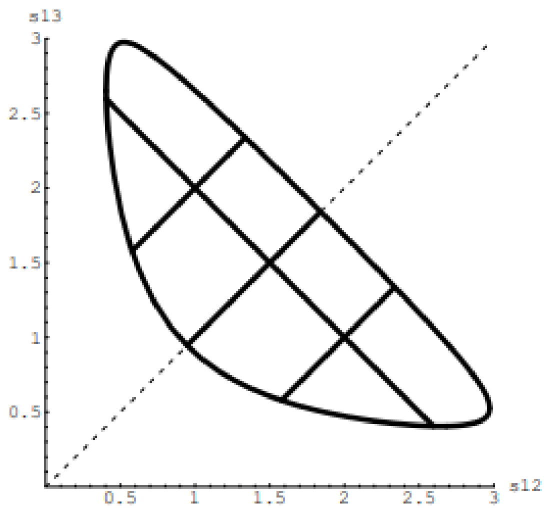
  - Removes two degrees of freedom, however, some of these decays have relatively small BF
  - $\mathcal{B}(D \to KK) = 4 \cdot 10^{-3}$ ($\mathcal{B}(D^0 \to K^-\pi^+) = 4 \cdot 10^{-2}$)

Measuring γ

- **The Atwood-Dunietz-Soni (ADS) method:**
  - Considers non CP invariant states, with known relative branching fraction, such as $D \to K\pi$
  - Despite requiring more external inputs for the γ measurement, it offers more data, as well as a higher CP asymmetry

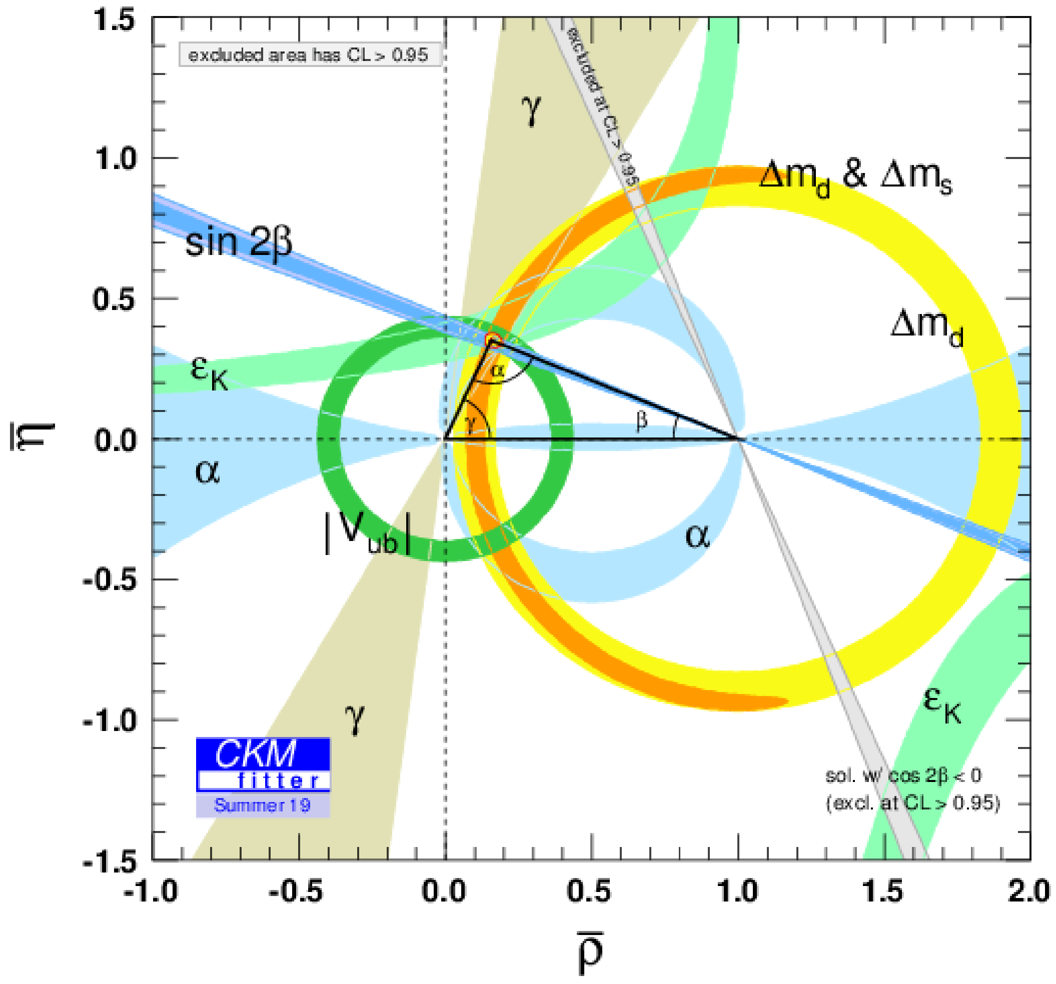
$$\mathcal{A}_{CP}^{ADS} = \frac{2r_D r_B \sin(\delta_B + \delta_D)\sin(\gamma)}{r_D^2 + r_B^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma)}$$

- **The Bondar-Poluektov-Giri-Grossman-Soffer-Zupan (BPGGSZ) method:**
  - Consider three body D decays such as $D \to K_s^0\pi\pi$ so the CP asymmetry can be measured in different areas of the phase space (or the Dalitz plot)
  - This removes the need for external constrains to measure $\mathcal{A}_{CP}$ but requires for a larger data sample.



Measuring γ

- **The Dalitz method:**
  - Consider instead three body B decays, such as $B^0 \to DK^+\pi^-$, so CP asymmetry can be computed in different areas of the phase space.
  - This approach can be combined with the three previous method, leading to **GLW-Dalitz, ADS-Dalitz** and **BPGGSZ-Dalitz** (or Double dalitz)
  - Extremely challenging, since they require large data samples as well as a good understanding of the Dalitz plot distribution for everyone of these decays



arxiv.org/pdf/2110.02350.pdf

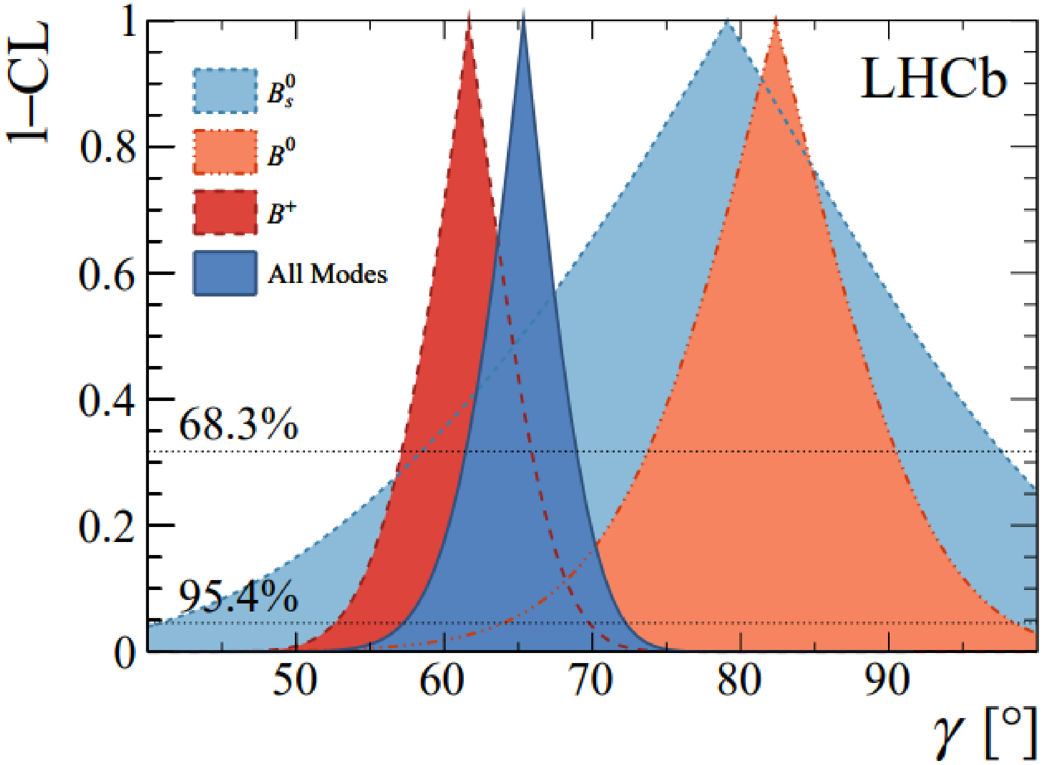
γ results:

- Best measurement obtained from combining results from many different analyses, combining all the previously mentioned methods.
- Combination from LHCb measurement leads the best precision with around 4º.
- Despite this, many analysis on the line that will help improve this result further
- For the first time, combination also includes **charm mixing parameters.**

B decay	D decay	Ref.	Dataset	Status since Ref. [24]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[28]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[29]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[26]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[30]	Run 1&2	**Updated**
$B^\pm \to D^* h^\pm$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[31]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[31]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[32]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[33]	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[34]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[35]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[36]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[37]	Run 1&2	**New**
–	$D^0 \to h^+h^-$	[38–40]	Run 1&2	**New**
–	$D^0 \to h^+h^-$	[41]	Run 1	**New**
–	$D^0 \to h^+h^-$	[42–45]	Run 1&2	**New**
–	$D^0 \to K^+\pi^-$	[46]	Run 1	**New**
–	$D^0 \to K^+\pi^-$	[47]	Run 1&2(*)	**New**
–	$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	[48]	Run 1	**New**
–	$D^0 \to K^0_S\pi^+\pi^-$	[49, 50]	Run 1&2	**New**
–	$D^0 \to K^0_S\pi^+\pi^-$	[51]	Run 1	**New**

γ results:

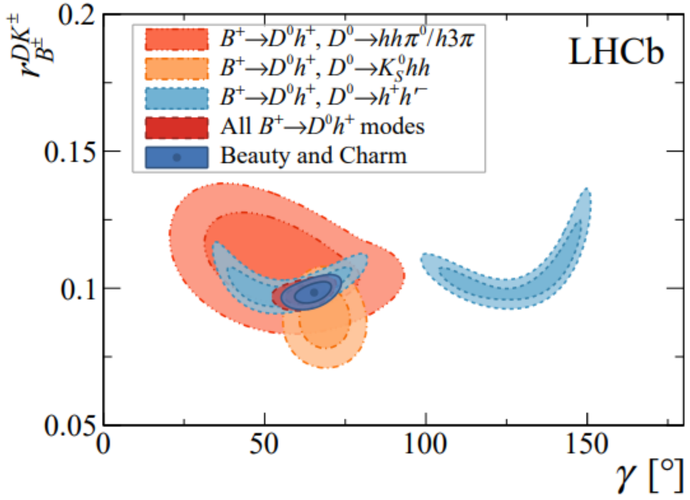
Quantity	Value	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
γ [°]	65.4	$^{+3.8}_{-4.2}$	[61.2, 69.2]	$^{+7.5}_{-8.7}$	[56.7, 72.9]
$r_{B^\pm}^{DK^\pm}$	0.0984	$^{+0.0027}_{-0.0026}$	[0.0958, 0.1011]	$^{+0.0056}_{-0.0052}$	[0.0932, 0.1040]
$\delta_{B^\pm}^{DK^\pm}$ [°]	127.6	$^{+4.0}_{-4.2}$	[123.4, 131.6]	$^{+7.8}_{-9.2}$	[118.4, 135.4]
$r_{B^\pm}^{D\pi^\pm}$	0.00480	$^{+0.00070}_{-0.00056}$	[0.00424, 0.00550]	$^{+0.0017}_{-0.0011}$	[0.0037, 0.0065]
$\delta_{B^\pm}^{D\pi^\pm}$ [°]	288	$^{+14}_{-15}$	[273, 302]	$^{+26}_{-31}$	[257, 314]
$r_{B^\pm}^{D^*K^\pm}$	0.099	$^{+0.016}_{-0.019}$	[0.080, 0.115]	$^{+0.030}_{-0.038}$	[0.061, 0.129]
$\delta_{B^\pm}^{D^*K^\pm}$ [°]	310	$^{+12}_{-23}$	[287, 322]	$^{+20}_{-71}$	[239, 330]
$r_{B^\pm}^{D^*\pi^\pm}$	0.0095	$^{+0.0085}_{-0.0061}$	[0.0034, 0.0180]	$^{+0.017}_{-0.0089}$	[0.0006, 0.026]
$\delta_{B^\pm}^{D^*\pi^\pm}$ [°]	139	$^{+22}_{-86}$	[53, 161]	$^{+32}_{-129}$	[10, 171]
$r_{B^\pm}^{DK^{*\pm}}$	0.106	$^{+0.017}_{-0.019}$	[0.087, 0.123]	$^{+0.031}_{-0.040}$	[0.066, 0.137]
$\delta_{B^\pm}^{DK^{*\pm}}$ [°]	35	$^{+20}_{-15}$	[20, 55]	$^{+57}_{-28}$	[7, 92]
$r_{B^0}^{DK^{*0}}$	0.250	$^{+0.023}_{-0.024}$	[0.226, 0.273]	$^{+0.044}_{-0.052}$	[0.198, 0.294]
$\delta_{B^0}^{DK^{*0}}$ [°]	197	$^{+10}_{-9.3}$	[187.7, 207]	$^{+24}_{-18}$	[179, 221]
$r_{B_s^0}^{D_s^\mp K^\pm}$	0.310	$^{+0.098}_{-0.092}$	[0.218, 0.408]	$^{+0.20}_{-0.21}$	[0.10, 0.51]
$\delta_{B_s^0}^{D_s^\mp K^\pm}$ [°]	356	$^{+19}_{-18}$	[338, 375]	$^{+39}_{-39}$	[317, 395]
$r_{B_s^0}^{D_s^\mp K^\pm\pi^+\pi^-}$	0.460	$^{+0.081}_{-0.084}$	[0.376, 0.541]	$^{+0.16}_{-0.17}$	[0.29, 0.62]
$\delta_{B_s^0}^{D_s^\mp K^\pm\pi^+\pi^-}$ [°]	345	$^{+13}_{-12}$	[333, 358]	$^{+26}_{-25}$	[320, 371]
$r_{B^0}^{D^\mp\pi^\pm}$	0.030	$^{+0.014}_{-0.012}$	[0.018, 0.044]	$^{+0.036}_{-0.028}$	[0.002, 0.066]
$\delta_{B^0}^{D^\mp\pi^\pm}$ [°]	30	$^{+26}_{-37}$	[−7, 56]	$^{+45}_{-81}$	[−51, 75]
$r_{B^\pm}^{DK^\pm\pi^+\pi^-}$	0.079	$^{+0.028}_{-0.034}$	[0.045, 0.107]	$^{+0.050}_{-0.079}$	[0.000, 0.129]*
$r_{B^\pm}^{D\pi^\pm\pi^+\pi^-}$	0.067	$^{+0.025}_{-0.029}$	[0.038, 0.092]	$^{+0.040}_{-0.067}$	[0.000, 0.107]*
x [%]	0.400	$^{+0.052}_{-0.053}$	[0.347, 0.452]	$^{+0.10}_{-0.11}$	[0.29, 0.50]
y [%]	0.630	$^{+0.033}_{-0.030}$	[0.600, 0.663]	$^{+0.069}_{-0.058}$	[0.572, 0.699]
$r_D^{K\pi}$	0.05867	$^{+0.00015}_{-0.00015}$	[0.05852, 0.05882]	$^{+0.00031}_{-0.00030}$	[0.05837, 0.05898]
$\delta_D^{K\pi}$ [°]	190.0	$^{+4.2}_{-4.1}$	[185.9, 194.2]	$^{+8.6}_{-8.3}$	[181.7, 198.6]
$\lvert q/p \rvert$	0.997	$^{+0.016}_{-0.016}$	[0.981, 1.013]	$^{+0.033}_{-0.033}$	[0.964, 1.030]
ϕ [°]	−2.4	±1.2	[−3.6, −1.2]	±2.5	[−4.9, 0.1]
ΔA_{CP}	−0.00152	±0.00029	[−0.00181, −0.00123]	±0.00058	[−0.00210, −0.00094]

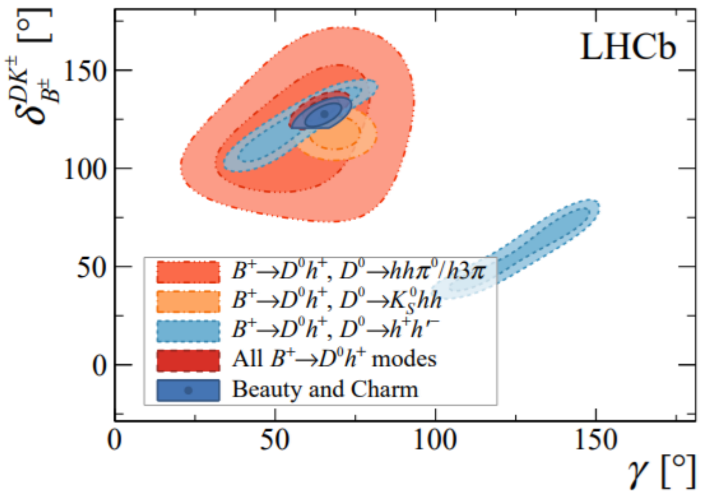


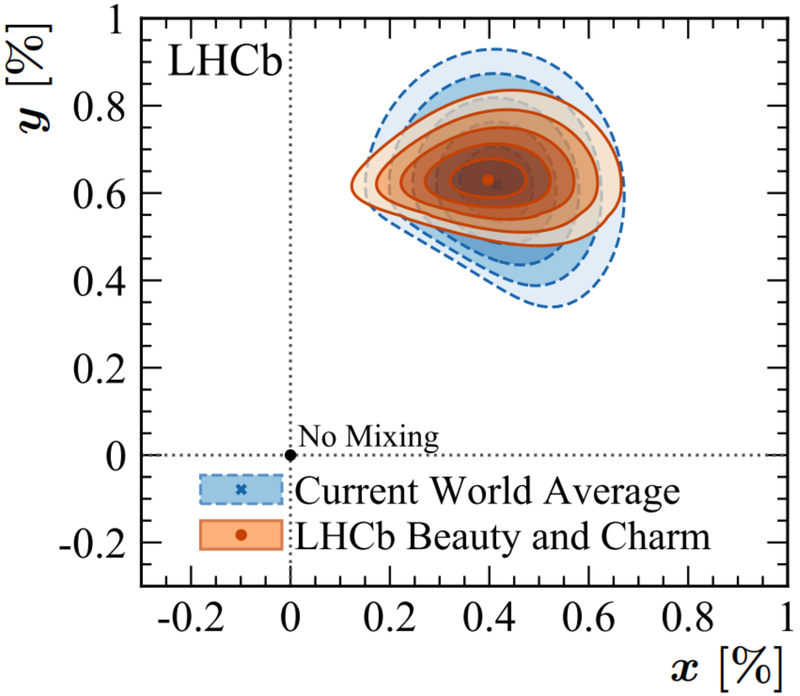
arxiv.org/pdf/2110.02350.pdf

γ results:

- Most precise measurement of both γ and charm mixing parameters from a single experiment
- Simultaneous combination has a small effect in γ measurement, but reduces the uncertainty of the charm mixing parameter y by half
- Still room for improvement, sensitivity in the B^0, B_s^0 and B^+ modes expected to improve significantly when including ongoing analyses





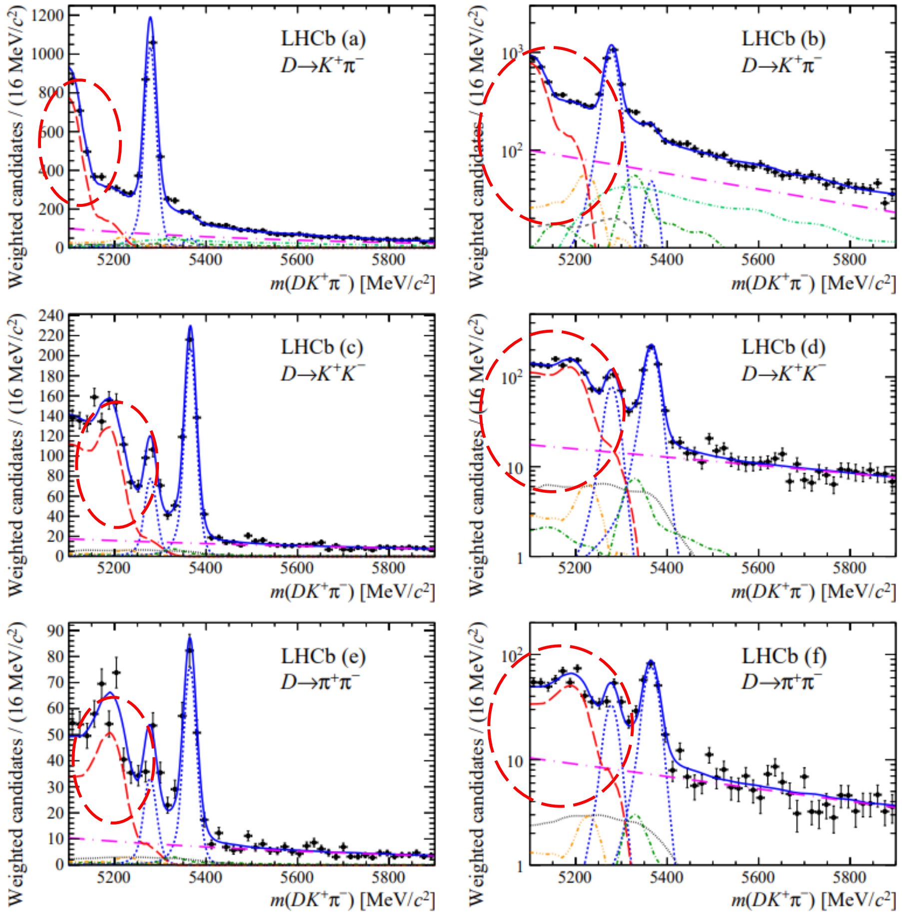


arxiv.org/pdf/1602.03455.pdf

First observation of $B^0_{(s)} \to \overline{D}^*(2007)^0 K^\pm \pi^\mp$: Motivation

- γ measurement in $B \to DK^+\pi^-$ decays, only computed using Run I data.

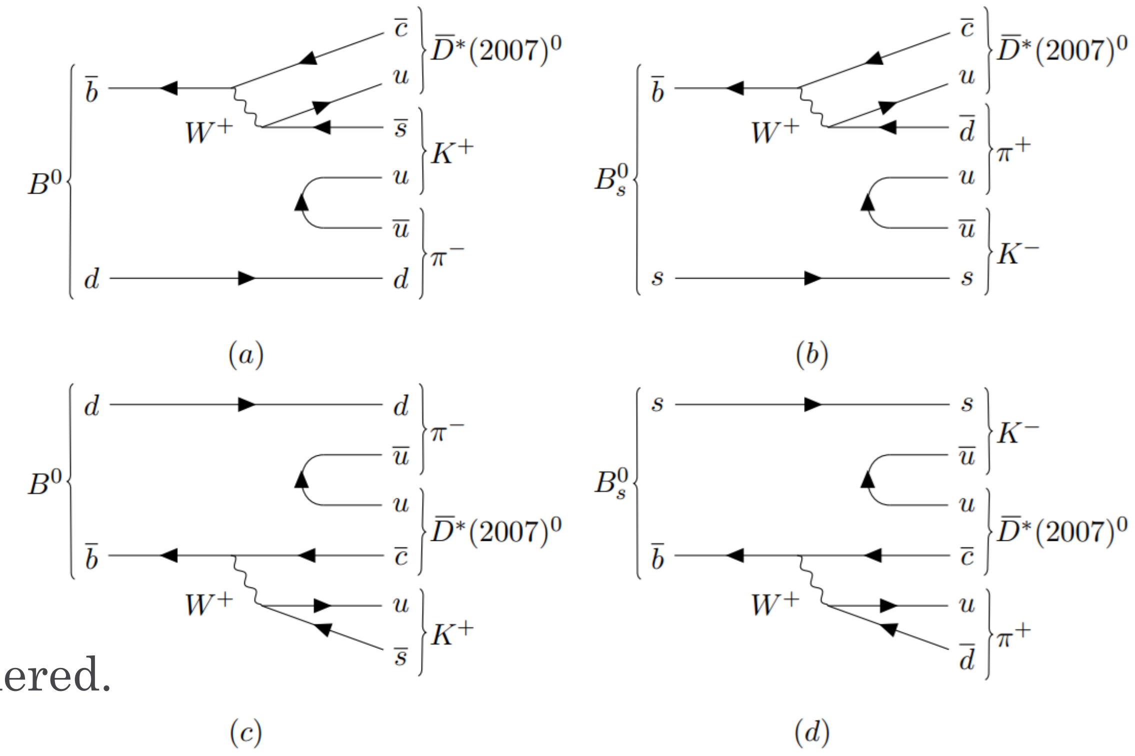
- Important source of systematic uncertainty due to the lack of knowledge of $B^0_{(s)} \to \overline{D}^*(2007)^0 K^\pm \pi^\mp$ decays



- Understanding of these decays Will direclty impact many analyses similar to $B^0 \to DK^+\pi^-$

- Also many other advantages:
  - First LHCb measurement that includes fully reconstructed $D^*(2007)$ decays
  - Also sensitive to γ measurements (although require larger data samples)
  - Provides an opportunity to inverstigate D_s^* ressonance states

Analysis strategy



- Utilizes Run II LHCb data (5.4 fb^{-1})
- Fully reconstructs the following channels:
  - $B^0 \to \overline{D}^*(2007)^0 K^+\pi^-$ (a) and (c)
  - $B^0_s \to \overline{D}^*(2007)^0 K^-\pi^+$ (b) and (d)
  - $B^0 \to \overline{D}^*(2007)^0 \pi^+\pi^-$ (normalization)

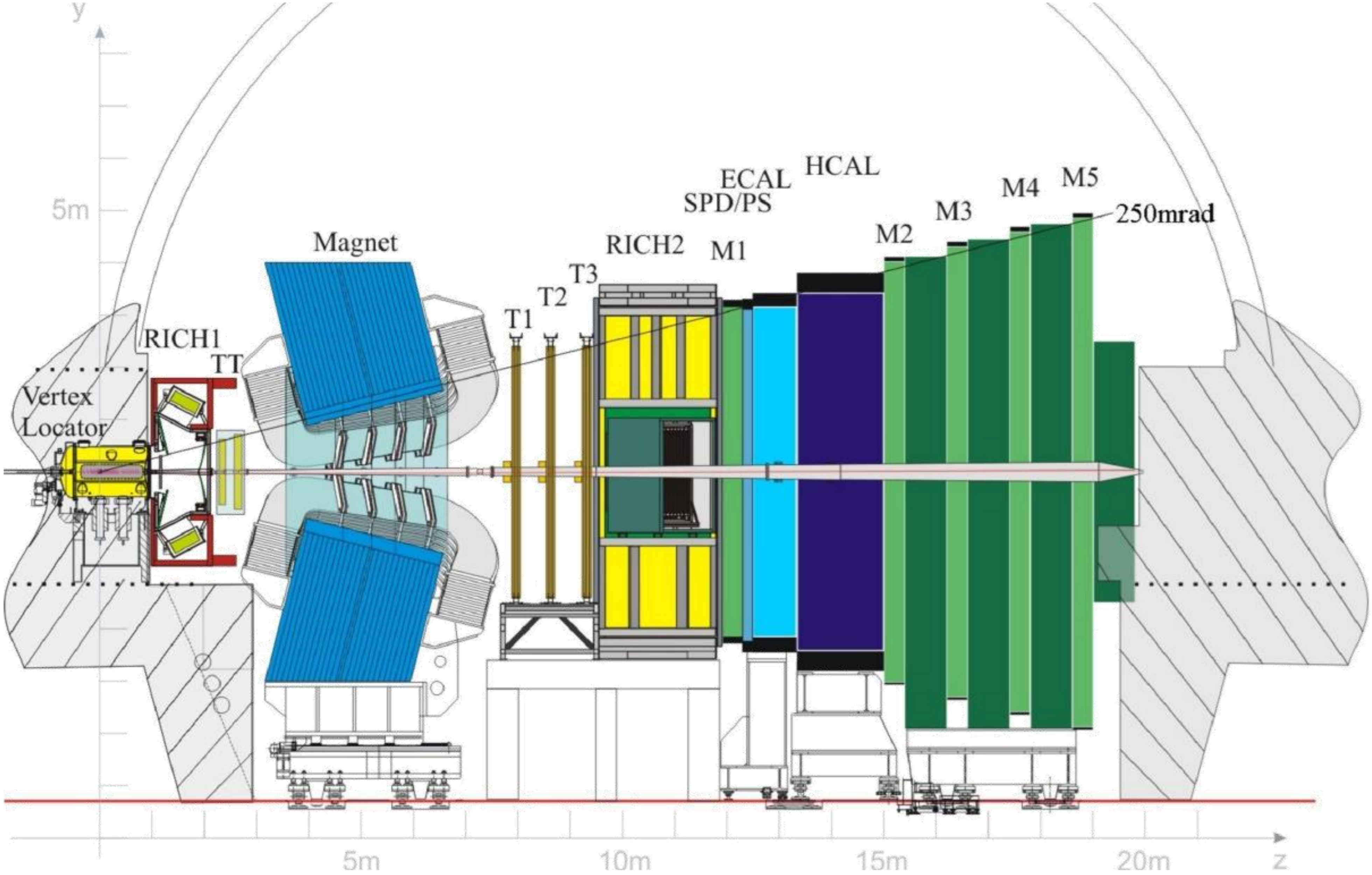
  - $\overline{D}^*(2007)^0 \to \overline{D}^0\gamma$ and $\overline{D}^*(2007)^0 \to \overline{D}^0\pi^0$ reconstructed separately.
    - Only favoured decay $\overline{D}^0 \to K^+\pi^-$ considered.
- Branching fraction measured as

$$\frac{\mathcal{B}(A)}{\mathcal{B}(B)} = \frac{Y_A}{Y_B} \cdot \frac{\epsilon_B}{\epsilon_A}$$

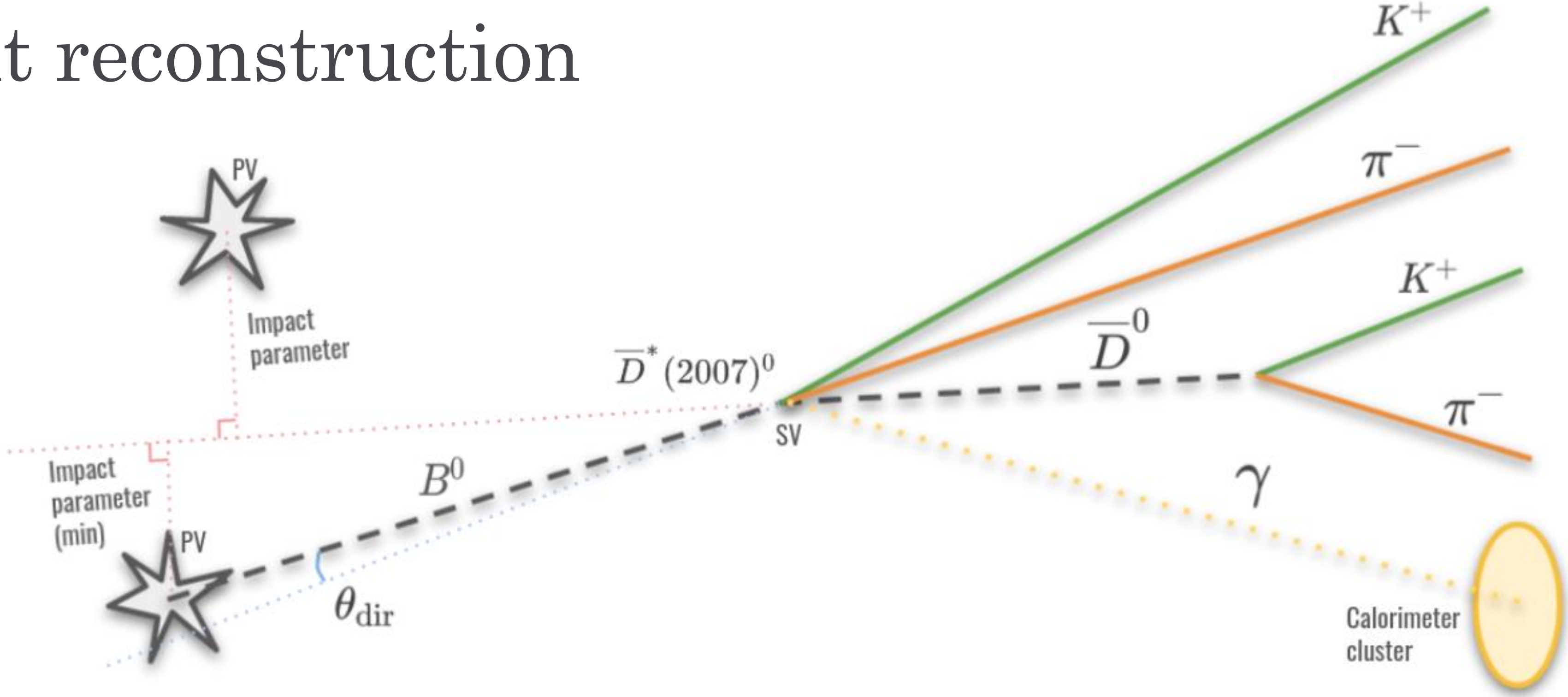
Y_A, Y_B : signal yields, obtained from a simultaneous fit of the B invariant mass distribution of all channels

ϵ_A, ϵ_B : signal efficiencies, extracted from MC generated samples, to account for acceptance, reconstruction and selection procedures. Also corrected to account for MC/Data disagreement.

The LHCb detector



Event reconstruction

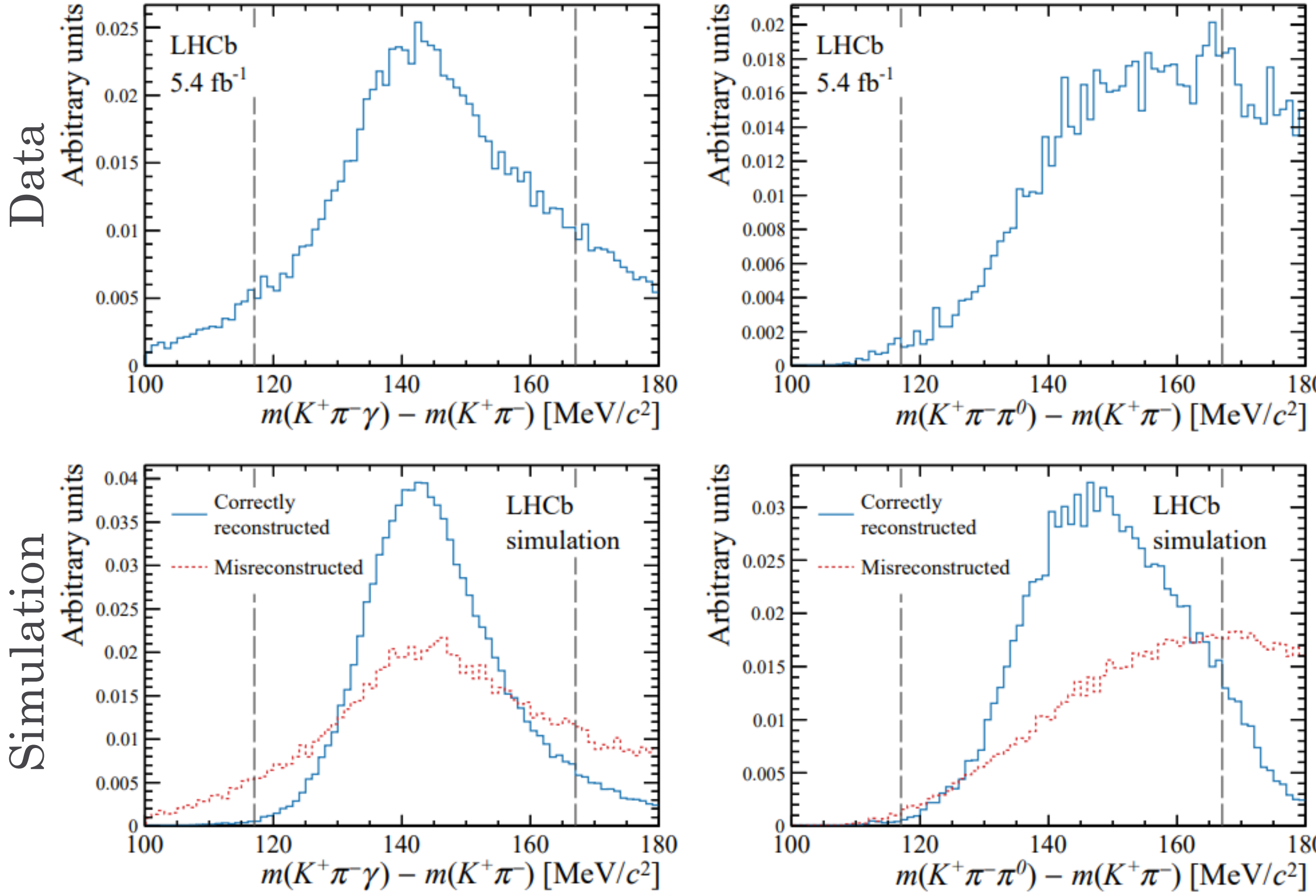


- All reconstructed particles required to be originated from common vertices
- $B^0_{(s)}$ reconstructed momentum required to match with direction reconstructed from vertices position
- $D^*(2007)^0$ required to have a large impact parameter w.r.t all possible vertices to reject prompt charm mesons.

Analysis challanges: Neutral particles reconstruction

- LHCb excels in the identification of secondary vertices and particle identification
- Reconstruction of soft neutral particles is however very challenging
  - This naturally leads to an important contribution of misreconstructed $D^*(2007)^0$ mesons

$\overline{D}^*(2007)^0 \rightarrow \overline{D}\gamma$ $\overline{D}^*(2007)^0 \rightarrow \overline{D}\pi^0$



- This is especially important when reconstructing π^0's, as two soft photons are required

- Important contribution of misreconstructed signal events (true signal event, but with a misreconstructed $D^*(2007)^0$) expected to populate the data sample.

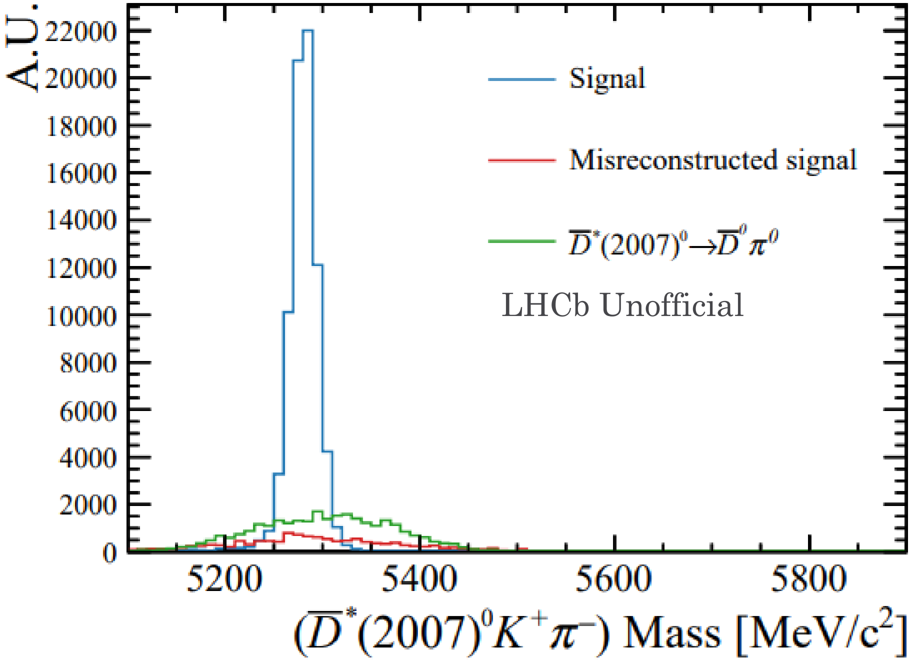
Analysis challanges: Neutral particles reconstruction

- Moreover, we have to also consider events in which the opposite $D^*(2007)^0$ decay have been reconstructed.

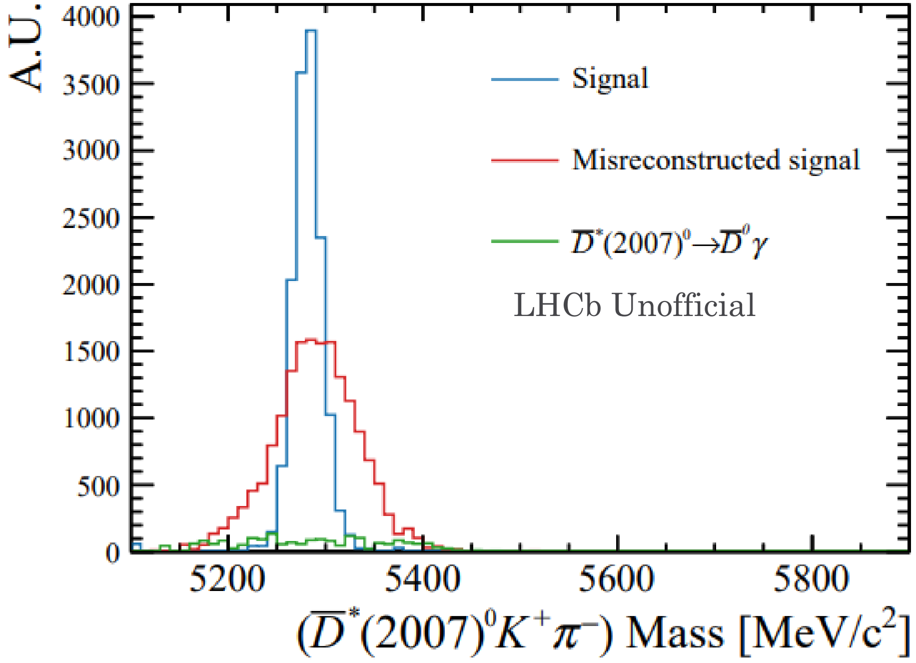
- These components are modelled independently from MC, and considered as backgrounds in the mass fit model

$B^0 \to \overline{D}^*(2007)K^+\pi^-$

$\overline{D}^*(2007)^0 \to \overline{D}\gamma$



$\overline{D}^*(2007)^0 \to \overline{D}\pi^0$



- The ratio between this components highly depends on photon multiplicity, which is typically not well reproduced in MC.
- Ratios from MC taken as reference, but set as a free parameter in the simultaneous fit.

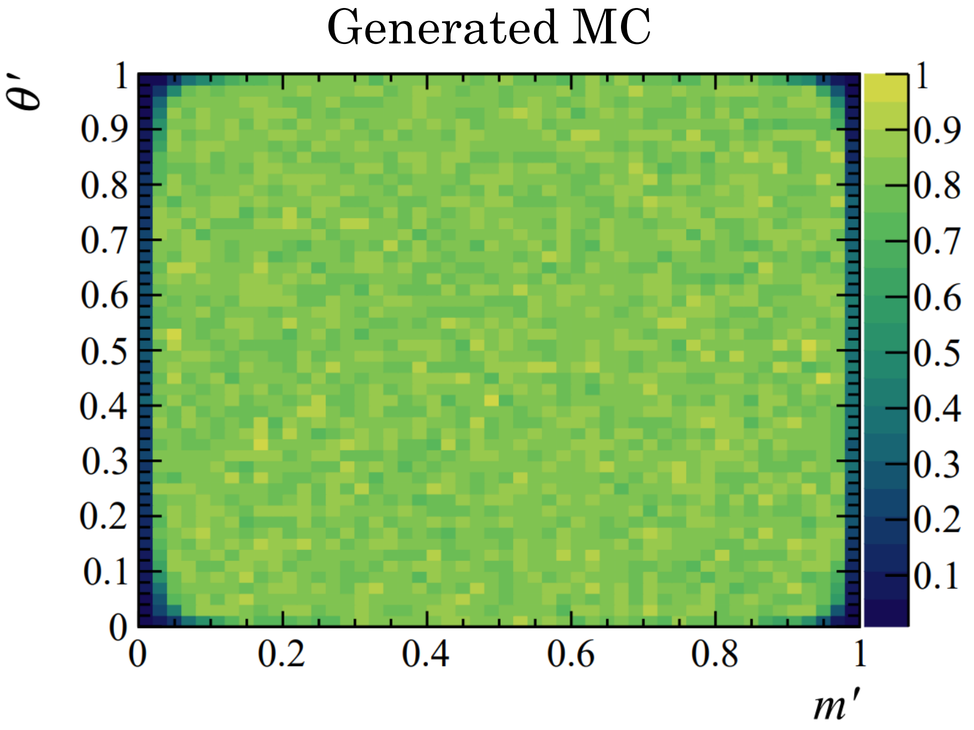
Analysis challanges: MC phase space distribution

- Since no previous model exists for the phase space distribution, MC samples are generated flat across the squared Dalitz plot (SDP), defined by

$$m' = \frac{1}{\pi}\arccos\left(2\frac{m_{12} - m_1 - m_2}{m_B - m_1 - m_2 - m_3} - 1\right)$$

$$\theta' = \frac{1}{\pi}\theta_{12}\,,$$

Where:
- m_B is the mass of the mother particle
- m_i is the mass of the i particle in the B decay
- m_{ij} is the invariant mass of the ij pair
- θ_{12} is the helicity angle of the "ij" system

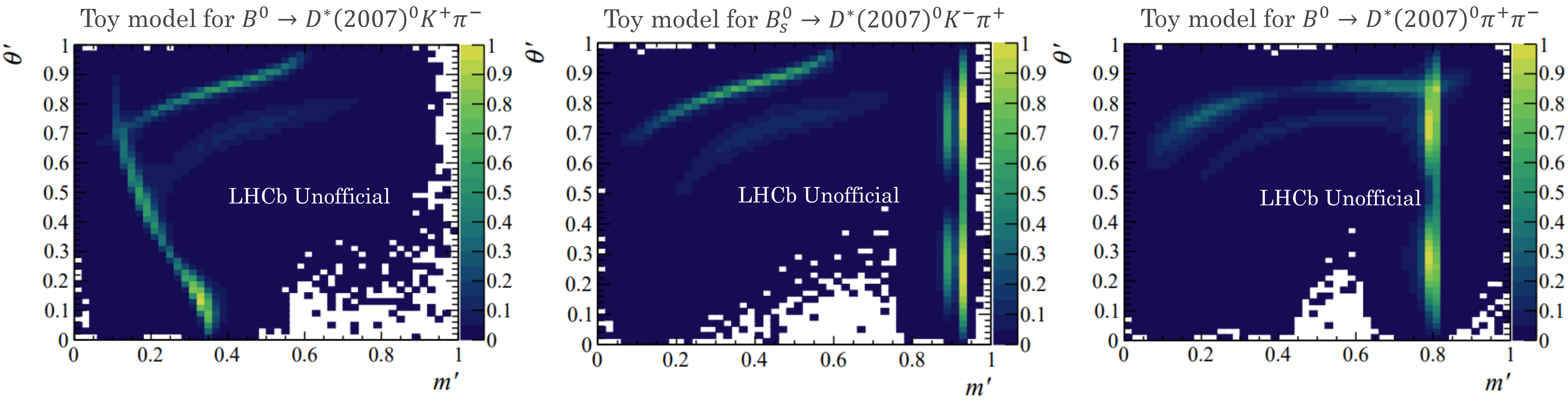


- This model ensures that all events are generated in all areas of the phase space.

- This however does not correspond to the physical phase space distribution, therefore, MC needs to be corrected for possible discrepancies

Analysis challanges: MC phase space distribution

- To correct for this effect, additional MC simples generated with approximate models with physical phase space distribution.



- Models based on previous analyses of similar decays. Considering only most important resonance states

- MC simples reweighted using:

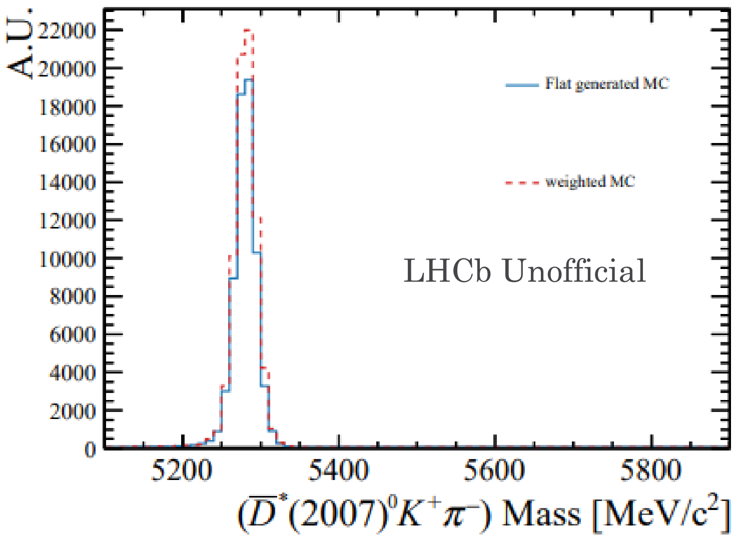
$$W(m', \theta') = \frac{f_{\mathrm{New}}(m', \theta')}{f_{\mathrm{Flat}}(m', \theta')},$$

Analysis challanges: MC phase space distribution

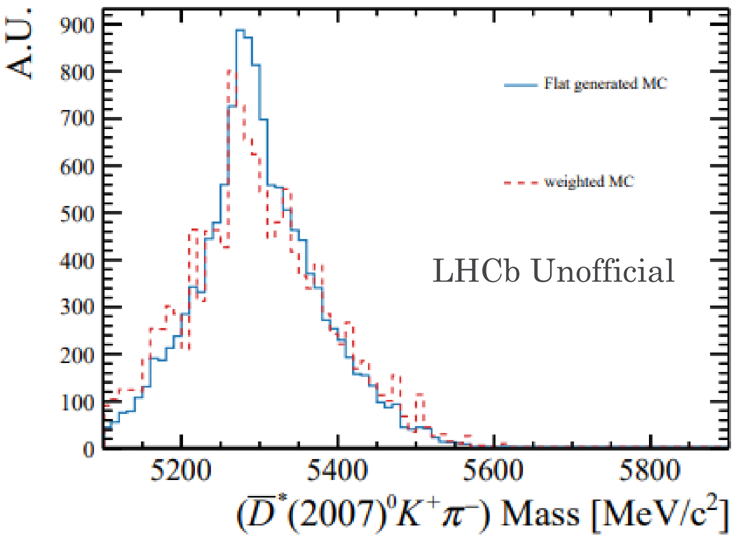
- This effect will affect both the B mass distribution as well as its efficiency.
  - For the efficiency, a data driven correction will be applied, after the mass fit model
  - However, the B mass distribution is needed for the mass fit.

$B^0 \to \overline{D}^*(2007)K^+\pi^-$

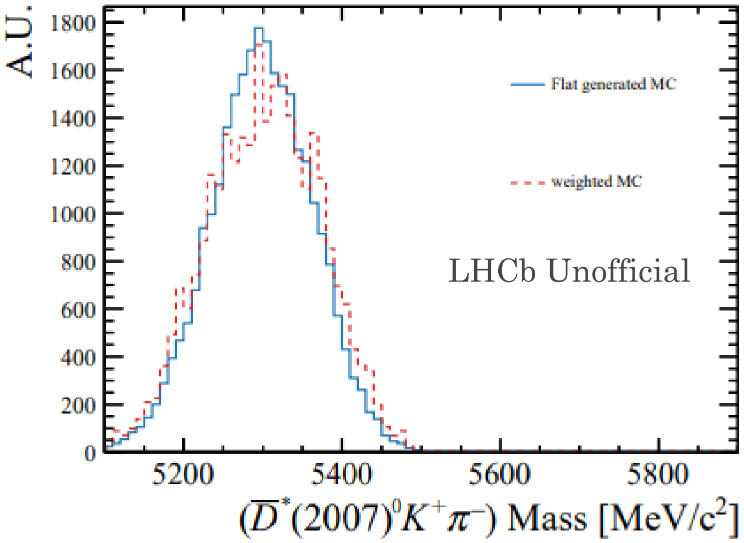
Fully rec. signal



Misrec. signal



Opposite $D^*(2007)^0$ decay



- Since B mass is mostly independent of the SDP, this has a small effect on the mass distribution shape.

Backgrounds: misidentified candidates

Since no PID requirements are applied during reconstruction, an important contribution is expecte from:

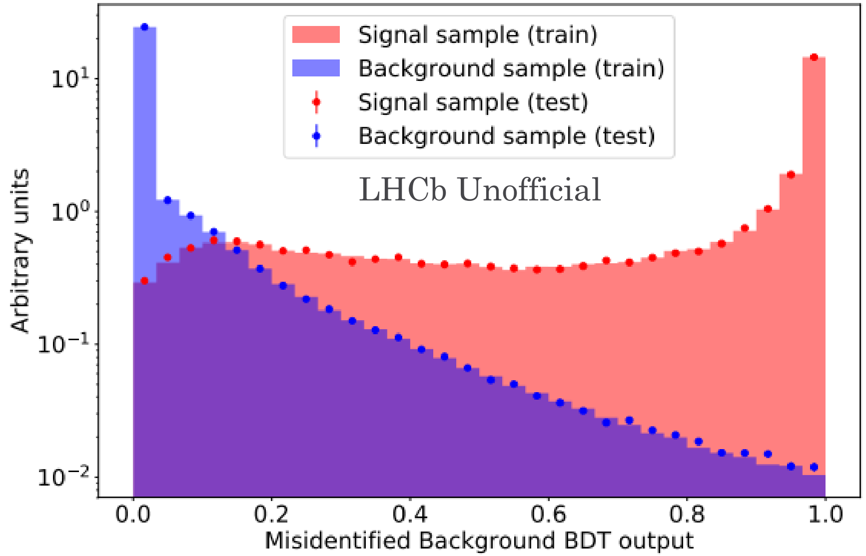
- $B^0 \to D^*(2007)^0 K^+ K^-$
- $B_s^0 \to D^*(2007)^0 K^+ K^-$
- $B^0 \to D^*(2007)^0 \pi^+ \pi^-$

(as well as crossfeed with the control channel).

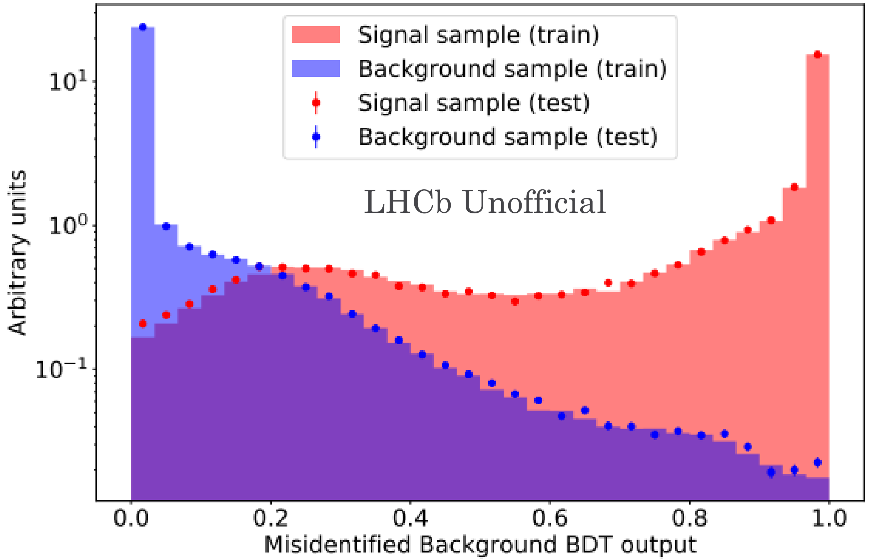
most of these events are rejected during the selection by using a Boosted Decision Tree (BDT)

- Uses PID variables as well as kinematic variables.
- Since misID backgrund are different in the control channel, a different BDT is trained.
- Both BDT are trained using MC generated simples for both the signal and background.

BDT perfomance for $B^0_{(s)} \to D^*(2007)^0 K^\pm \pi^\mp$



BDT perfomance for $B^0 \to D^*(2007)^0 \pi^+ \pi^-$

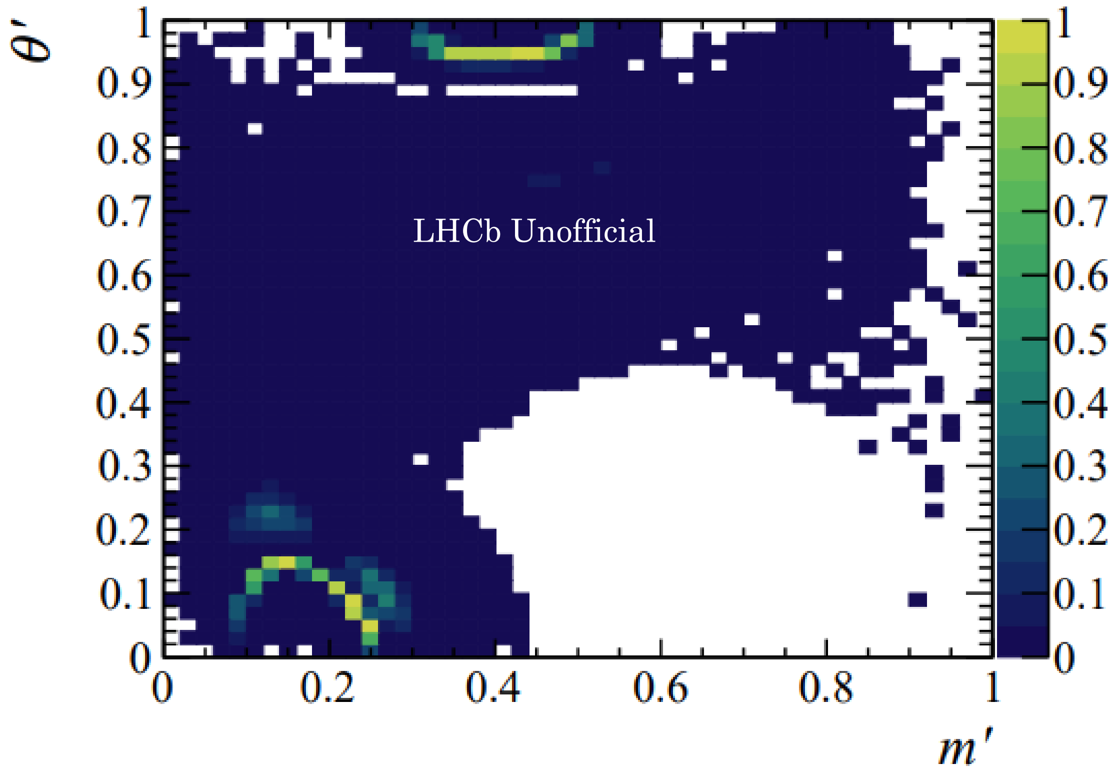


Backgrounds: misidentified candidates

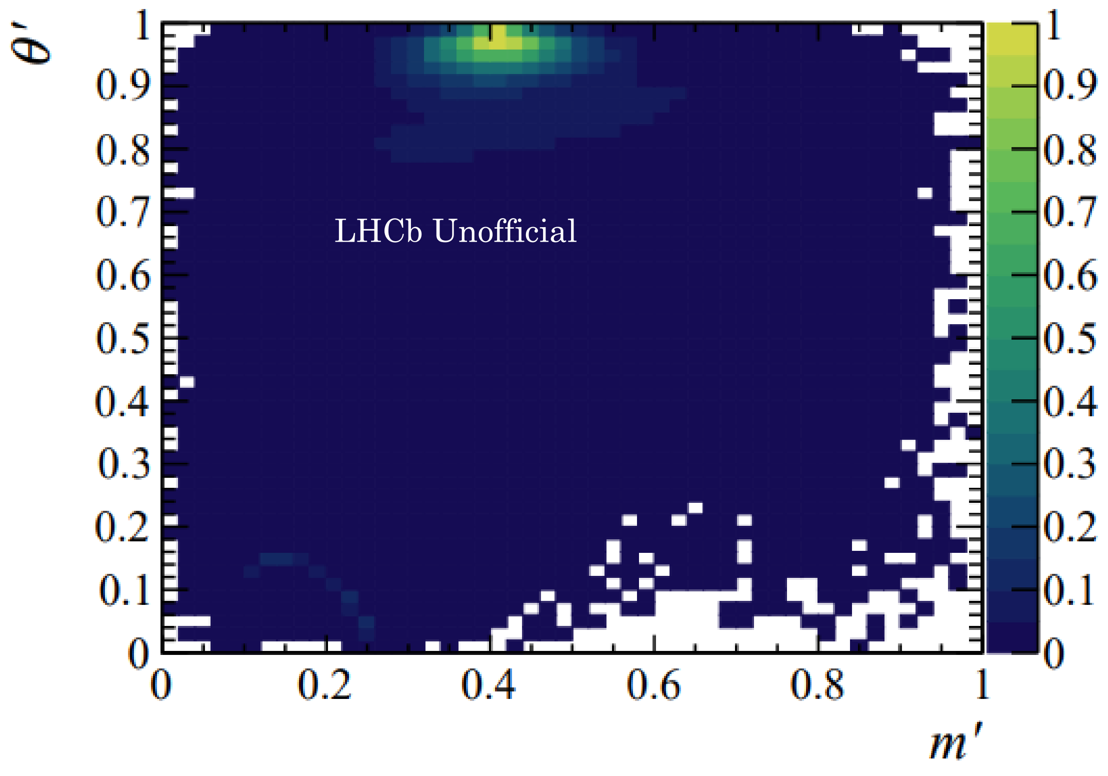
Similarly to the signal, the MC for misidentified backgrounds is generated flat across the SDP

Toy models also produced for $B^0_{(s)} \to D^*(2007)^0 K^+ K^-$ components

Toy model for $B^0 \to D^*(2007)^0 K^+ K^-$



Toy model for $B^0_s \to D^*(2007)^0 K^+ K^-$

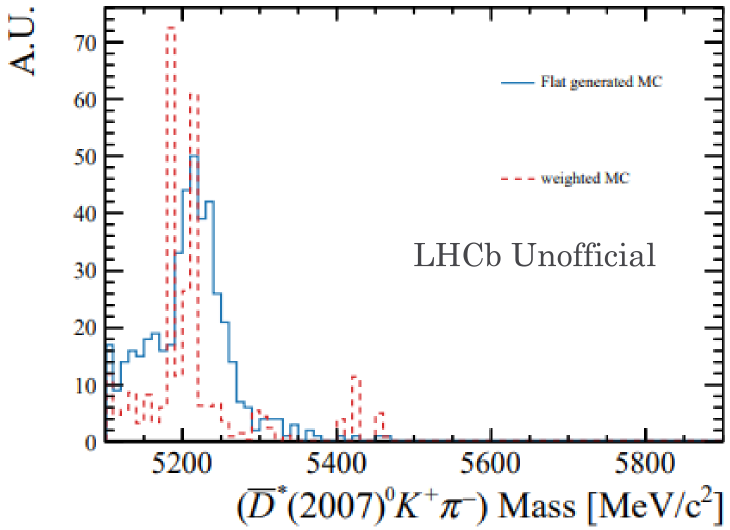


Backgrounds: misidentified candidates

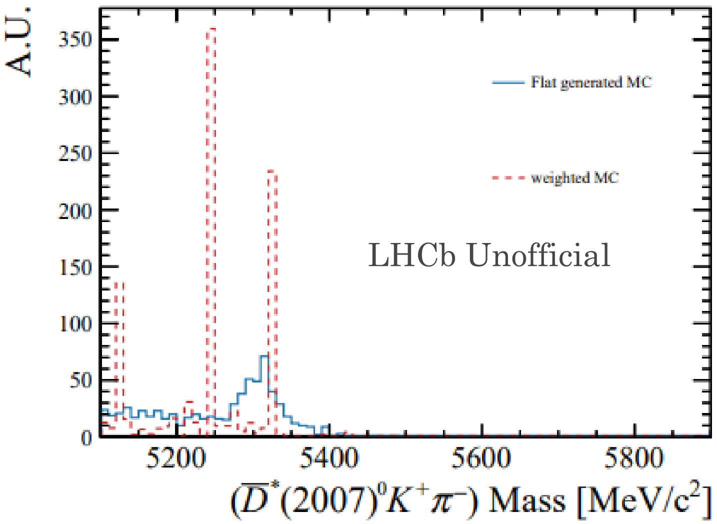
Since the misidentified rate depend on the particle's momenta, in this case the efficiency highly depends on the SDP position.

MC correction has a bigger effect in misidentified background components

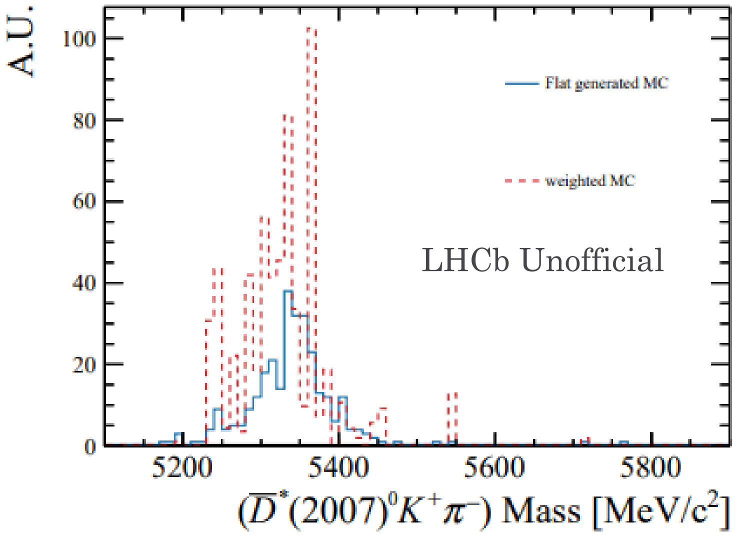
Misreconstructed $B^0 \to D^*\pi\pi$



Misreconstructed $B^0 \to D^*KK$



Misreconstructed $B_s^0 \to D^*KK$

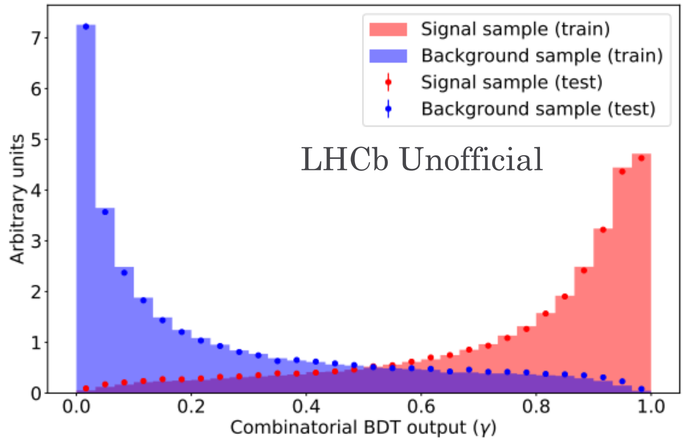


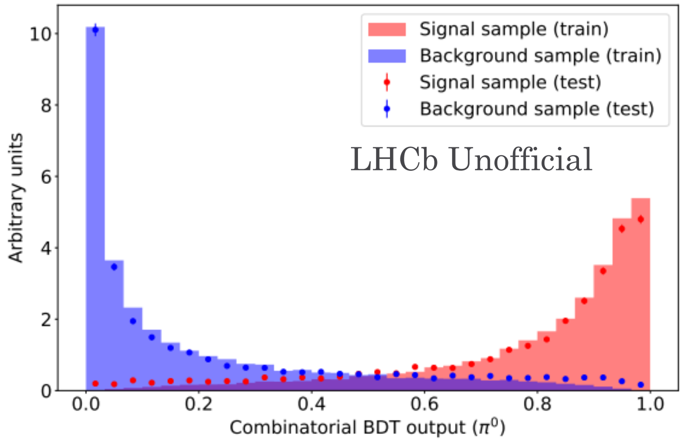
Very spiky shapes, dueto the lack of statistics for this components (most events rejected during the selection procedure)

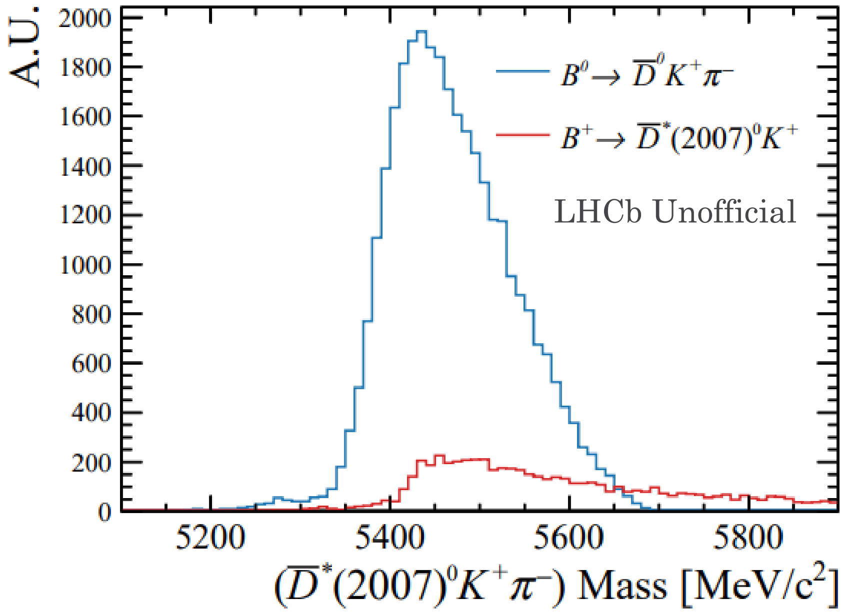
Backgrounds: partially combinatorial components

Most important component originated from $B \to Dhh$ decays, with fake neutral particle to build a fake $D^*(2007)$

Mostly rejected with a second BDT, which utilizes information from the neutrals







Contribution from $B^+ \to D^* h^+$ events also considered

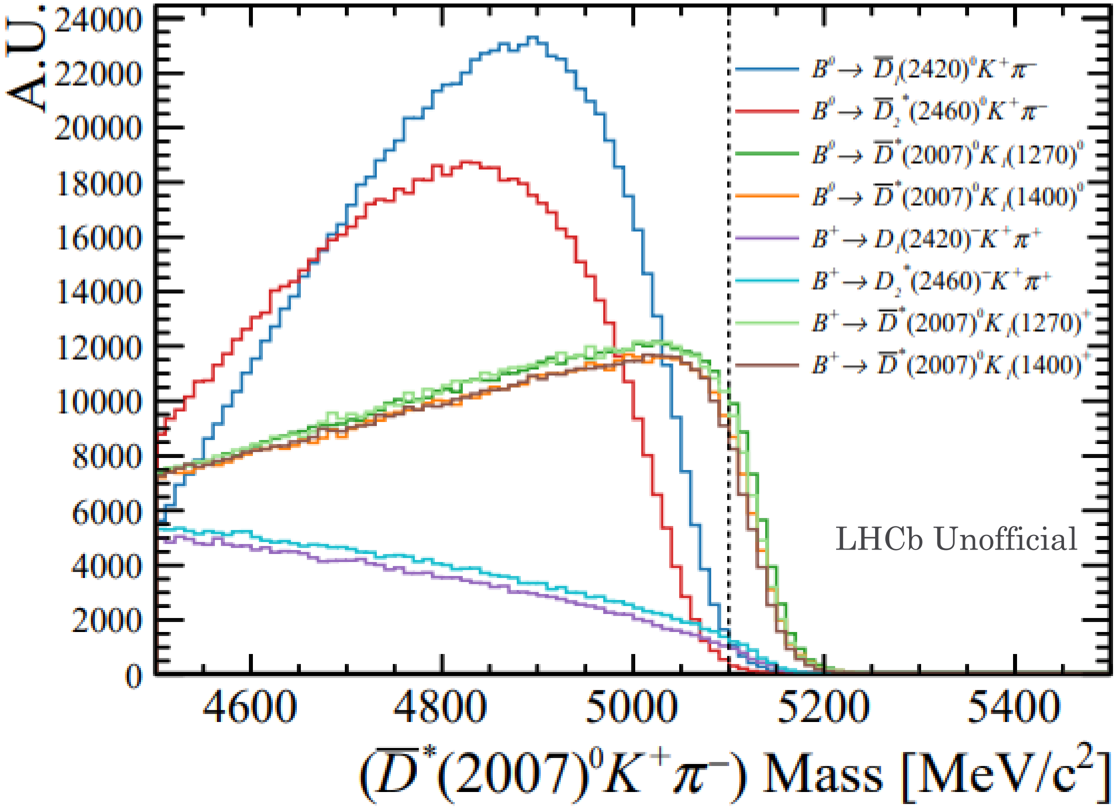
MC samples to characterize these components also generated flat in the SDP.
However, corrections not applied in this case since effects are expected to be minimal (no misidentification)

Backgrounds: partially reconstructed components

These events are not directly rejected during the selection, as they present similar topology to the signal.

Many possible channels considered. However, most components fall outside of the mass fit range

$B^0 \to \overline{D}^*(2007)^0 K^+ \pi^-$



Channel
Relevant for $B^0 \to \bar{D}^*(2007)^0 K^+ \pi^-$
$B^0 \to \bar{D}^*(2007)^0 K_1(1270)^0$
Relevant for $B_s^0 \to \bar{D}^*(2007)^0 K^- \pi^+$
$B_s^0 \to \bar{D}^*(2007)^0 \overline{K}_1(1270)^0$
Relevant for $B^0 \to \bar{D}^*(2007)^0 \pi^+ \pi^-$
$B^0 \to \bar{D}^*(2007)^0 a_1(1260)^0$ $B^0 \to \bar{D}^*(2007)^0 \eta'(958)$

Only small list needed to be added to the mass fit model.

Mass fit model (results)

Fit model contains a total of 49 degrees of freedom:

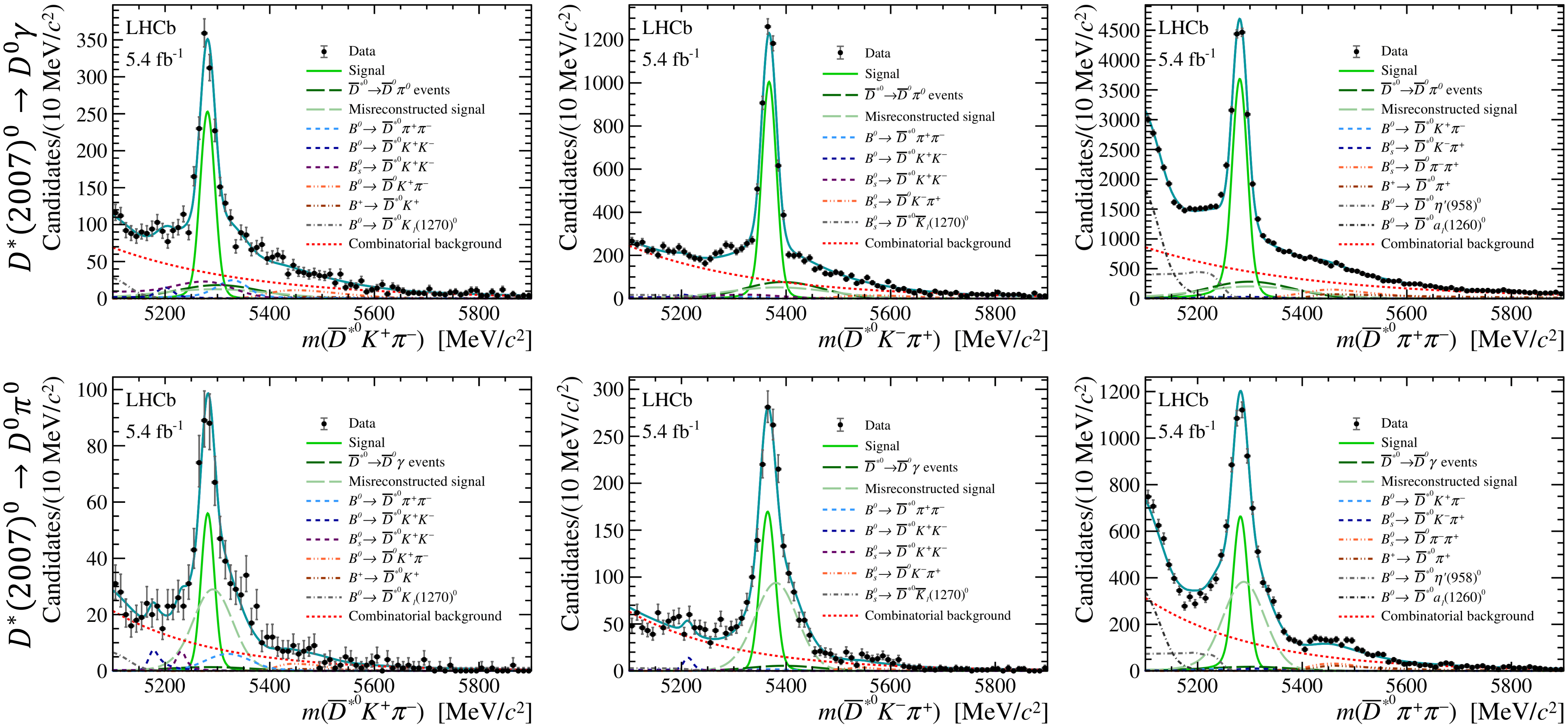
37 completely free parameters
- 6 signal yields
- 4 ratios of misreconstructed signal and wrong $D^*(2007)^0$ decay
- 6 combinatorial background yields
- 6 combinatorial background slopes
- 4 yields of misidentified $B^0 \rightarrow D^*(2007)^0 K^+ K^-$
- 3 yields of partially combinatorial $B^+ \rightarrow D^*(2007)^0 h^+$
- 4 ratios between partially reconstructed and signal yields
- 2 mean shifts
- 2 sigma scalings

12 parameters with Gaussian constraints
- 6 ratios relating misidentified background yields
- 6 ratios relating partially combinatorial background yields

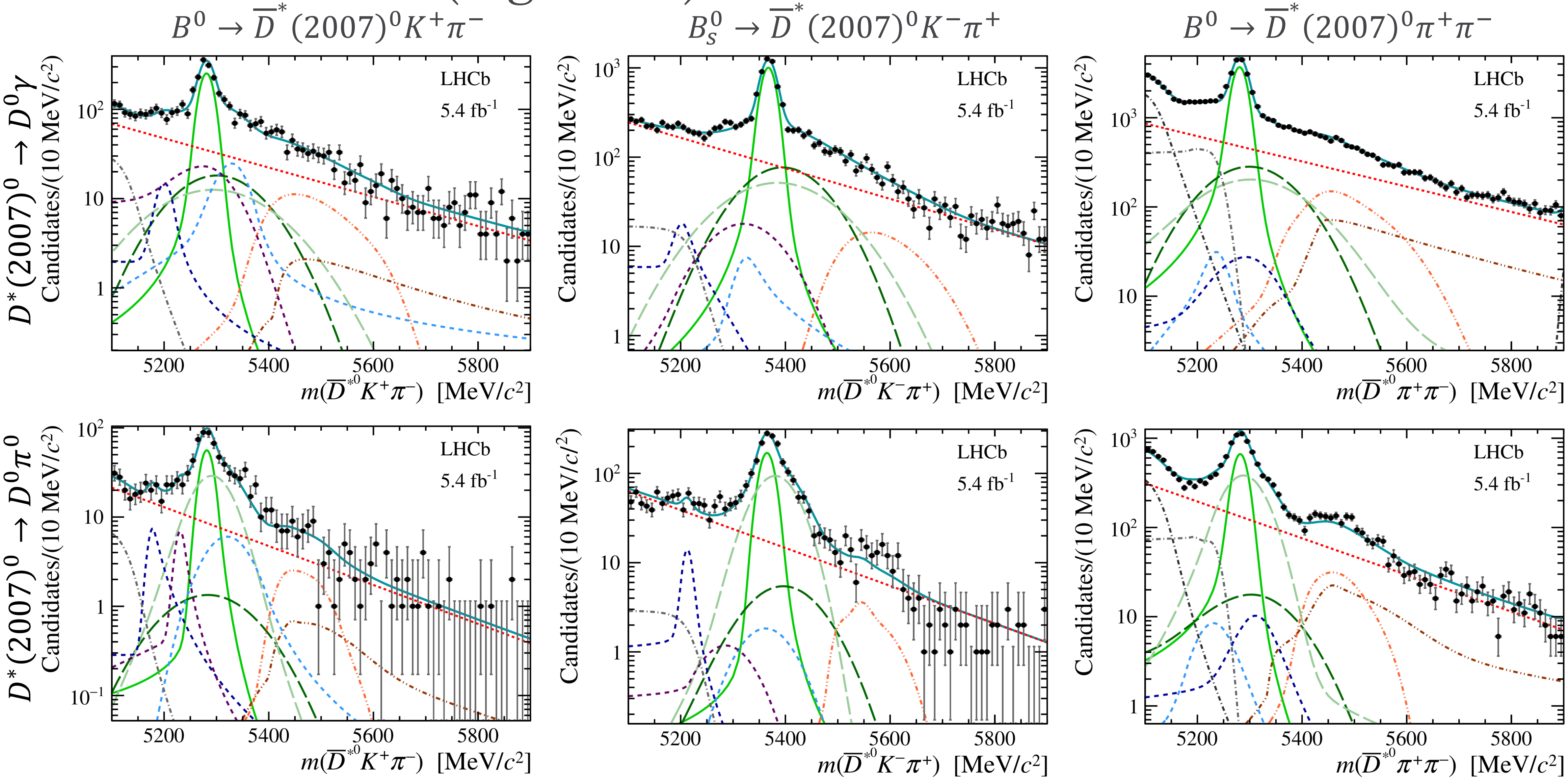
Mode	χ^2/N_{bins}
B^0, γ	1.03
B^0, π^0	0.69
B_s^0, γ	1.98
B_s^0, π^0	1.22
Control, γ	2.04
Control, π^0	2.28

Mass fit model

$B^0 \to \overline{D}^*(2007)^0 K^+\pi^-$ | $B_s^0 \to \overline{D}^*(2007)^0 K^-\pi^+$ | $B^0 \to \overline{D}^*(2007)^0 \pi^+\pi^-$



Mass fit model (log scale)



Efficiency

Computed from MC generated samples

- As before, needs to be corrected to account for differences in the phase space distribution
- To reduce systematic, we use data-driven method for this.
  - sPlot method:

$$Nf(m_B, m', \theta') = N_s g_s(m_B) h_s(m', \theta') + N_b g_b(m_B) h_b(m', \theta')$$

  - Then assume that there is a weight function such that

$$N_s h_s(m', \theta') = \int w_s(m_B) N f(m_B, m', \theta') dm_B$$

$$\langle w_s(m_B) \rangle = \int w_s(m_B) N g(m_B) dm_B = N_s \,,$$

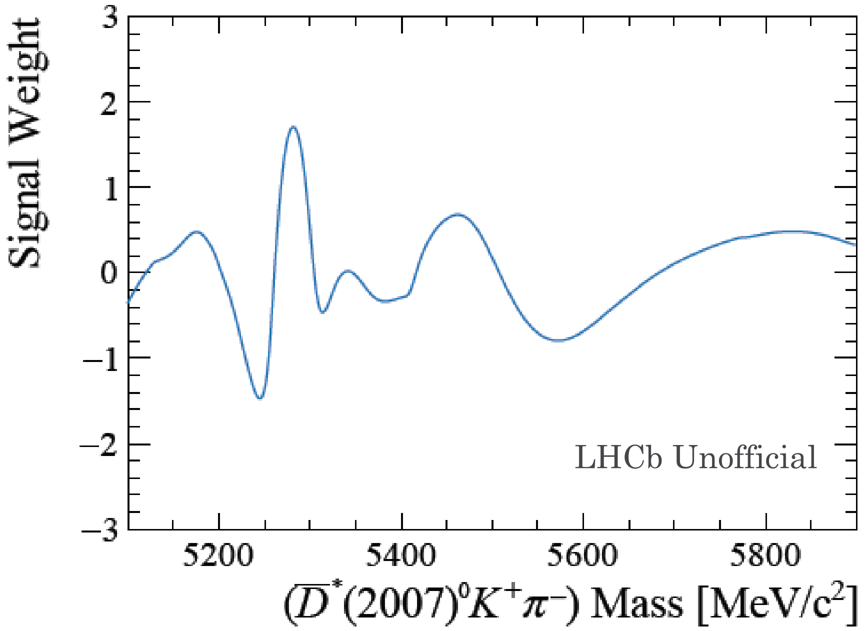
Efficiency

There are infinite $w_s(m_B)$ that satisfy this relation, common choice is to select $w_s(m_B)$ so it minimizes its variance

This leads to $$w_s(m_B) = \frac{\alpha_s g_s(m_B) + \alpha_b g_b(m_B)}{N g(m_B)} ,$$

$$\begin{pmatrix} W_{ss} & W_{sb} \\ W_{sb} & W_{bb} \end{pmatrix} \cdot \begin{pmatrix} \alpha_s \\ \alpha_b \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} ,$$

$$W_{xy} = \int \frac{g_x(m_B) g_y(m_B)}{N g(m_B)} dm_B .$$



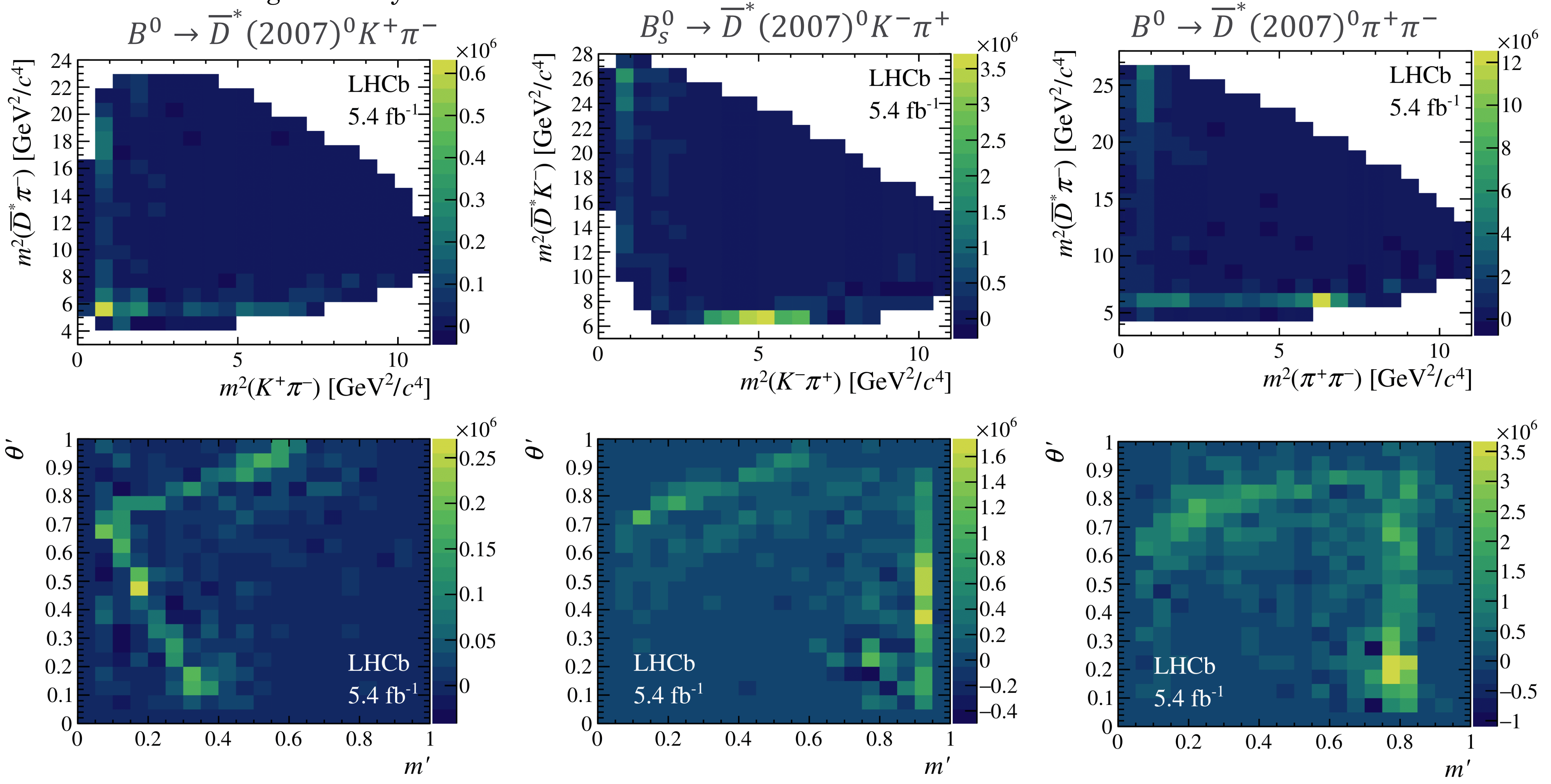
This can be extended to N components to obtain a different weight to Project each one of the components present in the mass fit.

However, this method is very dependent on statistics, and thus some of the minor components are not very reliable.

However, this works incredibly well to project signal phase space distributions!

Phase space distributions

The reweighting method not only is crucial for the efficiency estimation, but also enables to study the pase space dsitrbution of signal decays



Efficiency

With weight distribution, we can apply the weights to obtain corrected efficiency

$$\langle \epsilon(X) \rangle = \frac{\sum_i w_X(m_{B\,i})}{\sum_i w_X(m_{B\,i})/\epsilon_X(m'_i, \theta'_i)} \,.$$

Or alternatively cosnsists in modifying our equation for the relative branching fraction

$$\frac{\mathcal{B}(A)}{\mathcal{B}(B)} = \frac{N(A)/\langle \epsilon(A) \rangle}{N(B)/\langle \epsilon(B) \rangle} = \frac{\sum_i w_A(m_{B\,i})/\epsilon_A(m'_i, \theta'_i)}{\sum_j w_B(m_{B\,j})/\epsilon_B(m'_j, \theta'_j)} \,,$$

This has a small effect on channels with $D^*(2007)^0 \to D^0\gamma$ but has a big impact in the π^0 channels

Channel	$\langle \epsilon \rangle_{\mathrm{SDP}}$	$\langle \epsilon \rangle_{\mathrm{data}}$
$B^0 \to \overline{D}^*(2007)^0 K^+\pi^-, \overline{D}^*(2007)^0 \to \overline{D}^0\gamma$	$1.86 \cdot 10^{-4}$	$2.00 \cdot 10^{-4}$
$B^0 \to \overline{D}^*(2007)^0 K^+\pi^-, \overline{D}^*(2007)^0 \to \overline{D}^0\pi^0$	$3.10 \cdot 10^{-5}$	$2.08 \cdot 10^{-5}$
$B^0_s \to \overline{D}^*(2007)^0 K^-\pi^+, \overline{D}^*(2007)^0 \to \overline{D}^0\gamma$	$1.99 \cdot 10^{-4}$	$2.18 \cdot 10^{-4}$
$B^0_s \to \overline{D}^*(2007)^0 K^-\pi^+, \overline{D}^*(2007)^0 \to \overline{D}^0\pi^0$	$3.38 \cdot 10^{-5}$	$2.17 \cdot 10^{-5}$
$B^0 \to \overline{D}^*(2007)^0 \pi^+\pi^-, \overline{D}^*(2007)^0 \to \overline{D}^0\gamma$	$2.55 \cdot 10^{-4}$	$2.65 \cdot 10^{-4}$
$B^0 \to \overline{D}^*(2007)^0 \pi^+\pi^-, \overline{D}^*(2007)^0 \to \overline{D}^0\pi^0$	$4.10 \cdot 10^{-5}$	$2.48 \cdot 10^{-5}$

Systematic uncertainties

Large list of systematic uncertainties considered, depending on their origin, we can divide them in two groups

- Systematics that affect the yields
    - Fit stability *
    - Contributions from additional backgrounds
    - Multiple and Duplicated candidates *
    - Background modelling
- Systematics that affect the efficiency
    - Resampling of PID variables
    - MC statistics
    - Binning scheme in reweighting procedure *
    - Trigger efficiency systematics
    - MC/Data disagreement
    - sWeights biases due to correlations *

Systematic uncertainties: summary

	$\frac{\mathcal{B}(B^0\to\bar{D}^{*0}_{\gamma}K^+\pi^-)}{\mathcal{B}(B^0\to\bar{D}^{*0}_{\gamma}\pi^+\pi^-)}$	$\frac{\mathcal{B}(B^0\to\bar{D}^{*0}_{\pi^0}K^+\pi^-)}{\mathcal{B}(B^0\to\bar{D}^{*0}_{\pi^0}\pi^+\pi^-)}$	$\frac{\mathcal{B}(B^0_s\to\bar{D}^{*0}_{\gamma}K^-\pi^+)}{\mathcal{B}(B^0\to\bar{D}^{*0}_{\gamma}\pi^+\pi^-)}$	$\frac{\mathcal{B}(B^0_s\to\bar{D}^{*0}_{\pi^0}K^-\pi^+)}{\mathcal{B}(B^0\to\bar{D}^{*0}_{\pi^0}\pi^+\pi^-)}$	$\frac{\mathcal{B}(B^0\to\bar{D}^{*0}_{\gamma}K^+\pi^-)}{\mathcal{B}(B^0_s\to\bar{D}^{*0}_{\gamma}K^-\pi^+)}$	$\frac{\mathcal{B}(B^0\to\bar{D}^{*0}_{\pi^0}K^+\pi^-)}{\mathcal{B}(B^0_s\to\bar{D}^{*0}_{\pi^0}K^-\pi^+)}$
Central value	0.083	0.0850	1.189	1.099	0.070	0.077
σ_{stat}	$5.1\cdot10^{-3}$ (6.1%)	$6.9\cdot10^{-3}$ (8.1%)	$3.2\cdot10^{-2}$ (2.7%)	$5.0\cdot10^{-2}$ (4.5%)	$4.1\cdot10^{-3}$ (5.9%)	$5.7\cdot10^{-3}$ (7.4%)
$\sigma^*_{\text{fit bias}}$	$4.8\cdot10^{-4}$ (0.6%)	$6.9\cdot10^{-4}$ (0.8%)	$3.8\cdot10^{-3}$ (0.3%)	$1.5\cdot10^{-3}$ (0.1%)	$6.3\cdot10^{-4}$ (0.9%)	$7.3\cdot10^{-4}$ (1.0%)
σ^*_{model}	$4.7\cdot10^{-3}$ (5.6%)	$3.2\cdot10^{-3}$ (3.8%)	$5.9\cdot10^{-2}$ (4.9%)	$2.3\cdot10^{-2}$ (2.1%)	$4.4\cdot10^{-4}$ (0.6%)	$4.6\cdot10^{-3}$ (6.0%)
$\sigma^*_{\Lambda^0_b}$	$2.5\cdot10^{-4}$ (0.3%)	$1.3\cdot10^{-3}$ (1.5%)	$2.9\cdot10^{-2}$ (2.5%)	$4.8\cdot10^{-2}$ (4.4%)	$1.6\cdot10^{-3}$ (2.3%)	$2.1\cdot10^{-3}$ (2.7%)
$\sigma^*_{\text{mult cand}}$	$2.0\cdot10^{-3}$ (2.4%)	$2.1\cdot10^{-3}$ (2.5%)	$5.9\cdot10^{-2}$ (5.0%)	$1.8\cdot10^{-3}$ (0.2%)	$5.4\cdot10^{-3}$ (7.8%)	$2.1\cdot10^{-3}$ (2.7%)
$\sigma^\dagger_{\text{MC stats}}$	$9.9\cdot10^{-4}$ (1.2%)	$4.8\cdot10^{-3}$ (5.7%)	$1.4\cdot10^{-2}$ (1.2%)	$6.0\cdot10^{-2}$ (5.5%)	$9.8\cdot10^{-4}$ (1.4%)	$5.4\cdot10^{-3}$ (7.1%)
σ^*_{PID}	$1.1\cdot10^{-4}$ (0.10%)	$1.9\cdot10^{-5}$ (0.0%)	$3.2\cdot10^{-3}$ (0.3%)	$2.5\cdot10^{-3}$ (0.2%)	$1.1\cdot10^{-4}$ (0.2%)	$1.8\cdot10^{-4}$ (0.2%)
$\sigma^*_{\text{data/MC}}$	$5.8\cdot10^{-5}$ (0.1%)	$2.3\cdot10^{-3}$ (3.4%)	$7.0\cdot10^{-3}$ (0.6%)	$2.7\cdot10^{-2}$ (2.4%)	$3.6\cdot10^{-4}$ (0.5%)	$7.3\cdot10^{-4}$ (1.0%)
$\sigma^*_{\text{trigger}}$	$9.2\cdot10^{-4}$ (1.1%)	$3.5\cdot10^{-4}$ (0.4%)	$5.3\cdot10^{-3}$ (0.4%)	$1.3\cdot10^{-2}$ (1.2%)	$4.7\cdot10^{-4}$ (0.7%)	$6.1\cdot10^{-4}$ (0.8%)
$\sigma^\dagger_{\text{SDP bins}}$	$1.2\cdot10^{-3}$ (1.4%)	$6.4\cdot10^{-3}$ (7.6%)	$2.3\cdot10^{-2}$ (1.9%)	$7.6\cdot10^{-2}$ (6.9%)	$1.5\cdot10^{-3}$ (2.1%)	$5.2\cdot10^{-3}$ (6.7%)
$\sigma^*_{\tau_{B^0_s}}$	— —	— —	$7.2\cdot10^{-3}$ (0.6%)	$5.4\cdot10^{-3}$ (0.5%)	$4.2\cdot10^{-4}$ (0.6%)	$3.8\cdot10^{-4}$ (0.5%)
$\sigma^*_{\text{weights}}$	$5.1\cdot10^{-4}$ (0.6%)	$5.2\cdot10^{-4}$ (0.6%)	$1.2\cdot10^{-2}$ (1.0%)	$1.1\cdot10^{-2}$ (1.0%)	$1.1\cdot10^{-3}$ (1.6%)	$1.2\cdot10^{-3}$ (1.6%)
$\sigma^{\dagger\ \text{total}}_{\text{syst}}$	$1.5\cdot10^{-3}$ (1.8%)	$8.1\cdot10^{-3}$ (9.5%)	$2.7\cdot10^{-2}$ (2.3%)	$9.7\cdot10^{-2}$ (8.8%)	$1.8\cdot10^{-3}$ (2.5%)	$7.5\cdot10^{-3}$ (9.8%)
$\sigma^{*\ \text{total}}_{\text{syst}}$	$5.2\cdot10^{-3}$ (6.2%)	$5.1\cdot10^{-3}$ (6.1%)	$9.0\cdot10^{-2}$ (7.7%)	$6.3\cdot10^{-2}$ (5.3%)	$5.9\cdot10^{-3}$ (8.3%)	$5.8\cdot10^{-3}$ (8.1%)
$\sigma^*_{f_s/f_d}$	— —	— —	$3.7\cdot10^{-2}$ (3.1%)	$3.4\cdot10^{-2}$ (3.1%)	$2.2\cdot10^{-3}$ (3.1%)	$2.4\cdot10^{-3}$ (3.1%)

Systematics with * are considered to be correlated, while systematics with † are considered as completely uncorrelated.

Larger systematics due to the challenging mass fit model and the large number of components

Channels with $D^*(2007)^0 \to D^0\pi^0$ are also affected by low statistics

Combining the results

Computing the BF for both D^* decays separately allow us to have the following cross check

$$\frac{\mathcal{B}(A)}{\mathcal{B}(B)} = \frac{Y_A}{Y_B} \cdot \frac{\epsilon_B}{\epsilon_A}$$

$$B^0 \to \overline{D}^*(2007)^0 K^+\pi^- \ : \quad \frac{\mathcal{B}(\overline{D}^*(2007)^0 \to \overline{D}^0\gamma)}{\mathcal{B}(\overline{D}^*(2007)^0 \to \overline{D}^0\pi^0)} = 0.53 \pm 0.06\,,$$

$$B_s^0 \to \overline{D}^*(2007)^0 K^-\pi^+ \ : \quad \frac{\mathcal{B}(\overline{D}^*(2007)^0 \to \overline{D}^0\gamma)}{\mathcal{B}(\overline{D}^*(2007)^0 \to \overline{D}^0\pi^0)} = 0.59 \pm 0.04\,,$$

$$B^0 \to \overline{D}^*(2007)^0 \pi^+\pi^- \ : \quad \frac{\mathcal{B}(\overline{D}^*(2007)^0 \to \overline{D}^0\gamma)}{\mathcal{B}(\overline{D}^*(2007)^0 \to \overline{D}^0\pi^0)} = 0.54 \pm 0.04\,,$$

Where here we have only included statistical uncertainties, as these are already consistent within 1σ with the previous results

$$\text{BESIII} \ : \quad \frac{\mathcal{B}(\overline{D}^*(2007)^0 \to \overline{D}^0\gamma)}{\mathcal{B}(\overline{D}^*(2007)^0 \to \overline{D}^0\pi^0)} = 0.55 \pm 0.02\,,$$

$$\text{LHCb} \ : \quad \frac{\mathcal{B}(\overline{D}^*(2007)^0 \to \overline{D}^0\gamma)}{\mathcal{B}(\overline{D}^*(2007)^0 \to \overline{D}^0\pi^0)} = 0.53 \pm 0.03\,,$$

Combining the results

Branching fraction measurements accsessible through both $D^*(2007)^0$ decays

$$\frac{\mathcal{B}(A)}{\mathcal{B}(B)} = \frac{Y_A}{Y_B} \cdot \frac{\epsilon_B}{\epsilon_A} \cdot \left(\frac{f_s}{f_d}\right)$$

$$\bar{D}^*(2007)^0 \to \bar{D}^0\gamma \ : \quad \frac{\mathcal{B}(B^0 \to \bar{D}^*(2007)^0 K^+\pi^-)}{\mathcal{B}(B^0 \to \bar{D}^*(2007)^0\pi^+\pi^-)} = 0.083 \pm 0.005\,,$$

$$\bar{D}^*(2007)^0 \to \bar{D}^0\pi^0 \ : \quad \frac{\mathcal{B}(B^0 \to \bar{D}^*(2007)^0 K^+\pi^-)}{\mathcal{B}(B^0 \to \bar{D}^*(2007)^0\pi^+\pi^-)} = 0.085 \pm 0.006\,,$$

$$\bar{D}^*(2007)^0 \to \bar{D}^0\gamma \ : \quad \frac{\mathcal{B}(B_s^0 \to \bar{D}^*(2007)^0 K^-\pi^+)}{\mathcal{B}(B^0 \to \bar{D}^*(2007)^0\pi^+\pi^-)} = 1.19 \pm 0.03\,,$$

$$\bar{D}^*(2007)^0 \to \bar{D}^0\pi^0 \ : \quad \frac{\mathcal{B}(B_s^0 \to \bar{D}^*(2007)^0 K^-\pi^+)}{\mathcal{B}(B^0 \to \bar{D}^*(2007)^0\pi^+\pi^-)} = 1.10 \pm 0.04\,,$$

$$\bar{D}^*(2007)^0 \to \bar{D}^0\gamma \ : \quad \frac{\mathcal{B}(B^0 \to \bar{D}^*(2007)^0 K^+\pi^-)}{\mathcal{B}(B_s^0 \to \bar{D}^*(2007)^0 K^-\pi^+)} = 0.070 \pm 0.004\,,$$

$$\bar{D}^*(2007)^0 \to \bar{D}^0\pi^0 \ : \quad \frac{\mathcal{B}(B^0 \to \bar{D}^*(2007)^0 K^+\pi^-)}{\mathcal{B}(B^0 \to \bar{D}^*(2007)^0 K^-\pi^+)} = 0.077 \pm 0.006\,,$$

Additional factor to statistical uncertainty added using

$$\sigma\left(\frac{\mathcal{B}(A)}{\mathcal{B}(B)}\right)^2 = \frac{\mathcal{B}(A)}{\mathcal{B}(B)}\left(\frac{\sigma_{N_A}^2}{N_A^2} + \frac{\sigma_{N_B}^2}{N_B^2} - 2\frac{\sigma_{N_A}}{N_A}\frac{\sigma_{N_B}}{N_B}\rho_{AB}\right)$$

	$N(B^0,\gamma)$	$N(B^0,\pi^0)$	$N(B_s^0,\gamma)$	$N(B_s^0,\pi^0)$	$N(\text{Control},\gamma)$	$N(\text{Control},\pi^0)$
$N(B^0,\gamma)$	–	0.018	0.223	0.018	0.094	0.056
$N(B^0,\pi^0)$	0.018	–	0.064	0.646	−0.025	0.675
$N(B_s^0,\gamma)$	0.223	0.064	–	0.100	0.113	0.093
$N(B_s^0,\pi^0)$	0.018	0.646	0.100	–	−0.035	0.866
$N(\text{Control},\gamma)$	0.094	−0.025	0.113	−0.035	–	−0.001
$N(\text{Control},\pi^0)$	0.056	0.675	0.093	0.866	−0.001	–

Correlations understood as a consequence of misreconstructed signal rations in the fit

arxiv.org/pdf/2112.11428.pdf

Combining the results

Results from both $D^*(2007)^0$ decays can be combined using

$$\mathcal{B}_{\text{Comb.}} = \frac{\frac{\mathcal{B}_\gamma}{\delta\mathcal{B}_\gamma^2} + \frac{\mathcal{B}_{\pi^0}}{\delta\mathcal{B}_{\pi^0}^2}}{\frac{1}{\delta\mathcal{B}_\gamma^2} + \frac{1}{\delta\mathcal{B}_{\pi^0}^2}} \quad \text{with} \quad \delta\mathcal{B}_{\text{Comb.}} = \frac{1}{\sqrt{\frac{1}{\delta\mathcal{B}_\gamma^2} + \frac{1}{\delta\mathcal{B}_{\pi^0}^2}}} \, .$$

	$\frac{\mathcal{B}(B^0)}{\mathcal{B}(\text{Control})}$	$\frac{\mathcal{B}(B_s^0)}{\mathcal{B}(\text{Control})}$	$\frac{\mathcal{B}(B^0)}{\mathcal{B}(B_s^0)}$
Comb. result	0.0836	1.178	0.0712
σ_{stat}	0.0043 (5.1%)	0.029 (2.4%)	0.0035 (4.9%)
σ_{sys}	0.0056 (6.7%)	0.091 (7.7%)	0.0062 (8.7%)
σ_{f_s/f_d}	— —	0.037 (3.1%)	0.0022 (3.1%)
σ_{TOTAL}	0.0070 (8.4%)	0.102 (8.6%)	0.0074 (10.4%)

$$\mathcal{B}(B^0 \to \bar{D}^*(2007)^0 K^+\pi^-) = (5.18 \pm 0.27 \pm 0.34 \pm 1.84) \times 10^{-5} \, ,$$
$$\mathcal{B}(B_s^0 \to \bar{D}^*(2007)^0 K^-\pi^+) = (7.30 \pm 0.18 \pm 0.56 \pm 2.59 \pm 0.23) \times 10^{-4}$$

Analysis dominated by systematic uncertainty.

Mostly due to the lack of understanding of some of the background components

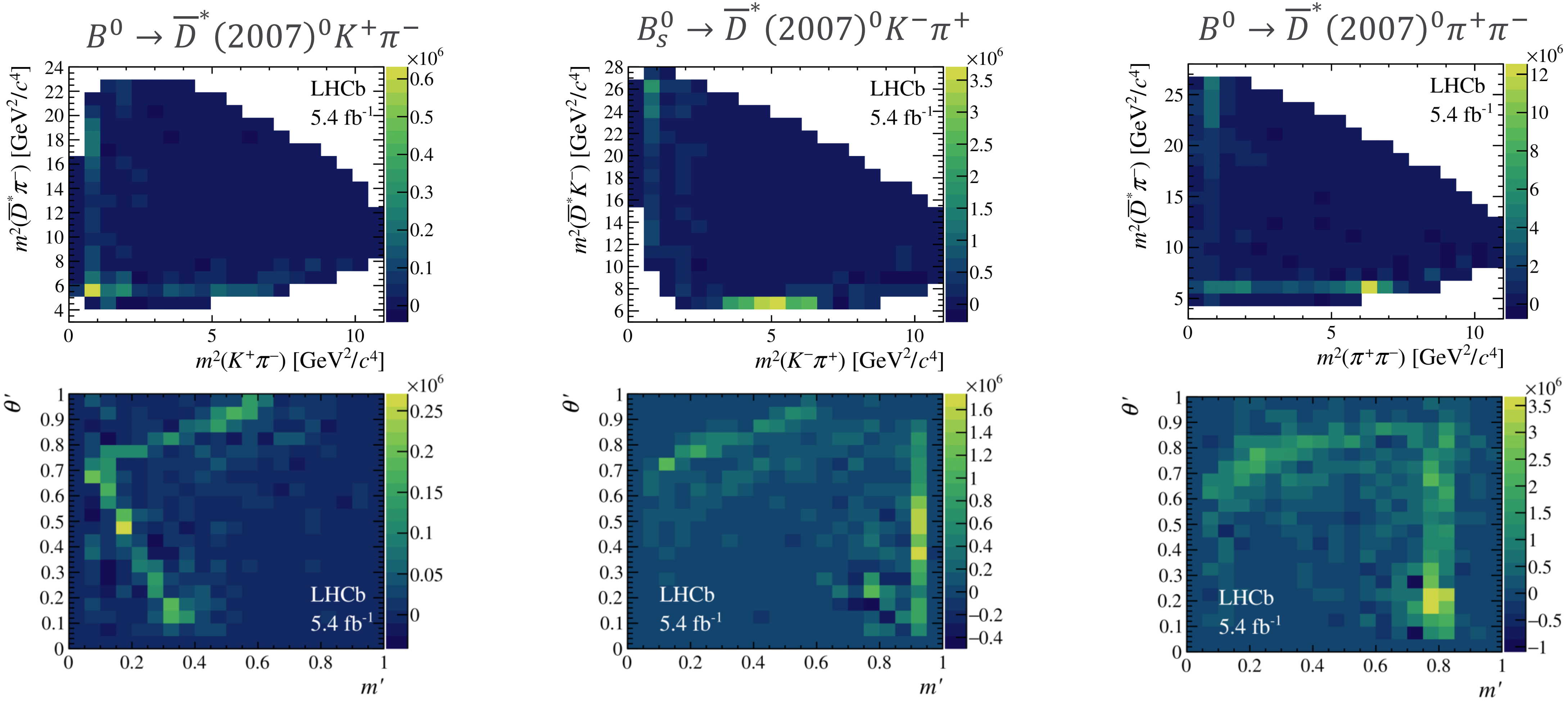
Statistical uncertainty of the same order. Need for more data to have a notable improvement on these results

Impressive final resolution of about 8%. Specially considering this is the first analysis in LHCb with fully reconstructed $D^*(2007)^0$ mesons

Using previous result on $B^0 \to D^*\pi\pi$ by the Belle collaboration:
$\mathcal{B}(B^0 \to \bar{D}^*(2007)^0\pi^+\pi^-) = (6.2 \pm 1.2 \pm 1.8) \times 10^{-4}$

Additional results

On top of the BF, *sPlot* technique allows to extract phase space distribution for this decays

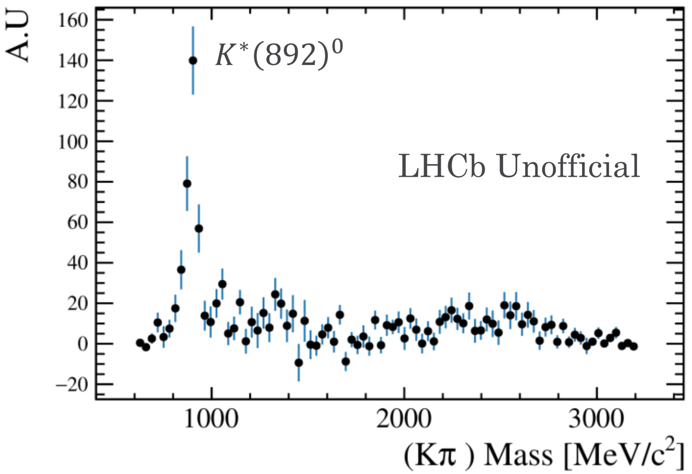


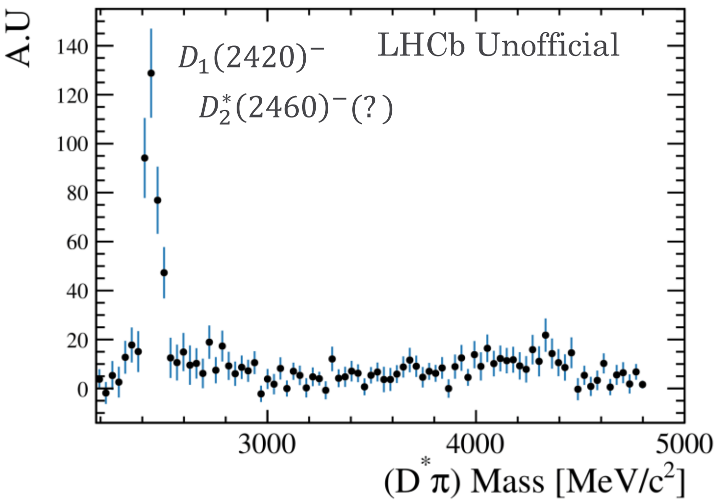
These can be used to characterize these decays as backgrounds in many other similar analyises

Additional results

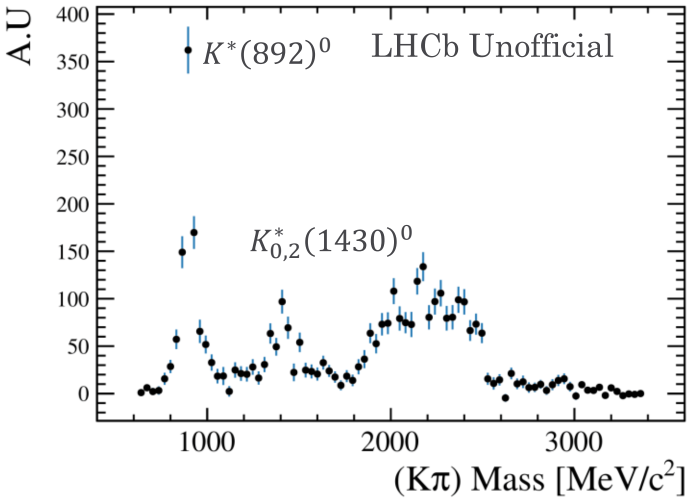
These can also be used as inputs for spectroscopy studies

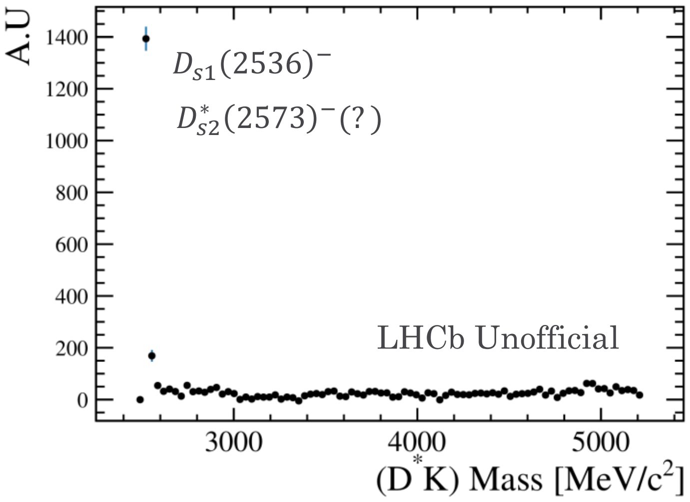
$B^0 \to \overline{D}^*(2007)^0 K^+\pi^-, \overline{D}^*(2007)^0 \to \overline{D}^0\gamma$



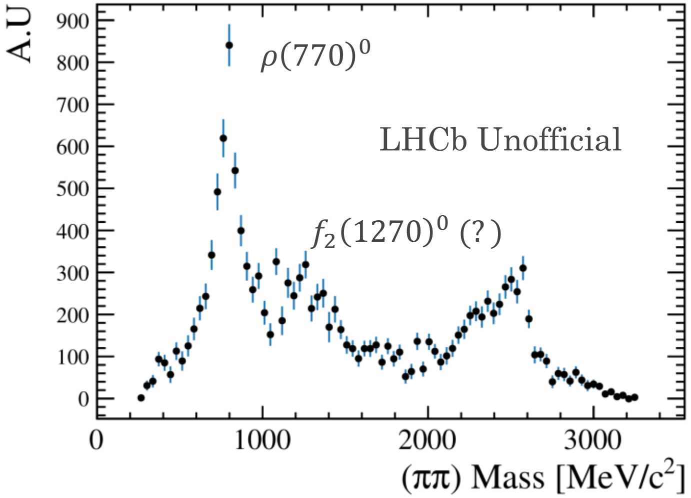


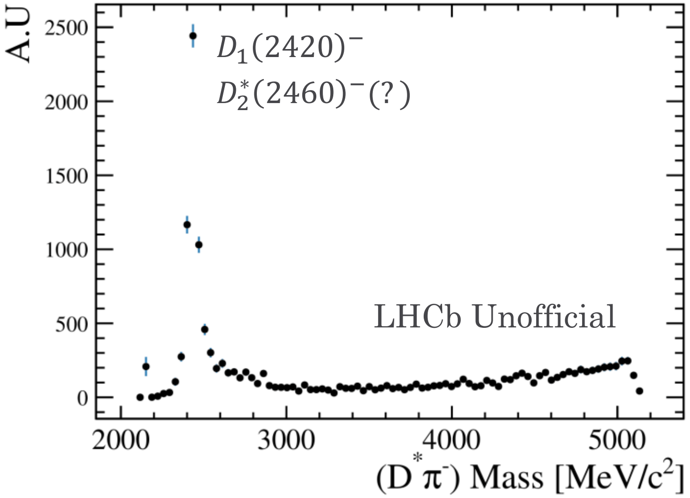
$B_s^0 \to \overline{D}^*(2007)^0 K^-\pi^+, \overline{D}^*(2007)^0 \to \overline{D}^0\gamma$





$B^0 \to \overline{D}^*(2007)^0 \pi^+\pi^-, \overline{D}^*(2007)^0 \to \overline{D}^0\gamma$





Conclusions and future prospects

- First observation of $B^0_{(s)} \to D^*(2007)^0 K^\pm \pi^\mp$ decays
  - First analysis including fully reconstructed $D^*(2007)^0$ decays
  - Phase space distributions are a crucial input to reduce systematic ucnertainty in many other $B \to DX$ analyses
  - These decays could be used to measure gamma, once more data is available
    - Need to include other D decay final states $D \to KK, D \to \pi\pi, D^0 \to K^+\pi^- \ldots$
  - This would motivate a future analysis on the BF of the control channel $B^0 \to \overline{D}^* \pi^+\pi^-$, which currently dominate the uncertainty
  - Analysis published in ArXiv, and currently under review at P.R.D.

Thanks for your attention!

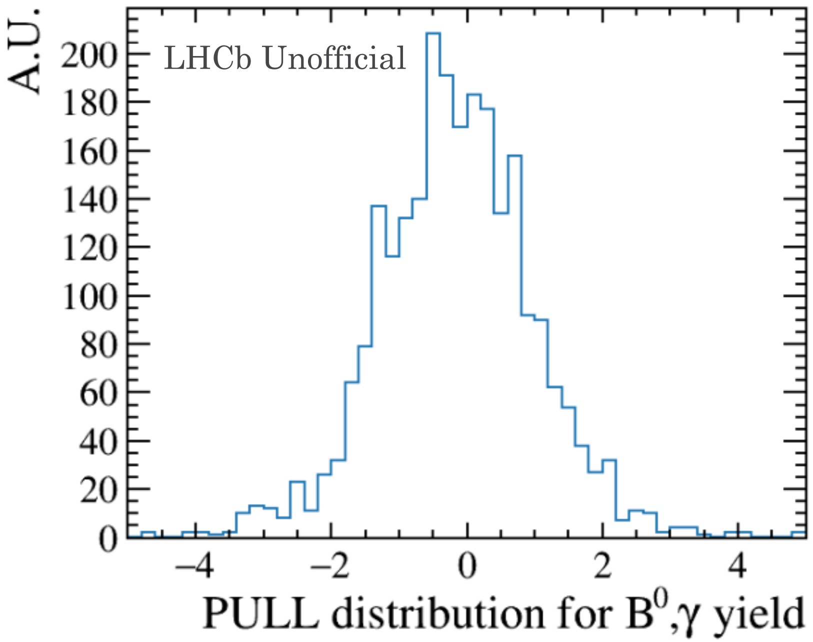
Mass fit model (results)

Parameter	Fitted value
$N(B^0\|\gamma)$	946.37 ± 53.39
$N(B^0\|\pi^0)$	184.66 ± 17.04
$N(B_s^0\|\gamma)$	3744.32 ± 76.85
$N(B_s^0\|\pi^0)$	632.72 ± 45.75
$N(\text{Control}\|\gamma)$	15020.91 ± 217.84
$N(\text{Control}\|\pi^0)$	2591.49 ± 189.70
$f^{\gamma}_{\text{w}\overline{D}^*}$	0.3848 ± 0.0055
$f^{\pi^0}_{\text{w}\overline{D}^*}$	0.1453 ± 0.0069
f^{γ}_{mrs}	0.3322 ± 0.0413
$f^{\pi^0}_{\text{mrs}}$	1.5218 ± 0.1630
$N(\text{Combinatorial Bg}\|B^0,\gamma)$	1758.16 ± 211.21
$N(\text{Combinatorial Bg}\|B^0,\pi^0)$	416.26 ± 41.77
$N(\text{Combinatorial Bg}\|B_s^0,\gamma)$	5944.49 ± 558.01
$N(\text{Combinatorial Bg}\|B_s^0,\pi^0)$	1258.17 ± 93.84
$N(\text{Combinatorial Bg}\|\text{Control},\gamma)$	23886.5 ± 1686.82
$N(\text{Combinatorial Bg}\|\text{Control},\pi^0)$	6310.04 ± 349.01
Combinatorial slope p_0 in B^0,γ	-0.003804 ± 0.000308
Combinatorial slope p_0 in B^0,π^0	-0.005086 ± 0.000372
Combinatorial slope p_0 in B_s^0,γ	-0.003915 ± 0.000227
Combinatorial slope p_0 in B_s^0,π^0	-0.004901 ± 0.000240
Combinatorial slope p_0 in Control, γ	-0.003231 ± 0.000156
Combinatorial slope p_0 in Control, π^0	-0.004766 ± 0.000153
$N(B_s^0 \to \overline{D}^*(2007)^0K^+K^-\|B^0,\gamma)$	374.33 ± 169.78
$N(B_s^0 \to \overline{D}^*(2007)^0K^+K^-\|B^0,\pi^0)$	23.54 ± 17.23
$N(B^0 \to \overline{D}^*(2007)^0K^+K^-\|B^0,\gamma)$	97.66 ± 50.81
$N(B^0 \to \overline{D}^*(2007)^0K^+K^-\|B^0,\pi^0)$	29.88 ± 11.19

Parameter	Fitted value	Gaussian constraint $(\mu \pm \sigma)$
f_{sKK}	0.7433 ± 0.2685	0.4324 ± 0.2518
f_{KK}	1.6276 ± 0.3220	1.3880 ± 0.3498
$f_{\pi\pi}$	0.00997 ± 0.00075	0.0097 ± 0.0008
$f_{s\pi\pi}$	0.00338 ± 0.000299	0.0034 ± 0.0003
$f_{K\pi}$	0.1586 ± 0.00409	0.1583 ± 0.0041
$f_{sK\pi}$	0.0686 ± 0.00339	0.0619 ± 0.0034
$N(B^0 \to \overline{D}^0K^+\pi^-\|B^0,\gamma)$	207.22 ± 43.81	
$N(B_s^0 \to \overline{D}^0K^-\pi^+\|B_s^0,\gamma)$	264.45 ± 54.05	
$N(B^0 \to \overline{D}^0\pi^+\pi^-\|\text{Control},\gamma)$	2894.61 ± 169.59	
f_{B2Dhh}	0.1396 ± 0.0012	0.1390 ± 0.0012
f^{MC}_{Bu}	0.3521 ± 0.0012	0.3521 ± 0.0012
f^{PDG}_{Bu}	0.0832 ± 0.0036	0.0834 ± 0.0036
$f_{Bu2Dsth}$	0.2239 ± 0.00673	0.2197 ± 0.0068
$f^{\text{MC}}_{B^+/B^0}$	0.3737 ± 0.00320	0.3736 ± 0.0032
$f^{\text{PDG}}_{B^+/B^0}$	2.0054 ± 0.1368	1.97 ± 0.14
$f^{B^0}_{\text{PR}}$	0.1168 ± 0.0569	
$f^{B_s^0}_{\text{PR}}$	0.0544 ± 0.0884	
$f^{\text{Control}}_{\text{PR1}}$	0.4841 ± 0.0164	
$f^{\text{Control}}_{\text{PR2}}$	0.4201 ± 0.0389	
$\Delta\mu^{\text{MC}}_{\gamma}$	-0.9402 ± 0.1775	
$\Delta\mu^{\text{MC}}_{\pi^0}$	-0.4096 ± 0.4460	
$\Delta\sigma^{\text{MC}}_{\gamma}$	1.0067 ± 0.0121	
$\Delta\sigma^{\text{MC}}_{\pi^0}$	0.9947 ± 0.0356	

Yield systematics: Fit stability

Computed by refiting toy simples generated with the fitted model.



Branching fraction	Baseline model	Modified model	$\delta\mathcal{B}$	$\delta\mathcal{B}/\mathcal{B}$
$\frac{\mathcal{B}(B^0\to\bar{D}^*(2007)^0K^+\pi^-,\gamma)}{\mathcal{B}(B^0\to\bar{D}^*(2007)^0\pi^+\pi^-,\gamma)}$	0.0832	0.0827	−0.0005	−0.0058
$\frac{\mathcal{B}(B^0\to\bar{D}^*(2007)^0K^+\pi^-,\pi^0)}{\mathcal{B}(B^0\to\bar{D}^*(2007)^0\pi^+\pi^-,\pi^0)}$	0.0850	0.0857	0.0007	0.0081
$\frac{\mathcal{B}(B_s^0\to\bar{D}^*(2007)^0K^-\pi^+,\gamma)}{\mathcal{B}(B^0\to\bar{D}^*(2007)^0\pi^+\pi^-,\gamma)}$	1.189	1.193	0.0038	0.0032
$\frac{\mathcal{B}(B_s^0\to\bar{D}^*(2007)^0K^-\pi^+,\pi^0)}{\mathcal{B}(B^0\to\bar{D}^*(2007)^0\pi^+\pi^-,\pi^0)}$	1.099	1.098	−0.0015	−0.0014
$\frac{\mathcal{B}(B^0\to\bar{D}^*(2007)^0K^+\pi^-,\gamma)}{\mathcal{B}(B_s^0\to\bar{D}^*(2007)^0K^-\pi^+,\gamma)}$	0.0700	0.0693	−0.0006	−0.0089
$\frac{\mathcal{B}(B^0\to\bar{D}^*(2007)^0K^+\pi^-,\pi^0)}{\mathcal{B}(B_s^0\to\bar{D}^*(2007)^0K^-\pi^+,\pi^0)}$	0.0773	0.0757	0.0007	0.0095

Despite the systematic uncertainty, a large standard deviation in the pull dsitribution indicates an underestimation of the statistical uncertainty, which is scaled accordingly

Yield systematics: Multiple and duplicate candidates

Due to the low reconstruction efficiency of the final state particles, there are events with multiple candidates

This is more predominant in channels with $D^*(2007)^0 \to D^0\pi^0$

Channel	Multiple candidates in dataset
B^0, γ	3.17%
B^0, π^0	8.59%
B_s^0, γ	2.98%
B_s^0, π^0	8.84%
Control γ	4.03%
Control π^0	8.98%

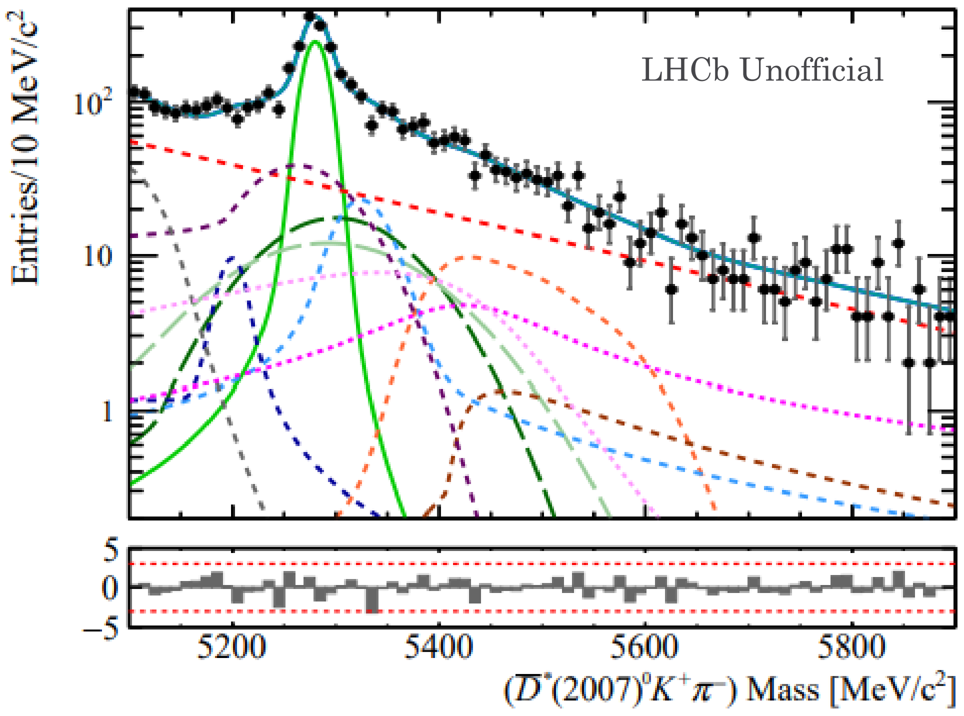
	B^0, γ	B^0, π^0	B_s^0, γ	B_s^0, π^0	Control γ	Control π^0
B^0, γ		1.09%	0.30%	0.00%	1.27%	0.00%
B^0, π^0	4.61%		0.00%	0.15%	0.00%	1.19%
B_s^0, γ	0.12%	0.00%		1.39%	0.90%	0.02%
B_s^0, π^0	0.00%	0.06%	5.64%		0.00%	0.32%
Control γ	0.08%	0.00%	0.14%	0.00%		1.24%
Control π^0	0.00%	0.07%	0.01%	0.05%	5.33%	

Similarly, due to the same effect, there is some cross feed between samples with different $D^*(2007)^0$ decays

Moreover, small crossfeed with the control channel due to misientified backgrounds

Yield systematics: Multiple and duplicate candidates

Fit model and efficiency computation reapplied after applying veto to remove all duplicate and multiple candidates

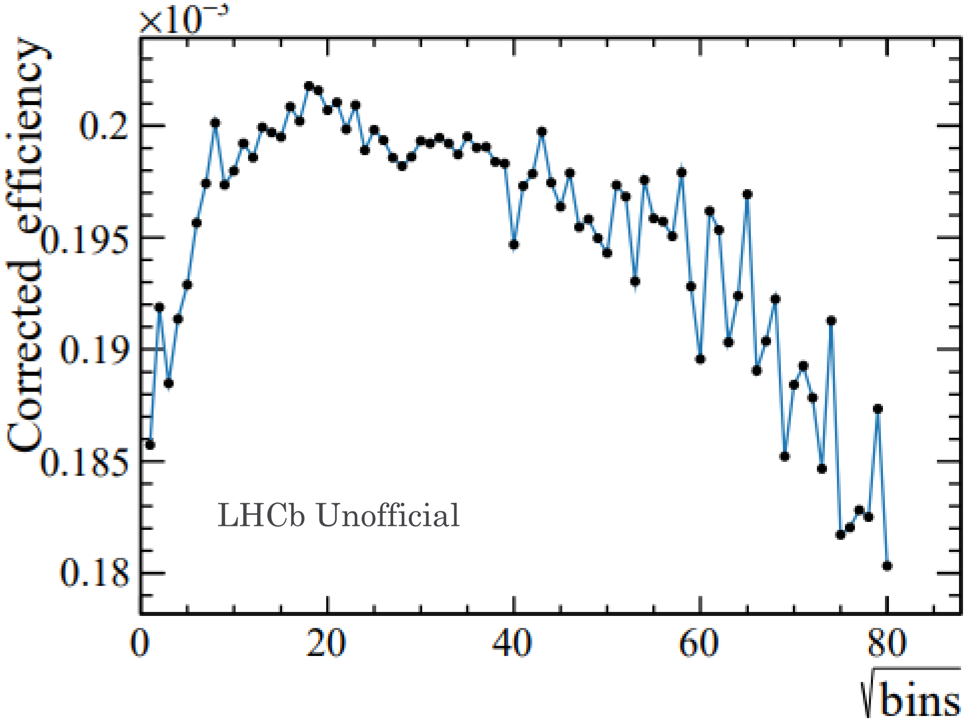


Branching fraction	Baseline model	Modified model	$\delta\mathcal{B}$	$\delta\mathcal{B}/\mathcal{B}$
$\frac{\mathcal{B}(B^0\to\bar{D}^*(2007)^0K^+\pi^-,\gamma)}{\mathcal{B}(B^0\to\bar{D}^*(2007)^0\pi^+\pi^-,\gamma)}$	0.0832	0.0852	0.0020	0.024
$\frac{\mathcal{B}(B^0\to\bar{D}^*(2007)^0K^+\pi^-,\pi^0)}{\mathcal{B}(B^0\to\bar{D}^*(2007)^0\pi^+\pi^-,\pi^0)}$	0.0850	0.0829	0.0021	0.0251
$\frac{\mathcal{B}(B_s^0\to\bar{D}^*(2007)^0K^-\pi^+,\gamma)}{\mathcal{B}(B^0\to\bar{D}^*(2007)^0\pi^+\pi^-,\gamma)}$	1.189	1.130	−0.060	0.050
$\frac{\mathcal{B}(B_s^0\to\bar{D}^*(2007)^0K^-\pi^+,\pi^0)}{\mathcal{B}(B^0\to\bar{D}^*(2007)^0\pi^+\pi^-,\pi^0)}$	1.099	1.101	0.0018	0.002
$\frac{\mathcal{B}(B^0\to\bar{D}^*(2007)^0K^+\pi^-,\gamma)}{\mathcal{B}(B_s^0\to\bar{D}^*(2007)^0K^-\pi^+,\gamma)}$	0.070	0.075	0.0054	0.078
$\frac{\mathcal{B}(B^0\to\bar{D}^*(2007)^0K^+\pi^-,\pi^0)}{\mathcal{B}(B_s^0\to\bar{D}^*(2007)^0K^-\pi^+,\pi^0)}$	0.077	0.075	0.0021	0.027

Efficiency systematics: Binning schemes

Many binning schemes tested

- local variation corresponds to systematic uncertainty
- long range variation just indicates the maxim number of bins suitable



Systematic uncertainty

Branching fraction	$D^* \to D^0\gamma$	$D^* \to D^0\pi^0$
$\frac{\mathcal{B}(B^0 \to \bar{D}^*(2007)^0 K^+\pi^-)}{\mathcal{B}(B^0 \to \bar{D}^*(2007)^0 \pi^+\pi^-)}$	$1.4 \cdot 10^{-2}$	$7.6 \cdot 10^{-2}$
$\frac{\mathcal{B}(B_s^0 \to \bar{D}^*(2007)^0 K^-\pi^+)}{\mathcal{B}(B^0 \to \bar{D}^*(2007)^0 \pi^+\pi^-)}$	$1.9 \cdot 10^{-2}$	$6.9 \cdot 10^{-2}$
$\frac{\mathcal{B}(B^0 \to \bar{D}^*(2007)^0 K^+\pi^-)}{\mathcal{B}(B_s^0 \to \bar{D}^*(2007)^0 K^-\pi^+)}$	$2.1 \cdot 10^{-2}$	$6.7 \cdot 10^{-2}$

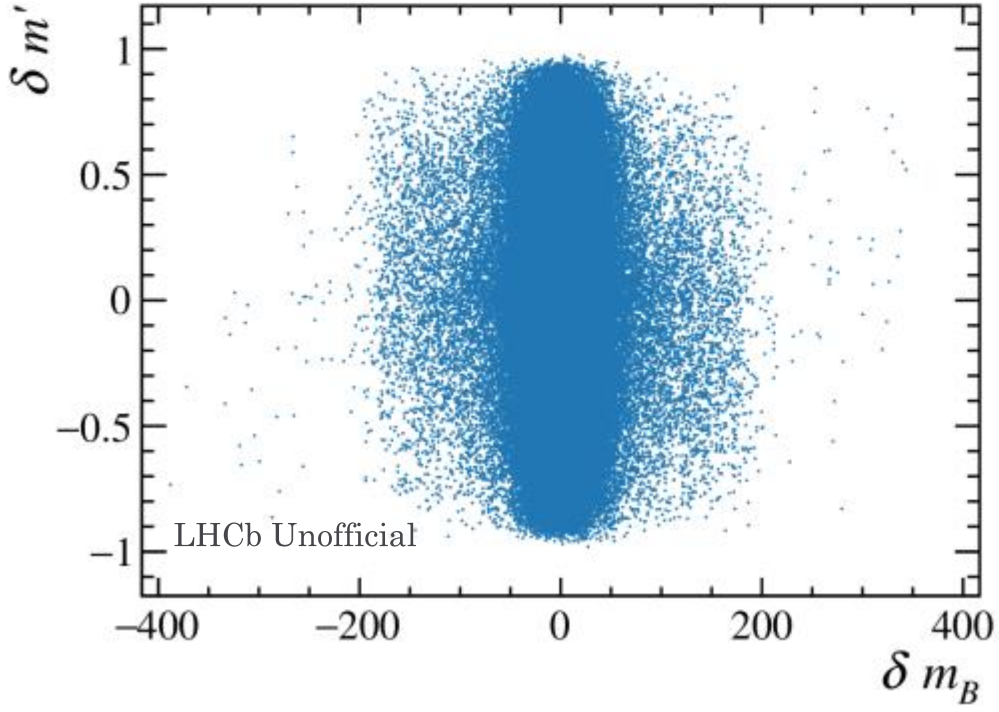
Efficiency systematics: sPlot biases due to correlations

Necessary ingridient in the *sPlot* procedure is that no correlation exists between fitted variable (m_B) and resampled variables (m', θ')

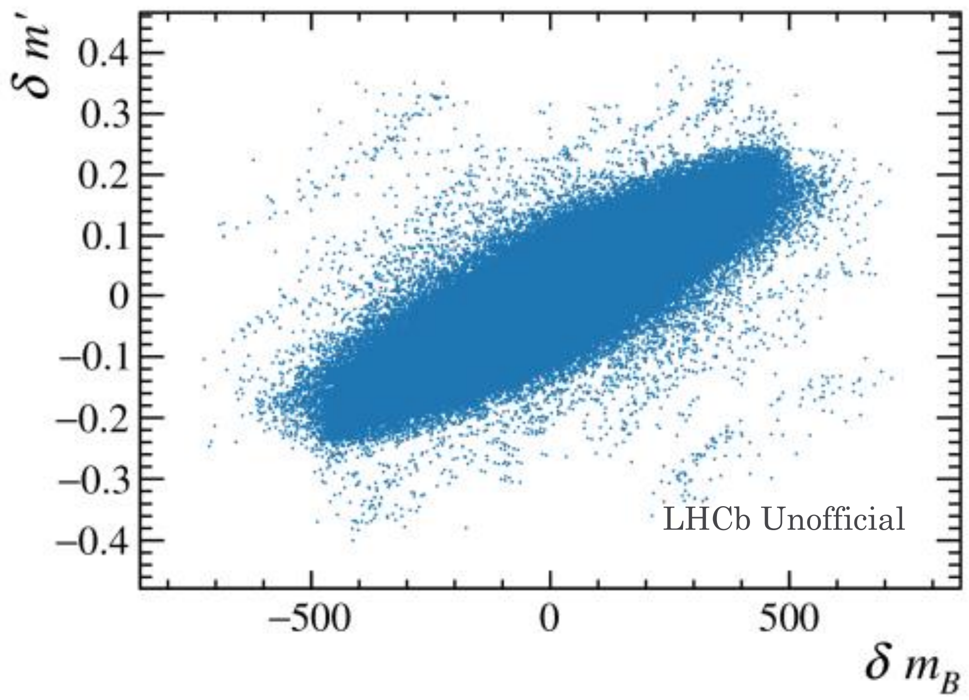
This is found to be mostly true for signal component, but its not the case for some backgrouds.

Difference in m_B and m' for each posible pair in the MC sample for

$Signal\ B^0 \to \overline{D}^*(2007)^0 K^+ \pi^-$



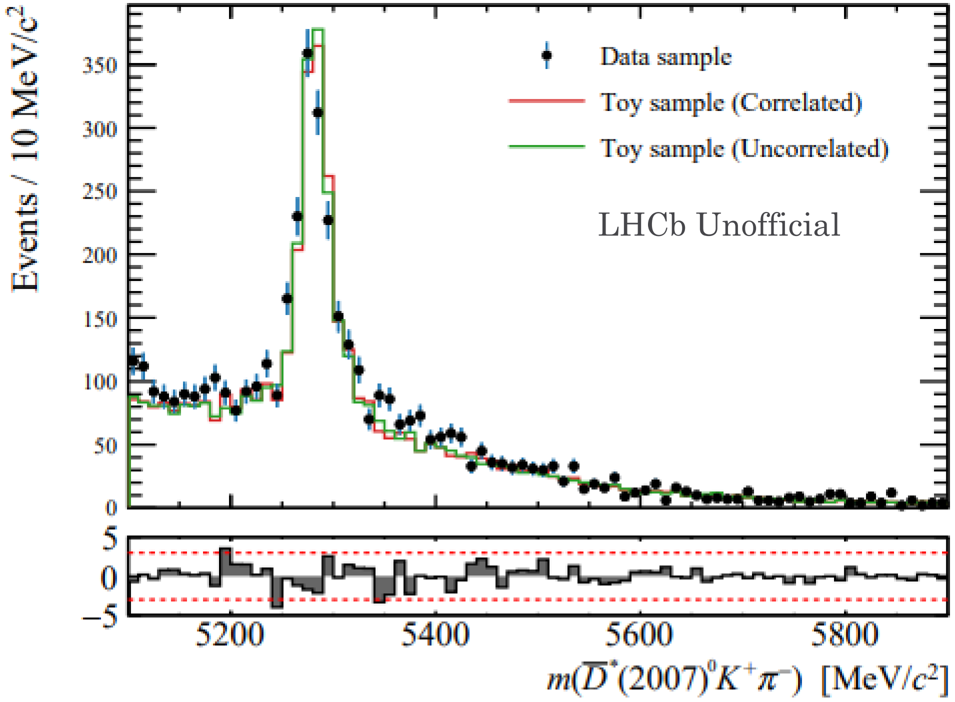
$B^+ \to \overline{D}^0 K^+\ reconstructed\ as\ B^0 \to \overline{D}^*(2007)^0 K^+ \pi^-$



Efficiency systematics: sPlot biases due to correlations

To study effects of such correlation, two toy samples have been generated, one maintaining the correlation ,and another one without the correlation

Then the reweighting procedure is applied to both toy samples



Branching fraction	$\delta\mathcal{B}/\mathcal{B}$
$\frac{\mathcal{B}(B^0\to\bar{D}^*(2007)^0K^+\pi^-)}{\mathcal{B}(B^0\to\bar{D}^*(2007)^0\pi^+\pi^-)}$	0.61%
$\frac{\mathcal{B}(B_s^0\to\bar{D}^*(2007)^0K^-\pi^+)}{\mathcal{B}(B^0\to\bar{D}^*(2007)^0\pi^+\pi^-)}$	1.02%
$\frac{\mathcal{B}(B^0\to\bar{D}^*(2007)^0K^+\pi^-)}{\mathcal{B}(B_s^0\to\bar{D}^*(2007)^0K^-\pi^+)}$	1.62%

Since correlation only appears in small components, this effect is very small, as expected