Measurement of the Unitary Triangle angle γ using $B^{\pm} \rightarrow D^{*0} K^{\pm}$ decays at LHCb

IoP Joint HEPP and APP Annual Conference 2019

Alexandra Rollings on behalf of the LHCb Collaboration

University of Oxford

8th April 2019

The CKM Matrix

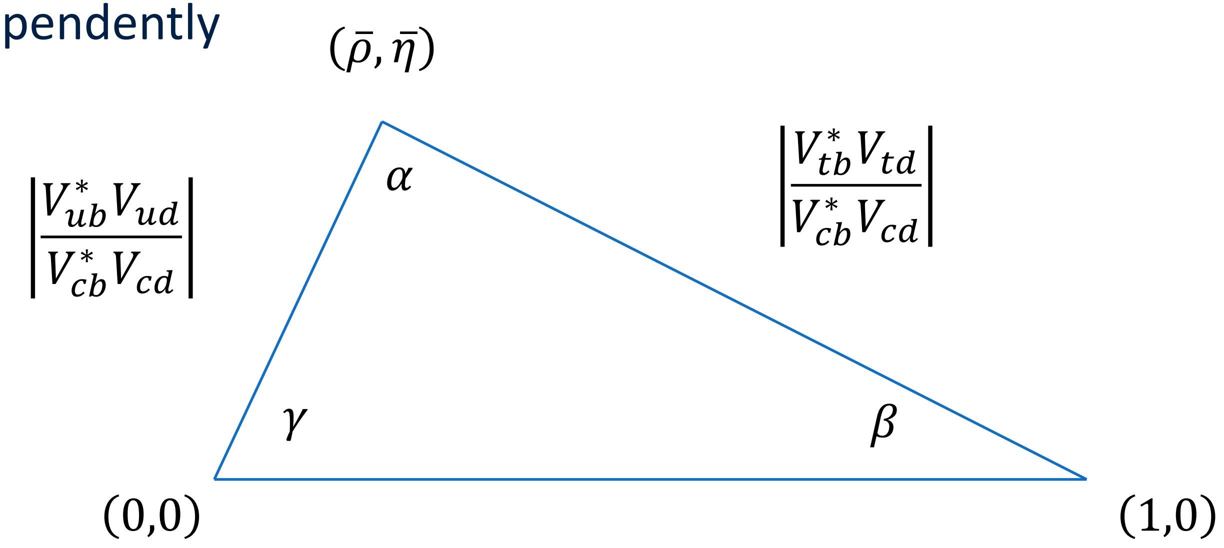
- Elements mediate the charged weak coupling between up-type and down-type quarks:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Complex 3 x 3 unitary matrix parameterised by 3 rotation angles and one irreducible complex phase
  - Phase changes sign under the CP operator
  - Only known source of CP violation within the quark sector

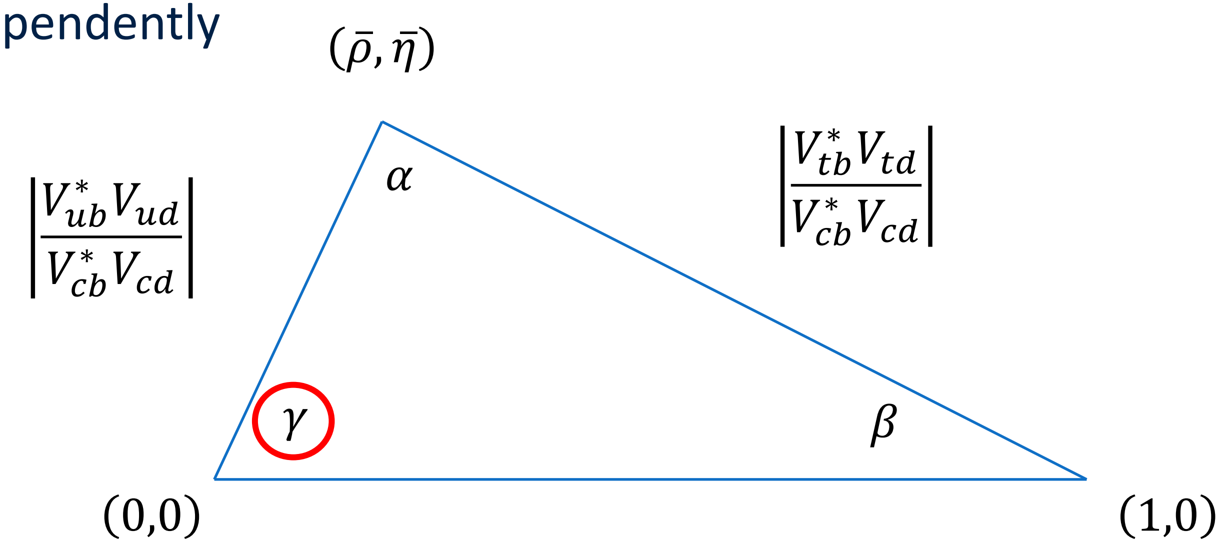
The Unitary Triangle

- Unitary matrix: $\sum_{k=1}^{3} V_{ik} V_{jk}^* = \delta_{ij}$
- Take dot product of 1st and 3rd columns:
  - $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
  - Triangle in the complex plane with sides and angles of similar size
  - All sides and angles can be measured independently
  - Over-constrain to test unitarity



The Unitary Triangle

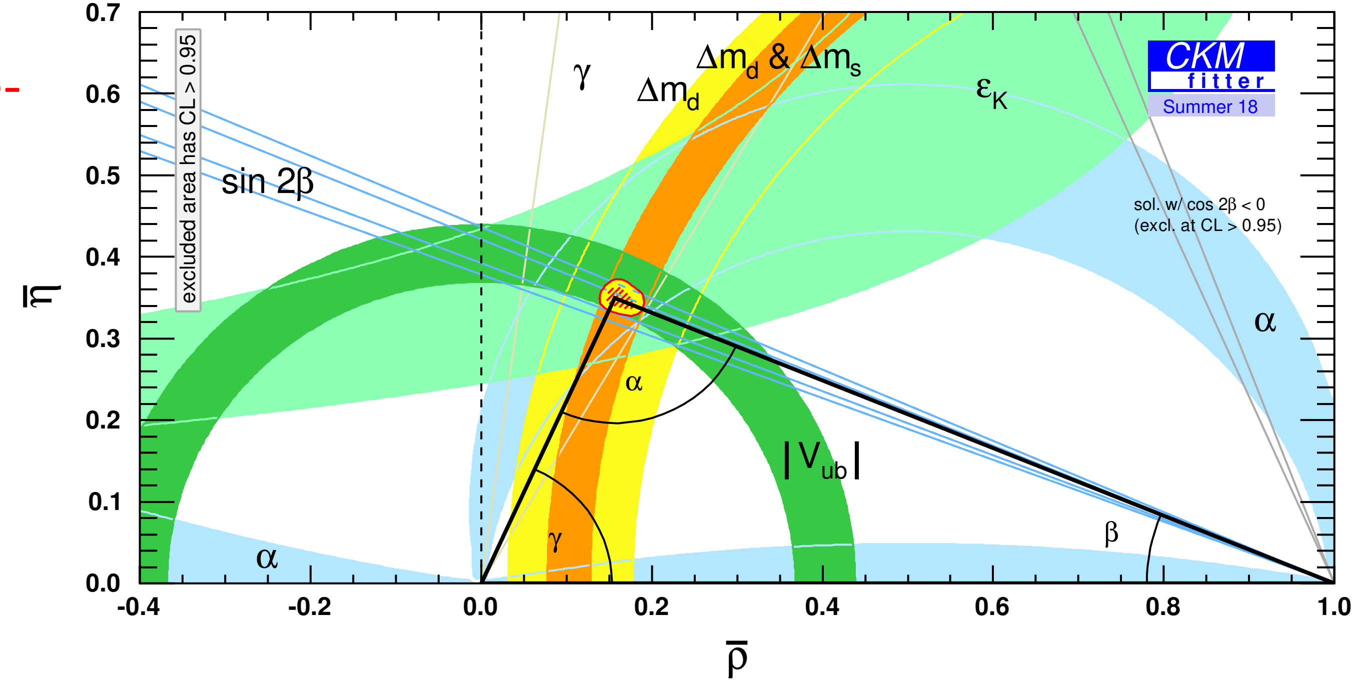
- Unitary matrix: $\sum_{k=1}^{3} V_{ik} V_{jk}^* = \delta_{ij}$
- Take dot product of 1st and 3rd columns:
  - $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
  - Triangle in the complex plane with sides and angles of similar size
  - All sides and angles can be measured independently
  - Over-constrain to test unitarity
- $\gamma = arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$



Measuring γ using tree and loop-level decays

- No top quark; accessible via tree-level decays of B mesons
  - $\gamma = \left(72.1^{+5.4}_{-5.7}\right)^{\circ}$
  - Theoretically clean

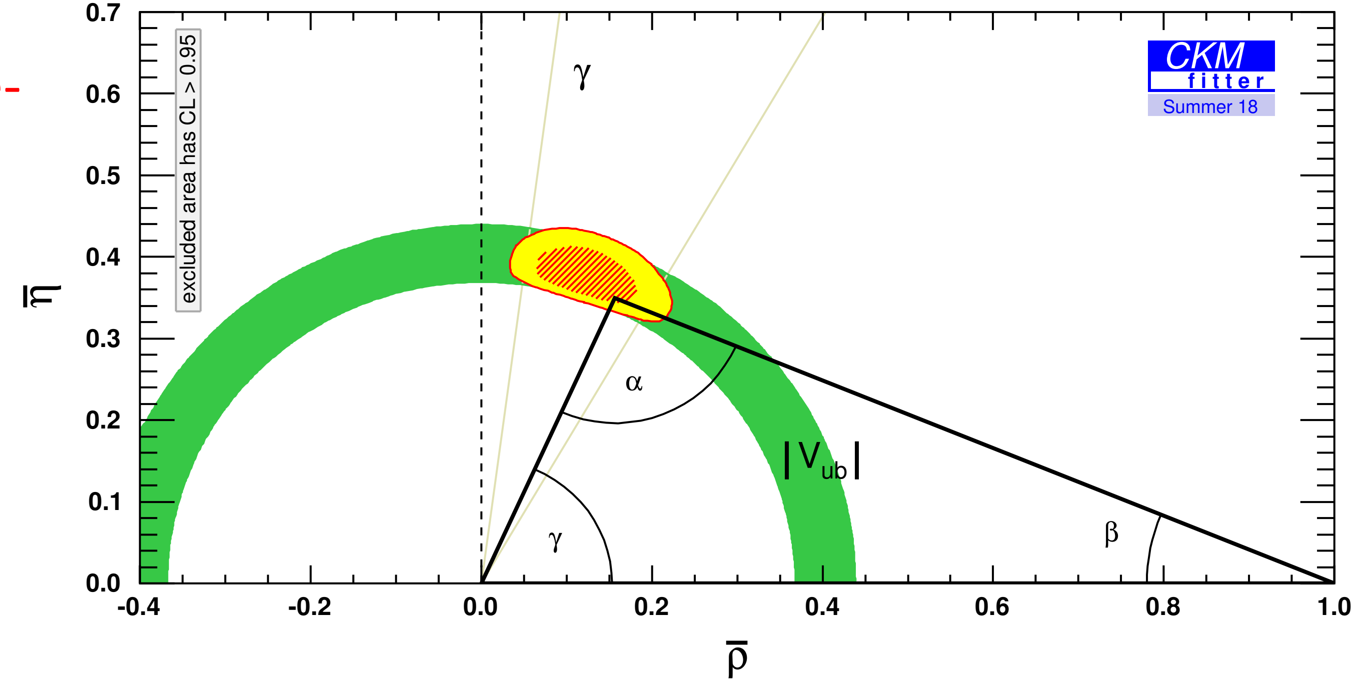
[http://ckmfitter.in2p3.fr]



Measuring γ using tree and loop-level decays

- No top quark; accessible via tree-level decays of B mesons
  - $\gamma = \left(72.1^{+5.4}_{-5.7}\right)^{\circ}$
  - Theoretically clean

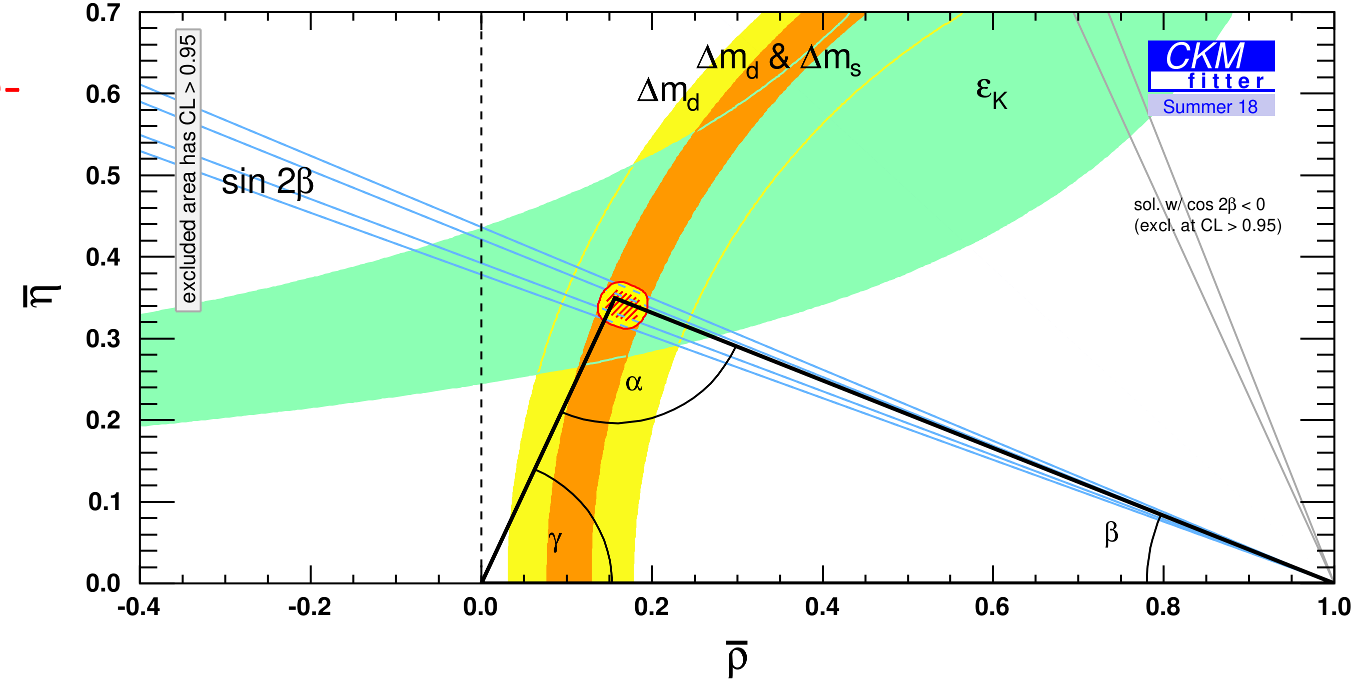
[http://ckmfitter.in2p3.fr]



Measuring γ using tree and loop-level decays

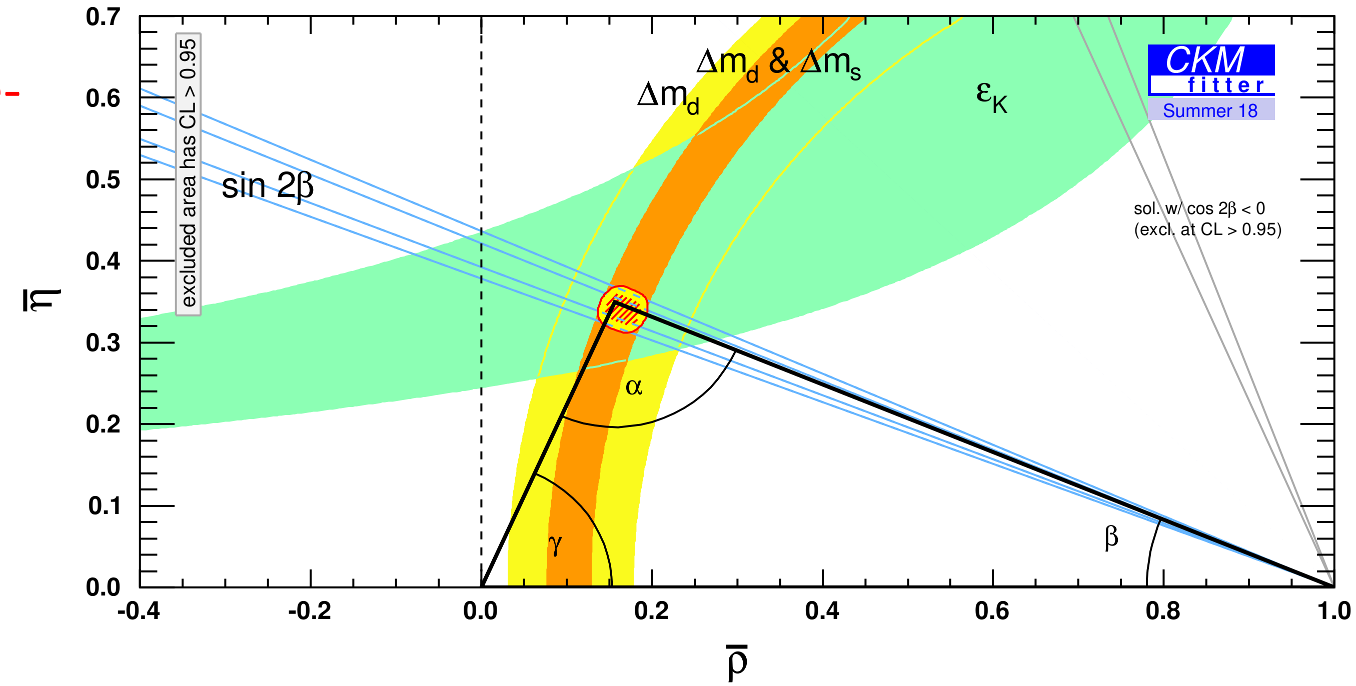
- No top quark; accessible via tree-level decays of B mesons
  - $\gamma = \left(72.1^{+5.4}_{-5.7}\right)^{\circ}$
  - Theoretically clean
- $(\bar{\rho}, \bar{\eta})$ apex can be constrained using loop-level decays
  - $\gamma = (65.64^{+0.97}_{-3.42})^{\circ}$

[http://ckmfitter.in2p3.fr]



Measuring γ using tree and loop-level decays

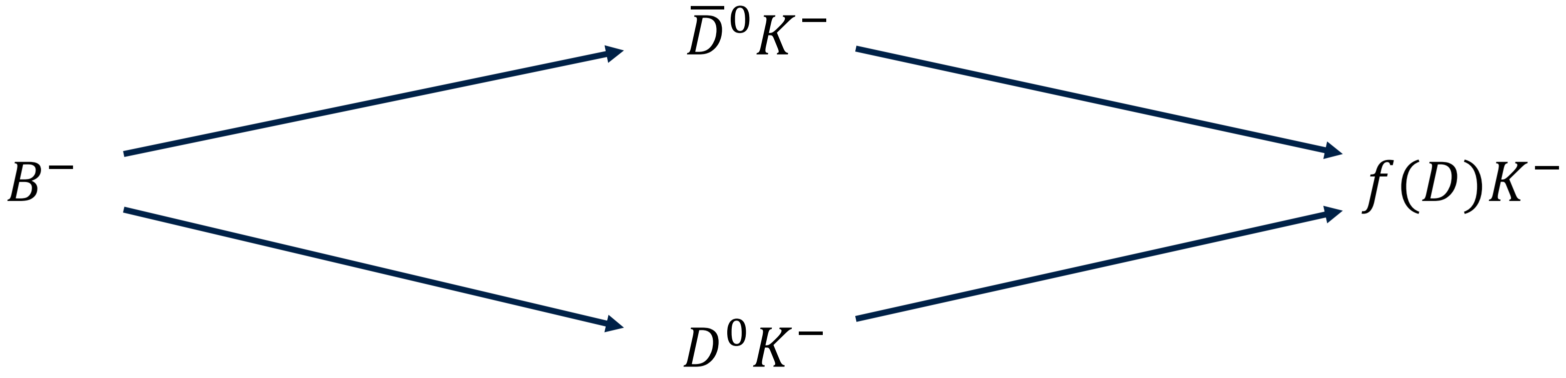
[http://ckmfitter.in2p3.fr]



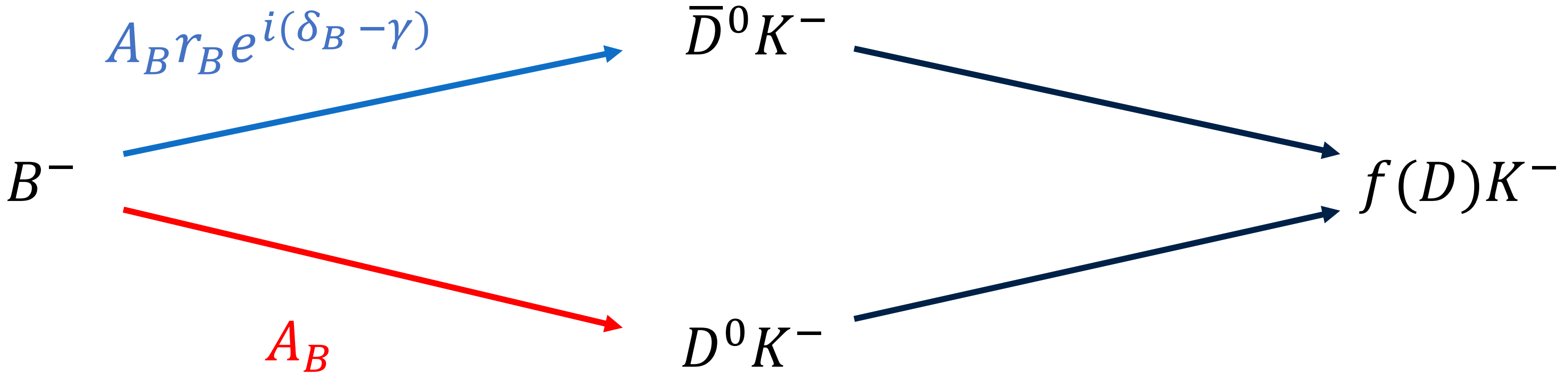
- No top quark; accessible via tree-level decays of B mesons
  - $\gamma = \left(72.1^{+5.4}_{-5.7}\right)^\circ$
  - Theoretically clean
- $(\bar{\rho}, \bar{\eta})$ apex can be constrained using loop-level decays
  - $\gamma = \left(65.64^{+0.97}_{-3.42}\right)^\circ$

- **Aim**: reduce uncertainty on tree-level measurement in order to verify compatibility or disagreement
- **Method**: combine interference from measurements of CP-violating observables from many tree-level B decays

Measuring γ with $B^{\pm} \to DK^{\pm}$ decays

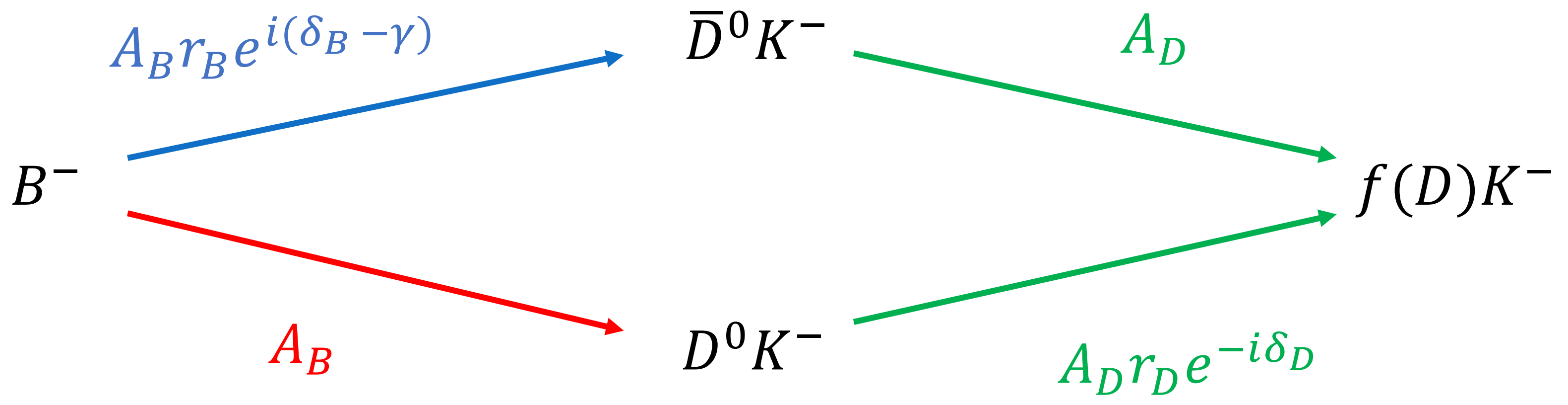


Measuring γ with $B^{\pm} \to DK^{\pm}$ decays



- $b \to u$ transition in $B^- \to \bar{D}^0 K^-$ suppressed w.r.t. $b \to c$ transition in $B^- \to D^0 K^-$
  - 2 contributing B decays with amplitude ratio r_B, strong phase δ_B and **weak phase γ**
  - γ CP violates, therefore changes sign under charge conjugation!

Measuring γ with $B^{\pm} \to DK^{\pm}$ decays



- $b \to u$ transition in $B^- \to \bar{D}^0 K^-$ suppressed w.r.t. $b \to c$ transition in $B^- \to D^0 K^-$
  - 2 contributing B decays with amplitude ratio r_B, strong phase δ_B and **weak phase $\boldsymbol{\gamma}$**
  - γ CP violates, therefore changes sign under charge conjugation!
- $D = D^0/\bar{D}^0$ decaying to the same final state with amplitude ratio r_D and phase δ_D
  - If the 2 paths proceed at similar rates, there will be a larger interference effect
  - Choose decay with $r_D \sim r_B$

The ADS Method

- $D^0 \to K^+\pi^-$, $\overline{D}^0 \to K^+\pi^-$ and charge conjugates
  - Former is doubly-Cabibbo suppressed w.r.t. the latter

- Look for differences in decay rates ($\Gamma \propto |\sum_i A_i|^2$) of B^- and B^+ mesons:

$$\Gamma(B^{\pm} \to DK^{\pm}) \propto r_D^2 + r_B^2 + 2r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$

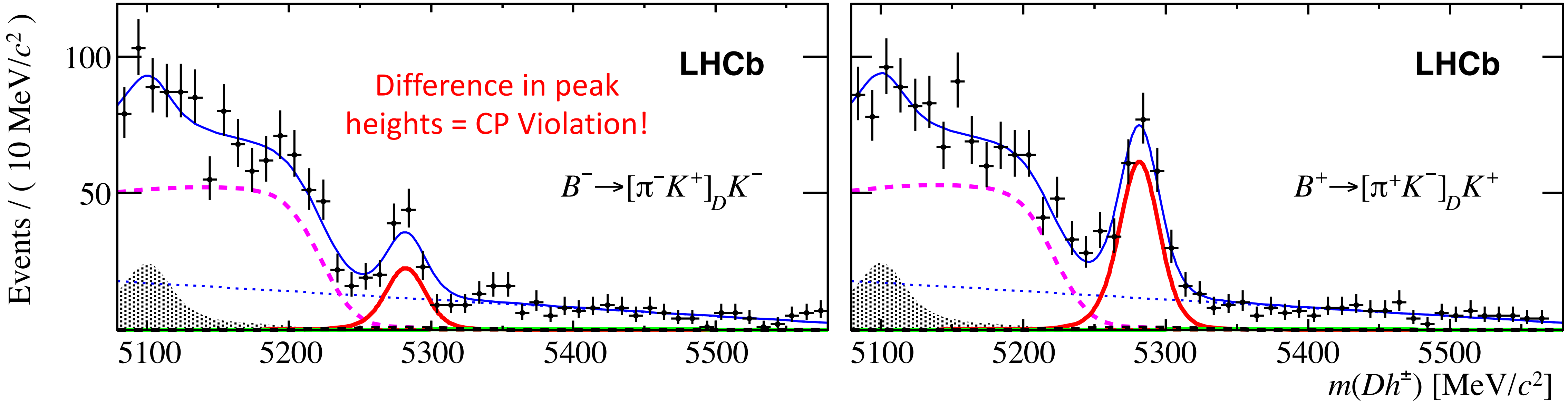
Interference term enhanced when $r_D \sim r_B$

The ADS Method

- $D^0 \to K^-\pi^+$, $\overline{D}^0 \to K^-\pi^+$ and charge conjugates
  - Former is doubly-Cabibbo suppressed w.r.t. the latter
- Look for differences in decay rates ($\Gamma \propto |\sum_i A_i|^2$) of B^- and B^+ mesons:

$$\Gamma(B^\pm \to DK^\pm) \propto r_D^2 + r_B^2 + 2r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$

[LHCb-PAPER-2016-003]



The GLW Method

- D meson reconstructed in CP-even final states $D \to K^+K^-$ and $D \to \pi^+\pi^-$
  - $r_D = 1, \delta_D = 0$!

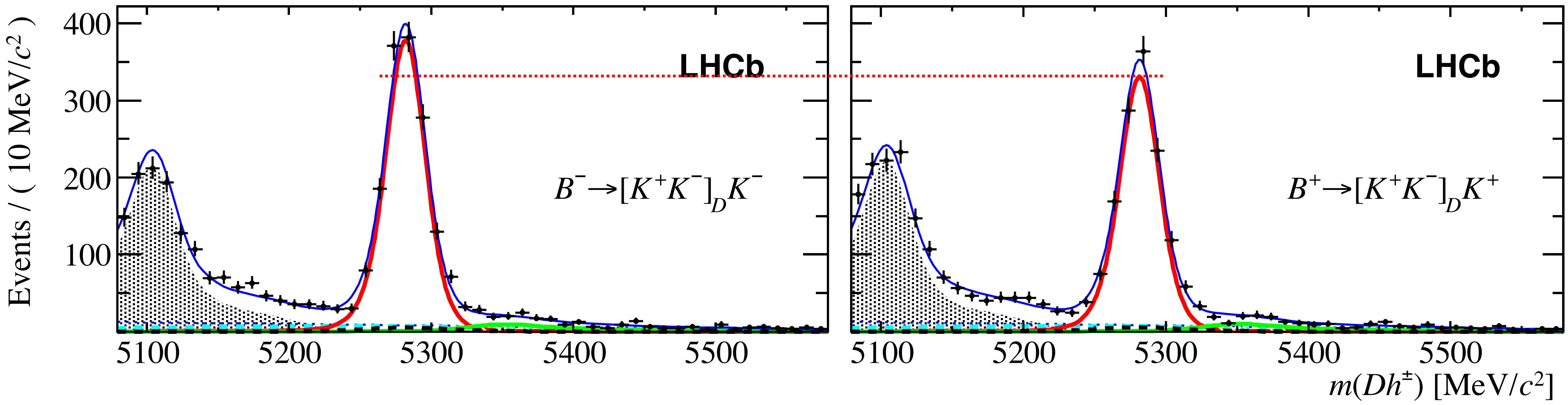
$$\Gamma(B^{\pm} \to DK^{\pm}) \propto 1 + r_B^2 + 2r_B \cos(\delta_B \pm \gamma)$$

The GLW Method

- D meson reconstructed in CP-even final states $D \to K^+K^-$ and $D \to \pi^+\pi^-$
  - $r_D = 1, \delta_D = 0$!

$$\Gamma(B^{\pm} \to DK^{\pm}) \propto 1 + r_B^2 + 2r_B \cos(\delta_B \pm \gamma)$$

[LHCb-PAPER-2016-003]



$B^{\pm} \rightarrow D^{*}K^{\pm}$

- Add a star to the D: select D^{*} vector meson $\rightarrow$ same quark-level process
  - Two sub-decays: $D^{*0} \rightarrow D^{0}\pi^{0}$ and $D^{*0} \rightarrow D^{0}\gamma$
  - 2 final states have 180° δ_{D} difference – opposite CP

$B^{\pm} \to D^{*}K^{\pm}$

- Add a star to the D: select D^{*} vector meson → same quark-level process
  - Two sub-decays: $D^{*0} \to D^{0}\pi^{0}$ and $D^{*0} \to D^{0}\gamma$
  - 2 final states have 180° δ_{D} difference – opposite CP
- Effect on GLW method:

$$\Gamma(B^{\pm} \to (D^{*} \to D\pi^{0}/\gamma)K^{\pm}) \propto 1 + {r_{B}^{D^{*}K}}^{2} \pm 2r_{B}^{D^{*}K}\cos\left(\delta_{B}^{D^{*}K} \pm \gamma\right)$$

- Enhanced ADS method [Phys. Rev. D 70, 091503(R)]:

$$\Gamma(B^{\pm} \to (D^{*} \to D\pi^{0}/\gamma)K^{\pm}) \propto r_{D}^{2} + {r_{B}^{D^{*}K}}^{2} \pm 2r_{D}r_{B}^{D^{*}K}\cos\left(\delta_{B}^{D^{*}K} + \delta_{D} \pm \gamma\right)$$

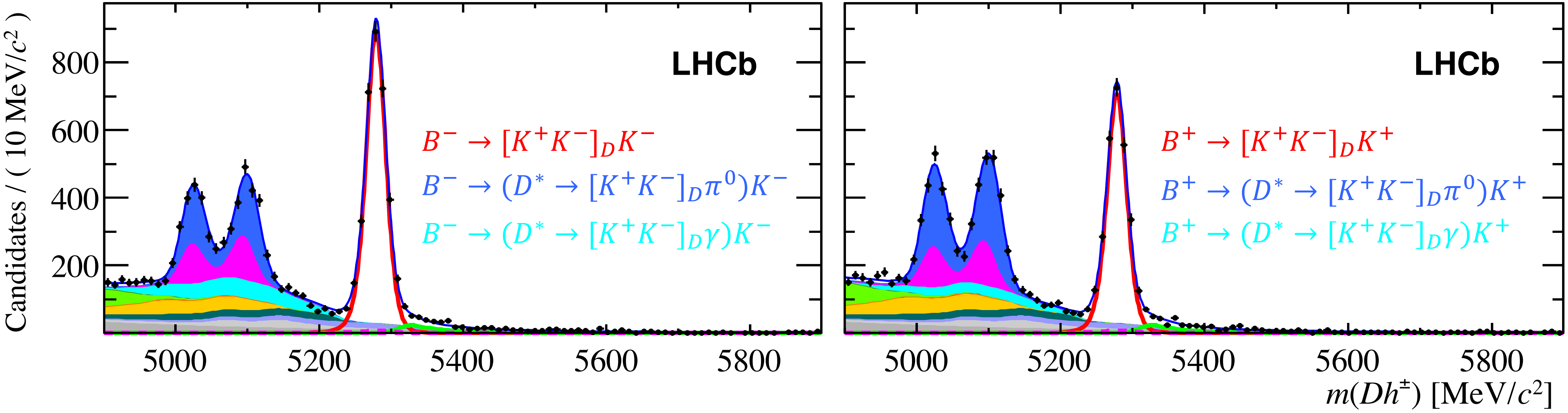
  - 4 independent equations with 3 unknowns: extract γ directly!
  - No current LHCb measurement using this method

$B^{\pm} \to D^{(*)}K^{\pm}$ GLW analysis (5 fb^{-1}) [Phys. Lett. B 777, (2018) 16-30]

- Partially reconstructed analysis: don't include the neutral in the final state, and select identically to $B^{\pm} \to DK^{\pm}$

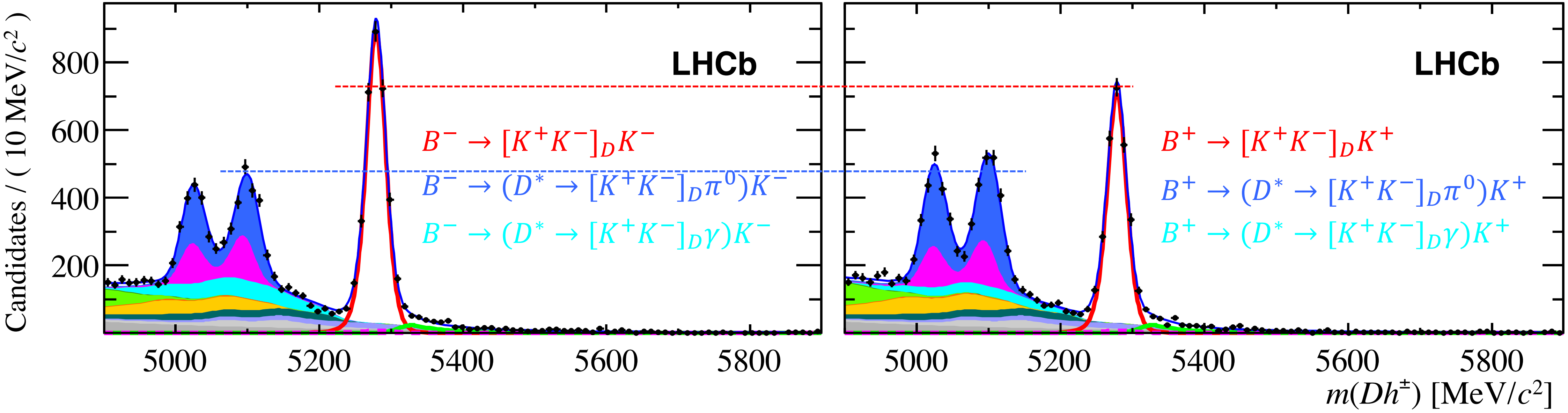
$B^\pm \to D^{(*)}K^\pm$ GLW analysis (5 fb^{-1}) [Phys. Lett. B 777, (2018) 16-30]

- Partially reconstructed analysis: don't include the neutral in the final state, and select identically to $B^\pm \to DK^\pm$
  - Decays have distinctive shapes sitting below the B mass due to angular properties of D^* daughters
  - Low purity: many partially-reconstructed physics backgrounds sit low in B mass



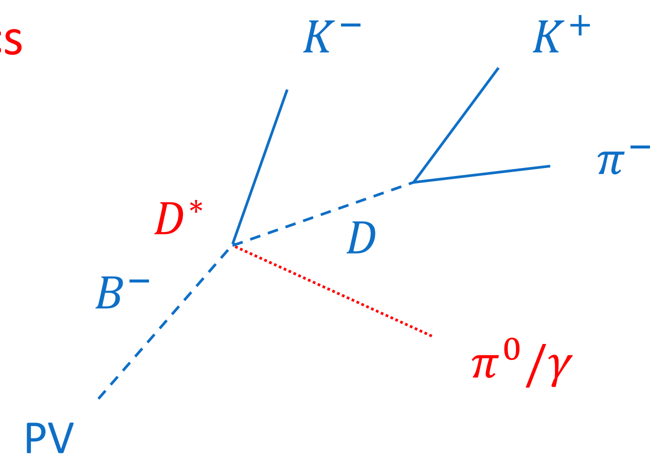
$B^{\pm} \to D^{(*)}K^{\pm}$ GLW analysis (5 fb^{-1}) [Phys. Lett. B 777, (2018) 16-30]

- Partially reconstructed analysis: don't include the neutral in the final state, and select identically to $B^{\pm} \to DK^{\pm}$
  - Decays have distinctive shapes sitting below the B mass due to angular properties of D^* daughters
  - Low purity: many partially-reconstructed physics backgrounds sit low in B mass



Fully Reconstructed $B^{\pm} \to D^{*}K^{\pm}$

- Full reconstruction: missing neutral is found and selected
  - Due to limited reconstruction efficiency, expect lower statistics



- Reconstructing neutrals at LHCb is difficult due large backgrounds in the relatively coarse calorimetry:
  - $\varepsilon(\gamma) \sim 20\%$ [LHCb-DP-2012-002]
  - $\varepsilon(\pi^0) \sim 4\%$ [LHCb-DP-2012-002]

- Fully reconstructed analysis is in progress and awaits collaboration approval
  - An estimation of the LHCb sensitivity from Run I data ($\int \mathcal{L}\, dt$ = 3 fb^{-1}) of the high statistics $B^{\pm} \to D^{*}\pi^{\pm}$ mode is presented

What does the data look like?

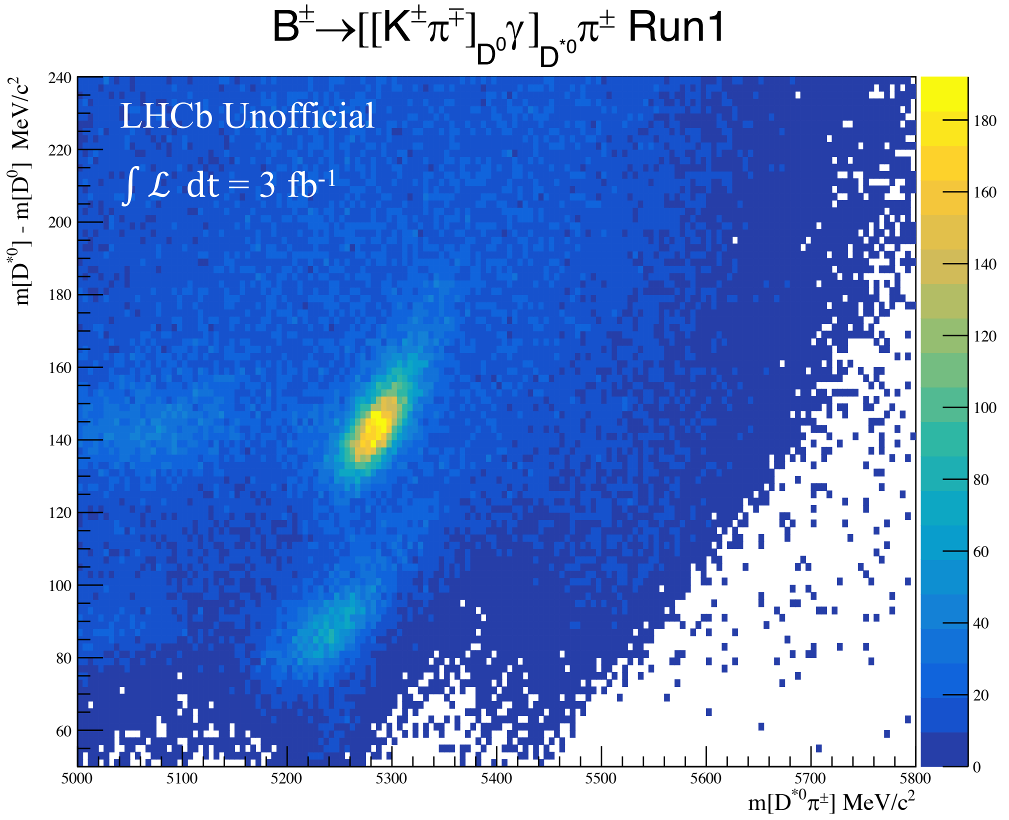
- Useful to look in 2 dimensions: Δm vs. $m_{D^*\pi}$
  - $D^* \to D\gamma$: $\Delta m = m_{D^*} - m_D$
  - $D^* \to D\pi^0$: $\Delta m = m_{D^*} - m_D - m_{\pi^0} + m_{\pi^0}^{PDG}$

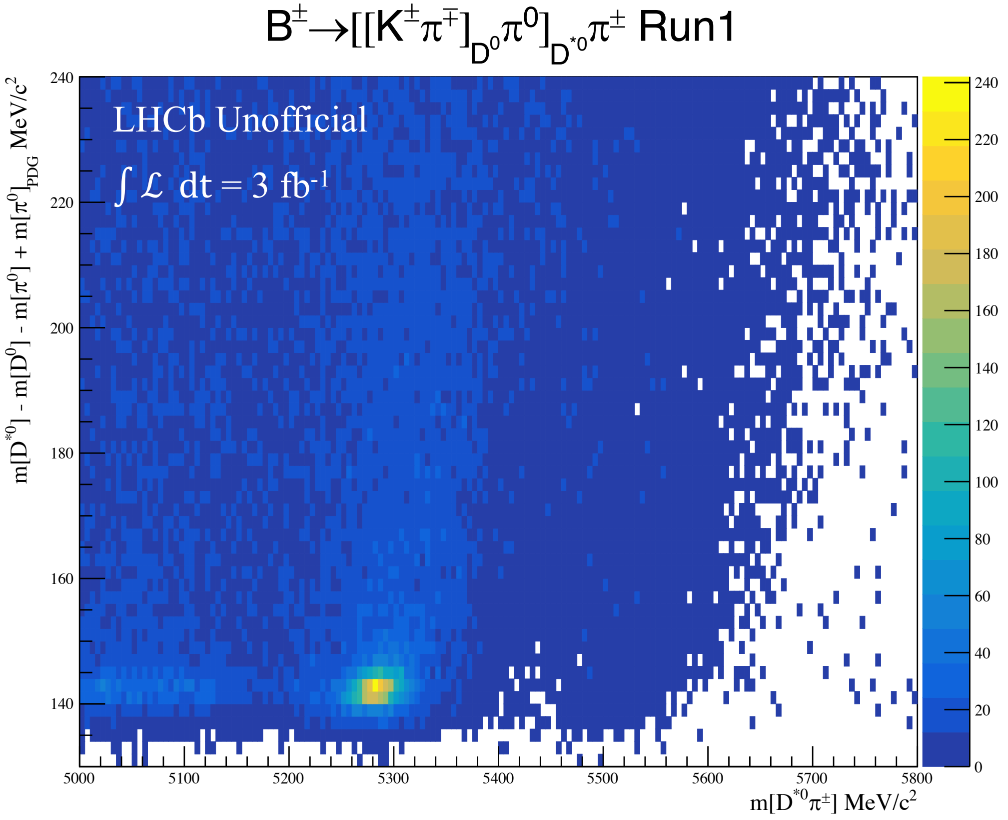
} Require true D^* to see a peak!

What does the data look like?

- Useful to look in 2 dimensions: Δm vs. $m_{D^*\pi}$
  - $D^* \to D\gamma$: $\Delta m = m_{D^*} - m_D$
  - $D^* \to D\pi^0$: $\Delta m = m_{D^*} - m_D - m_{\pi^0} + m_{\pi^0}^{PDG}$

Require true D^* to see a peak!

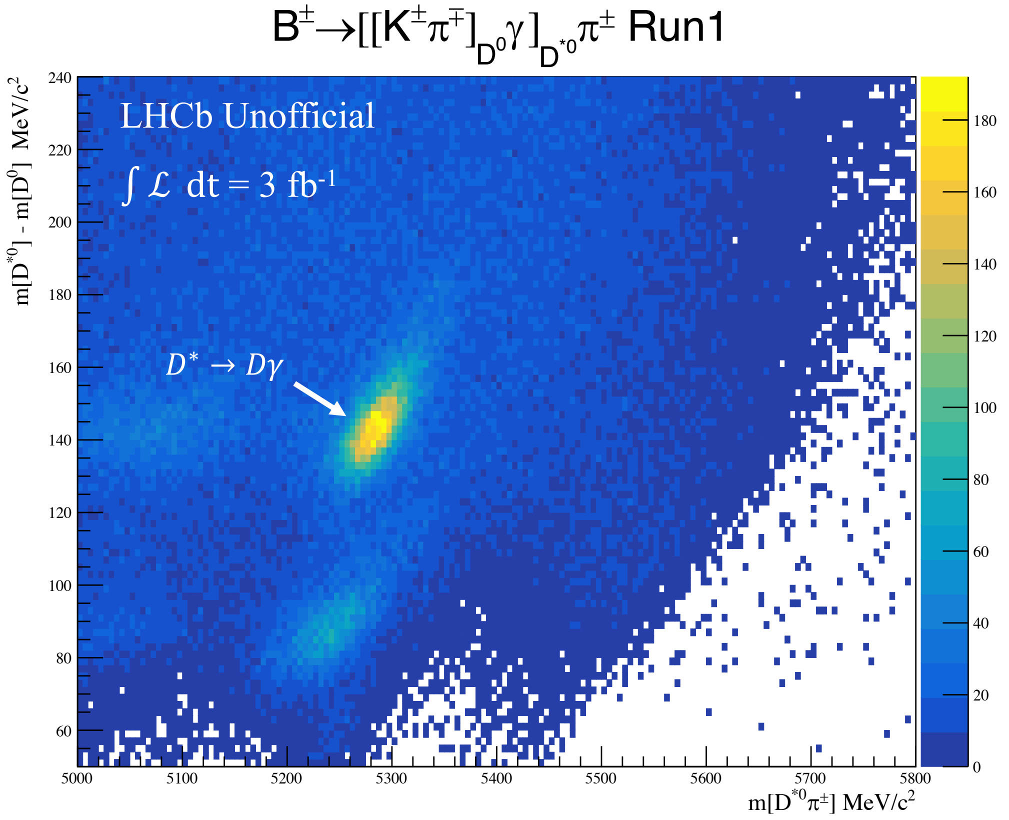


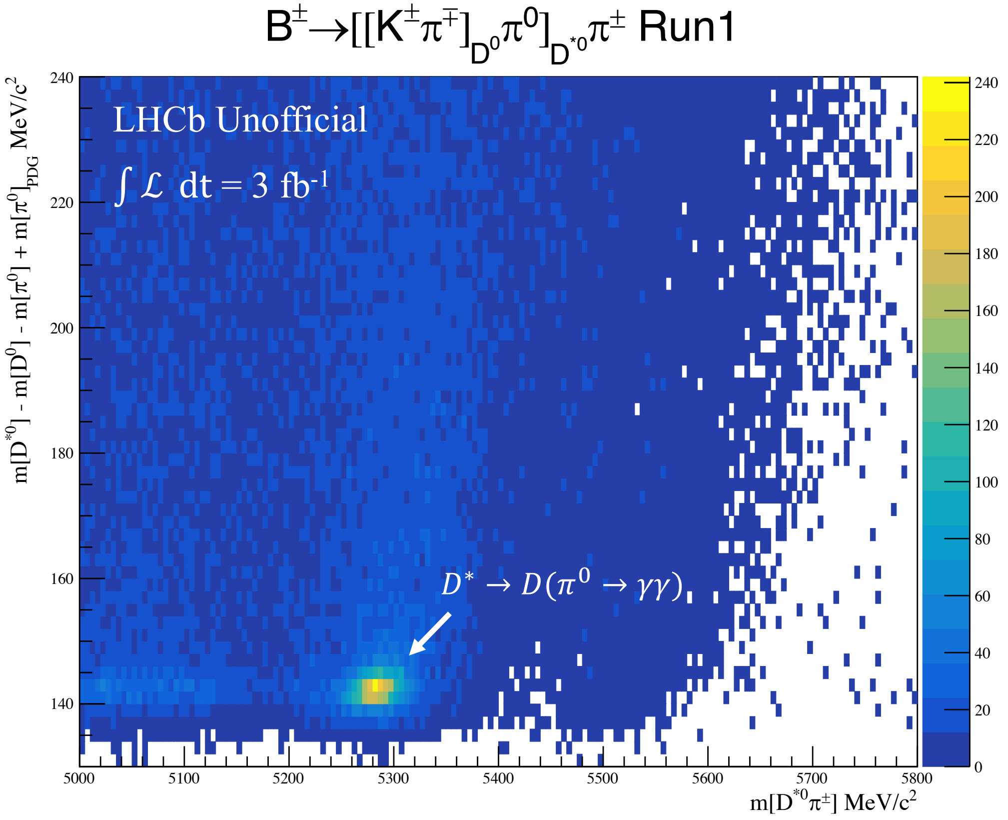


What does the data look like?

- Useful to look in 2 dimensions: Δm vs. $m_{D^*\pi}$
  - $D^* \to D\gamma$: $\Delta m = m_{D^*} - m_D$
  - $D^* \to D\pi^0$: $\Delta m = m_{D^*} - m_D - m_{\pi^0} + m_{\pi^0}^{PDG}$

Require true D^* to see a peak!



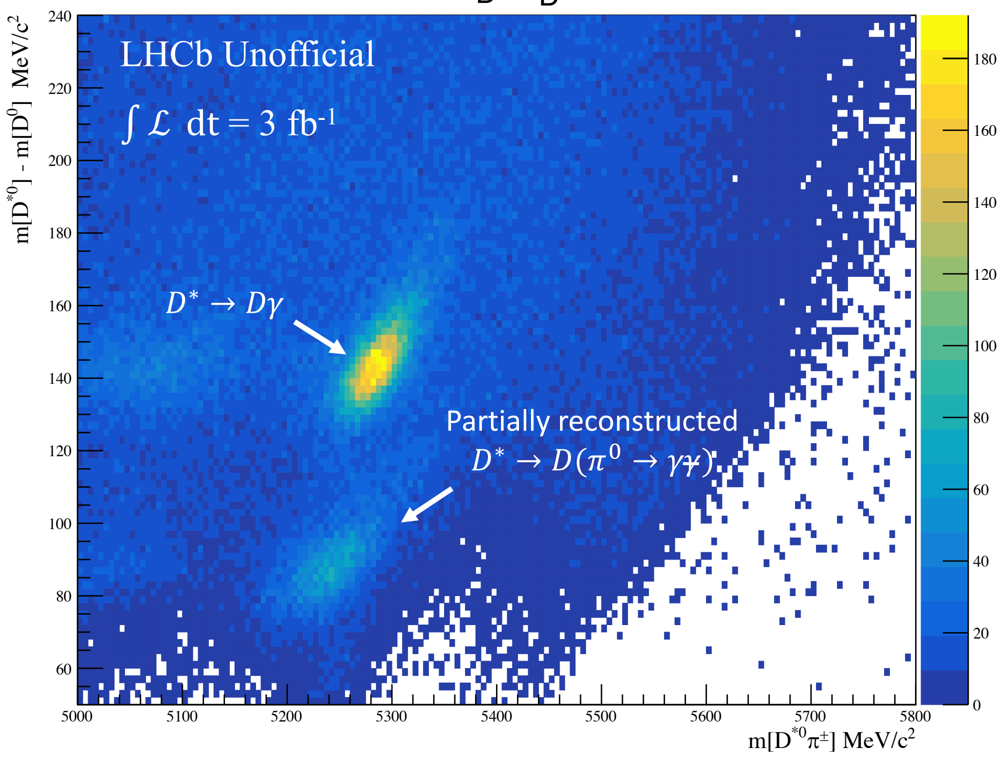


What does the data look like?

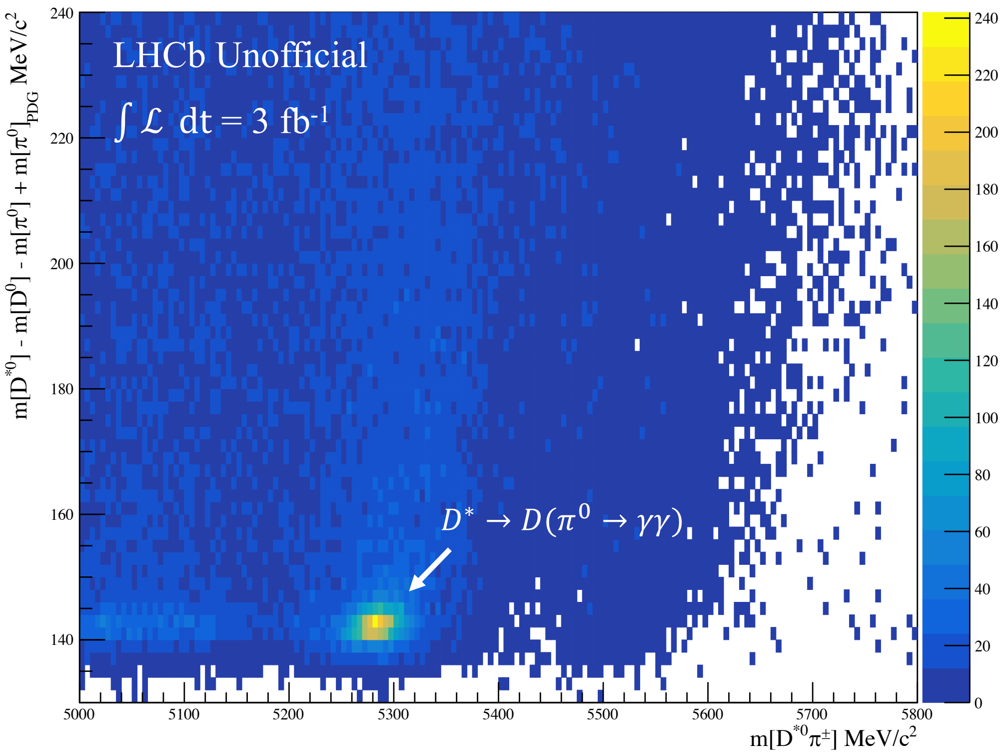
- Useful to look in 2 dimensions: Δm vs. $m_{D^*\pi}$
  - $D^* \to D\gamma$: $\Delta m = m_{D^*} - m_D$
  - $D^* \to D\pi^0$: $\Delta m = m_{D^*} - m_D - m_{\pi^0} + m_{\pi^0}^{PDG}$

Require true D^* to see a peak!

$B^{\pm} \to [[K^{\pm}\pi^{\mp}]_{D^0}\gamma]_{D^{*0}}\pi^{\pm}$ Run1



$B^{\pm} \to [[K^{\pm}\pi^{\mp}]_{D^0}\pi^0]_{D^{*0}}\pi^{\pm}$ Run1

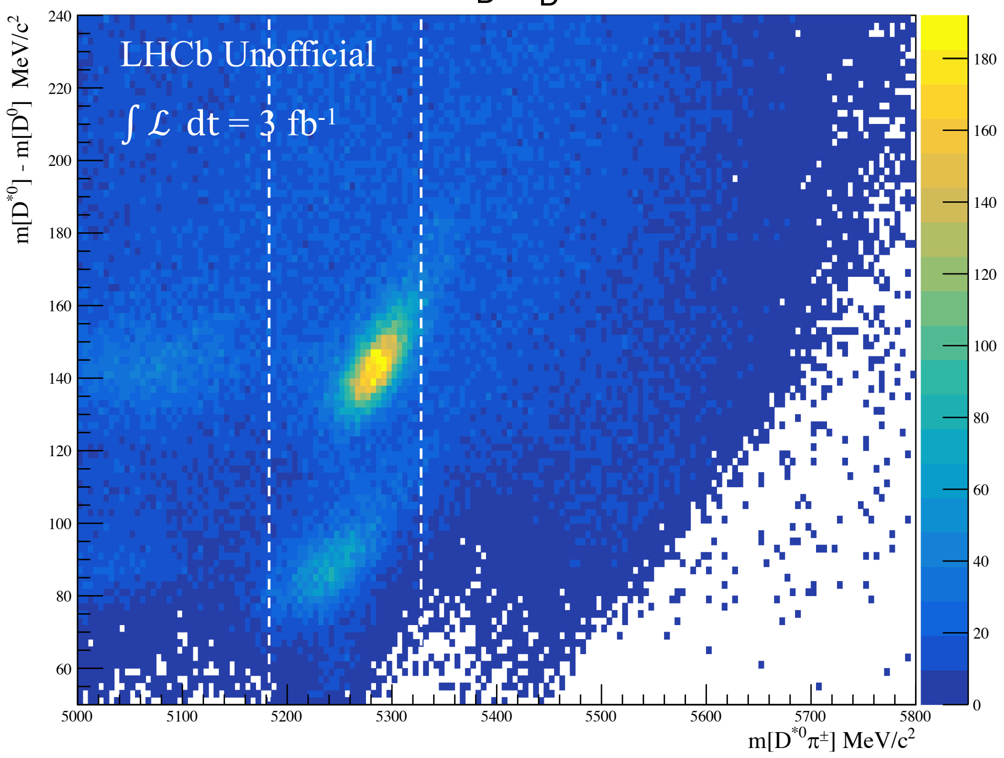


What does the data look like?

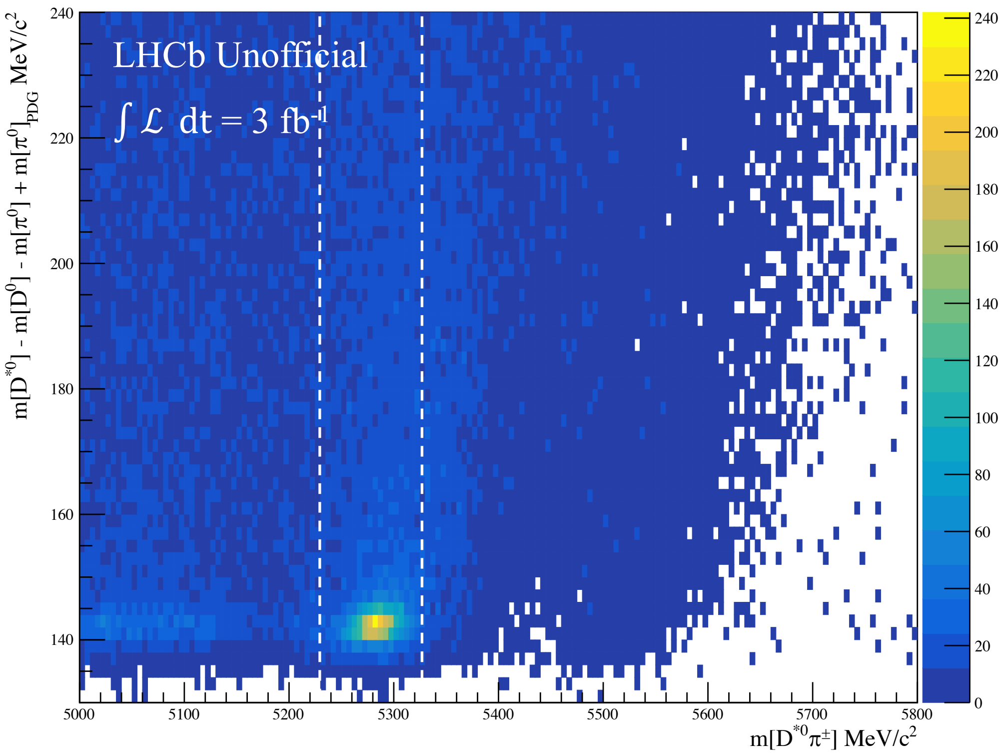
- Useful to look in 2 dimensions: Δm vs. $m_{D^*\pi}$
  - $D^* \to D\gamma$: $\Delta m = m_{D^*} - m_D$
  - $D^* \to D\pi^0$: $\Delta m = m_{D^*} - m_D - m_{\pi^0} + m_{\pi^0}^{PDG}$

} Require true D^* to see a peak!

$B^{\pm}\to[[K^{\pm}\pi^{\mp}]_{D^0}\gamma]_{D^{*0}}\pi^{\pm}$ Run1

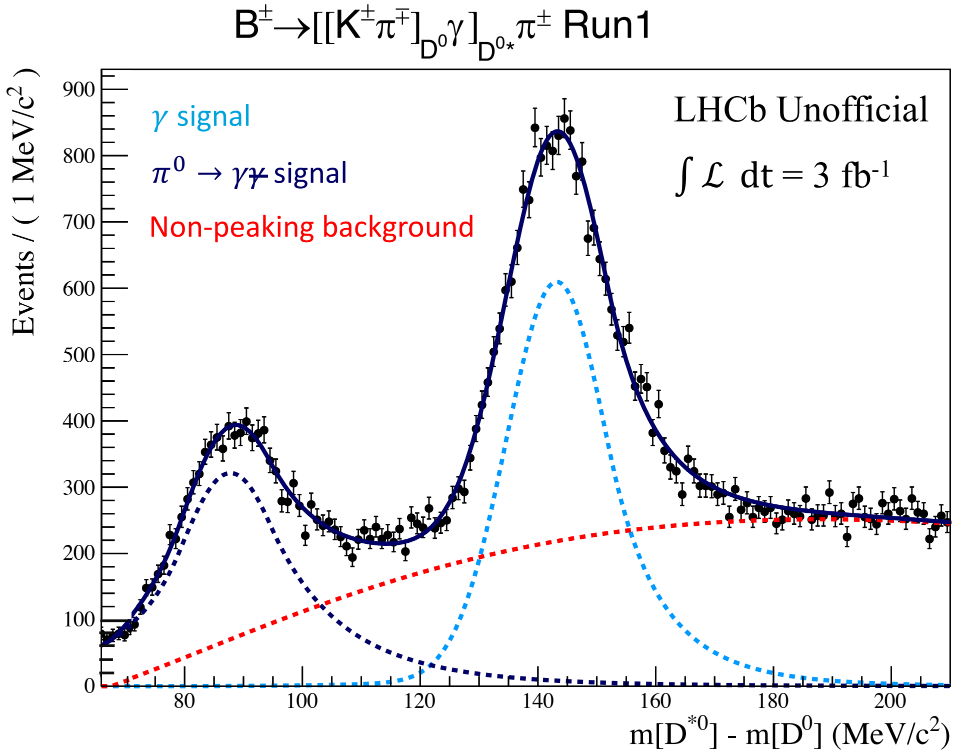


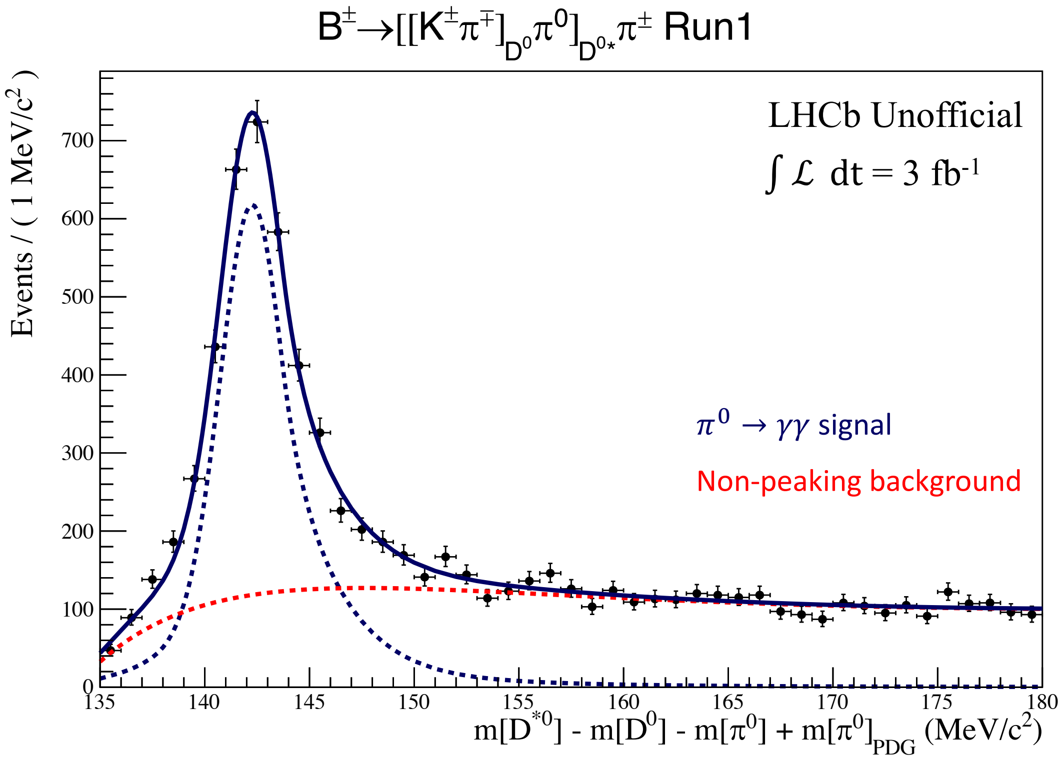
$B^{\pm}\to[[K^{\pm}\pi^{\mp}]_{D^0}\pi^0]_{D^{*0}}\pi^{\pm}$ Run1



Select within B mass signal region…

Taking a closer look at Δm





	$B^{\pm} \to (D^* \to D\gamma)\pi^{\pm}$	$B^{\pm} \to (D^* \to D\pi^0)\pi^{\pm}$
Events: Run I (3 fb^{-1})	14 533 ± 180	12 351 ± 193

ADS mode predictions at LHCb

	$\int \mathcal{L}\, dt$	$B^{\pm} \rightarrow (D^{*} \rightarrow D\gamma)\pi^{\pm}$	$B^{\pm} \rightarrow (D^{*} \rightarrow D\pi^{0})\pi^{\pm}$
Run I $B^{\pm} \rightarrow D^{*}\pi^{\pm}$	3 fb^{-1}	14 533 ± 180 events	12 351 ± 193
Run I $B^{\pm} \rightarrow D^{*}K^{\pm}$	3 fb^{-1}	~ 1180 events	~ 1050 events
Run I $B^{\pm} \rightarrow D_{ADS}{}^{*}K^{\pm}$	3 fb^{-1}	~ 18 events	~ 16 events
Run I & II $B^{\pm} \rightarrow D_{ADS}{}^{*}K^{\pm}$	9 fb^{-1}	~ 90 events	~ 80 events

- Row 1 → 2: $\frac{\mathcal{BF}(B^{\pm}\rightarrow D^{*}K^{\pm})}{\mathcal{BF}(B^{\pm}\rightarrow D^{*}\pi^{\pm})} \approx 0.081$ (PDG)
- Row 2 → 3: Scale to ADS suppressed mode: $R_{ADS} \approx 0.015$
- Extrapolations to Run II have been scaled by an additional factor of 2 due to:
  - Linear increase in $b\bar{b}$ cross-section with $\sqrt{s}$
  - Increased trigger efficiency

Conclusion: comparison to B factories

	$\int \mathcal{L}\, dt$	$B^{\pm} \to (D^* \to D\gamma)\pi^{\pm}$	$B^{\pm} \to (D^* \to D\pi^0)\pi^{\pm}$
2010: BaBar [arXiv:1709.10308v5]	0.5 ab^{-1}	5.0 ± 6.4 events	10.3 ± 5.5 events
2020: Belle II	5 ab^{-1}	$\sim$ 50 events	$\sim$ 100 events
2020: LHCb	9 fb^{-1}	$\sim$ 90 events	$\sim$ 80 events

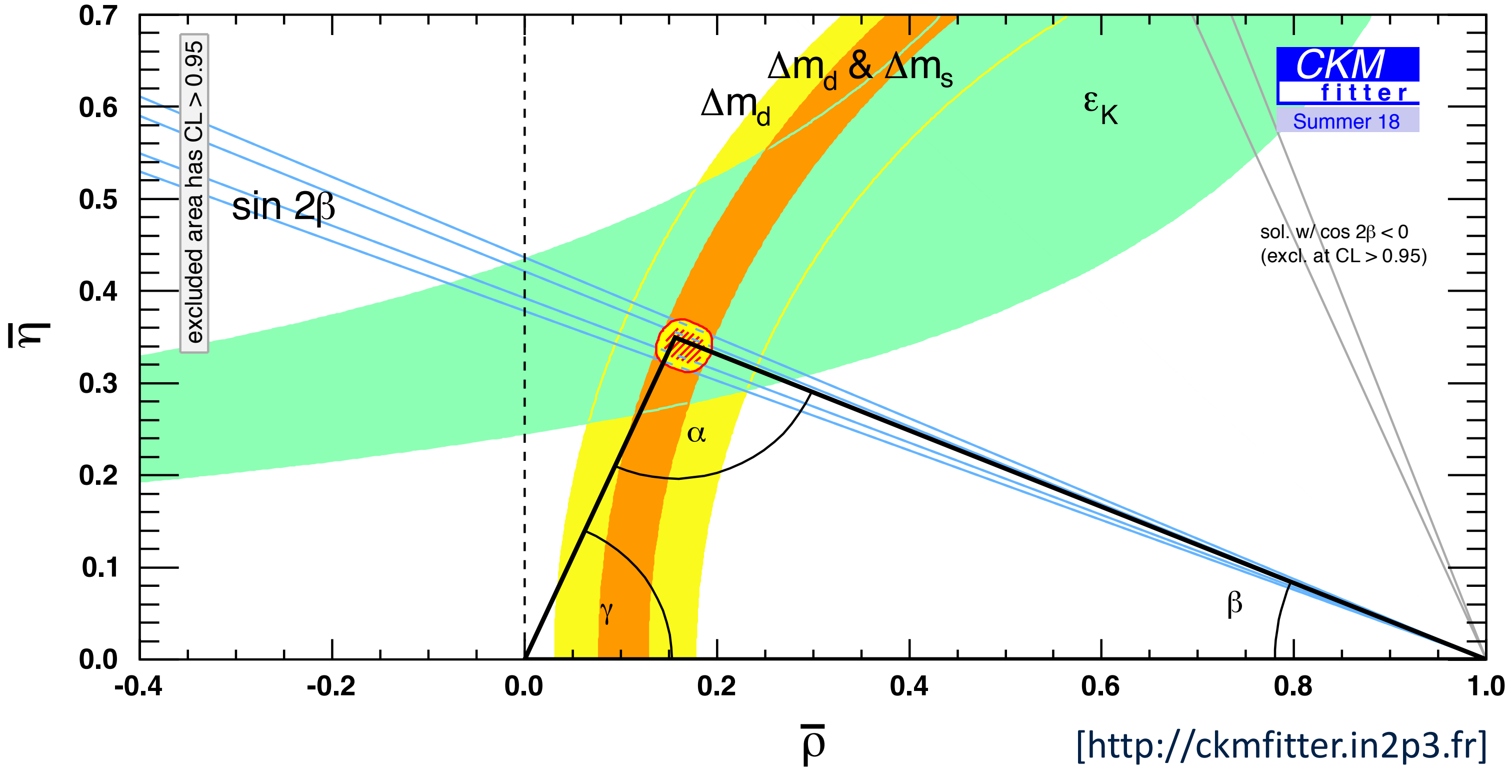
- Extrapolations made using predicted $\int \mathcal{L}\, dt$ for Belle II [arXiv:1709.10308v5]
  - Note: only an estimation of signal yields, not purity
- LHCb and Belle II have similar sensitivity on similar timescales to the full reconstruction of $B^{\pm} \to D^{*0} K^{\pm}$ decays
  - LHCb's partially reconstructed technique can bring additional information to the table

Thank you!

Back Up

Measurement using loop decays

- $\sin(2\beta)$ from $B^0 \to J/\psi K_s^0$ decays
- Δm_s and Δm_d from $B^0_{(s)}$ mixing
- ϵ_K from neutral kaon systems



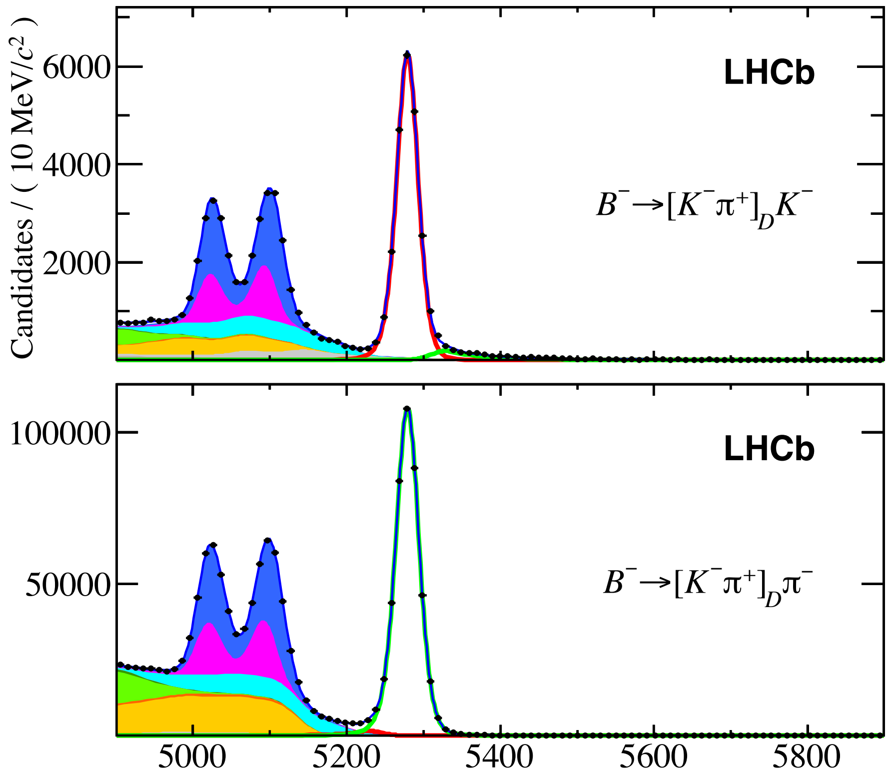
[http://ckmfitter.in2p3.fr]

Final states accessible to both D^0 and $\bar{D}^0$

- GLW: $D \to KK, \pi\pi, \pi\pi\pi\pi, KK\pi^0, \pi\pi\pi^0$
- ADS: $D \to \pi K, \pi K\pi\pi, \pi\pi\pi^0$
- GGSZ: $D \to K_s^0\pi\pi, K_s^0 KK$ [JHEP 08 (2018) 176]
- GLS: $D \to K_s^0 K\pi$

$B^\pm \to D^{(*)}K^\pm$ GLW analysis (5 fb^{-1}) [Phys. Lett. B 777, (2018) 16-30]

- Life is never simple…
- Study favoured mode data ($D^0 \to K^+\pi^-$) to help understand signal and background contributions:



Fully reconstructed signal:

- $B^\pm \to D\pi^\pm$
- $B^\pm \to DK^\pm$

Partially reconstructed signal:

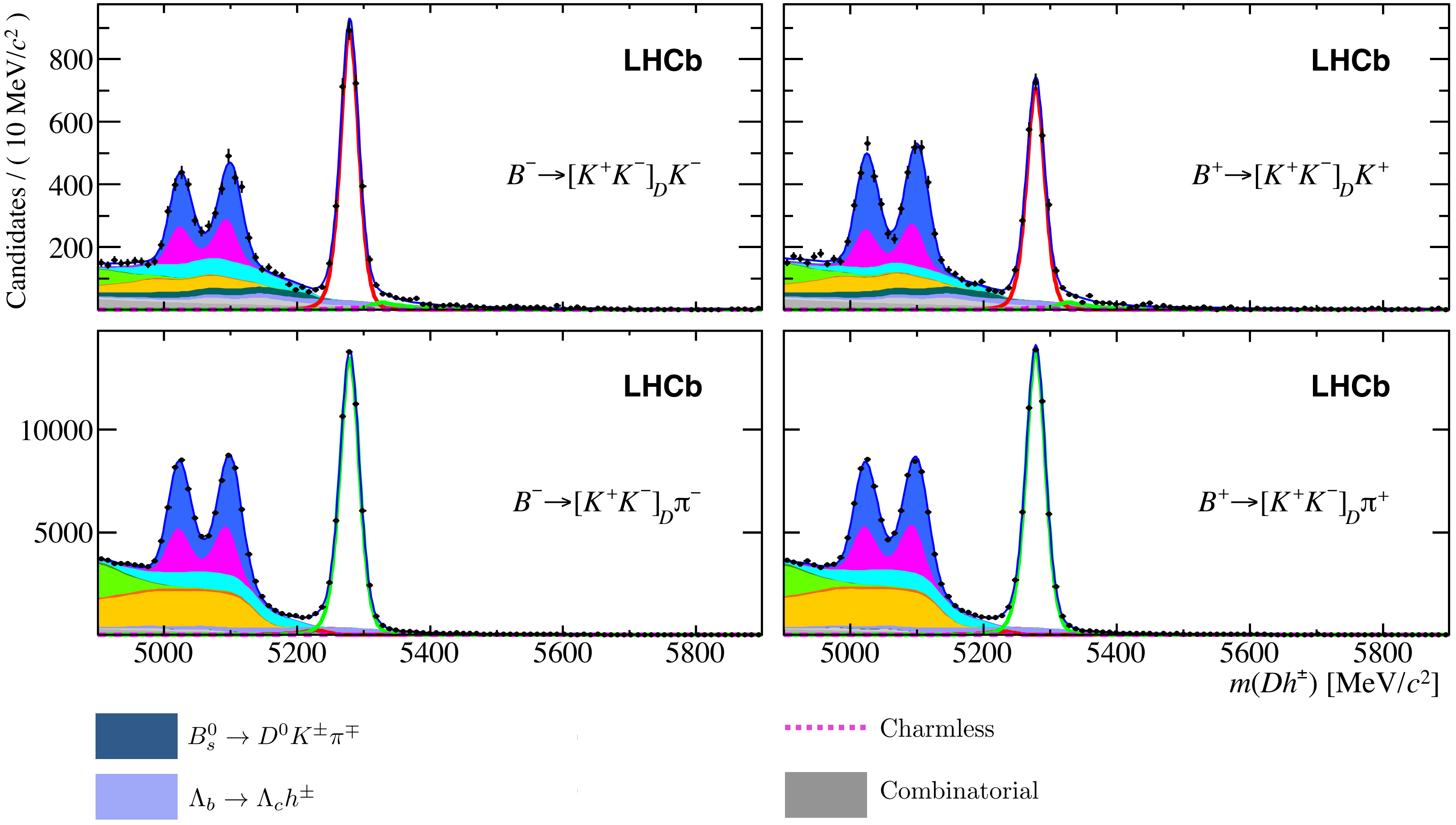
- $B^\pm \to (D^{*0} \to D^0\pi^0)h^\pm$
- $B^\pm \to (D^{*0} \to D^0\gamma)h^\pm$

Partially reconstructed backgrounds:

- $B^0 \to (D^{*\mp} \to D^0\pi^\mp)h^\pm$
- $B^\pm \to D^0 h^\pm \pi^0$
- $B \to D^* h^\pm \pi$
- Part. reco. mis-ID

$B^{\pm} \to D^{(*)}K^{\pm}$ GLW analysis (5 fb^{-1}) [Phys. Lett. B 777, (2018) 16-30]

- $D \to K^+K^-$ results:



$A^{KK} = +0.126 \pm 0.014 \pm 0.002$

$A^{CP,\gamma} = +0.276 \pm 0.094 \pm 0.047$

$A^{CP,\pi^0} = -0.151 \pm 0.033 \pm 0.011$

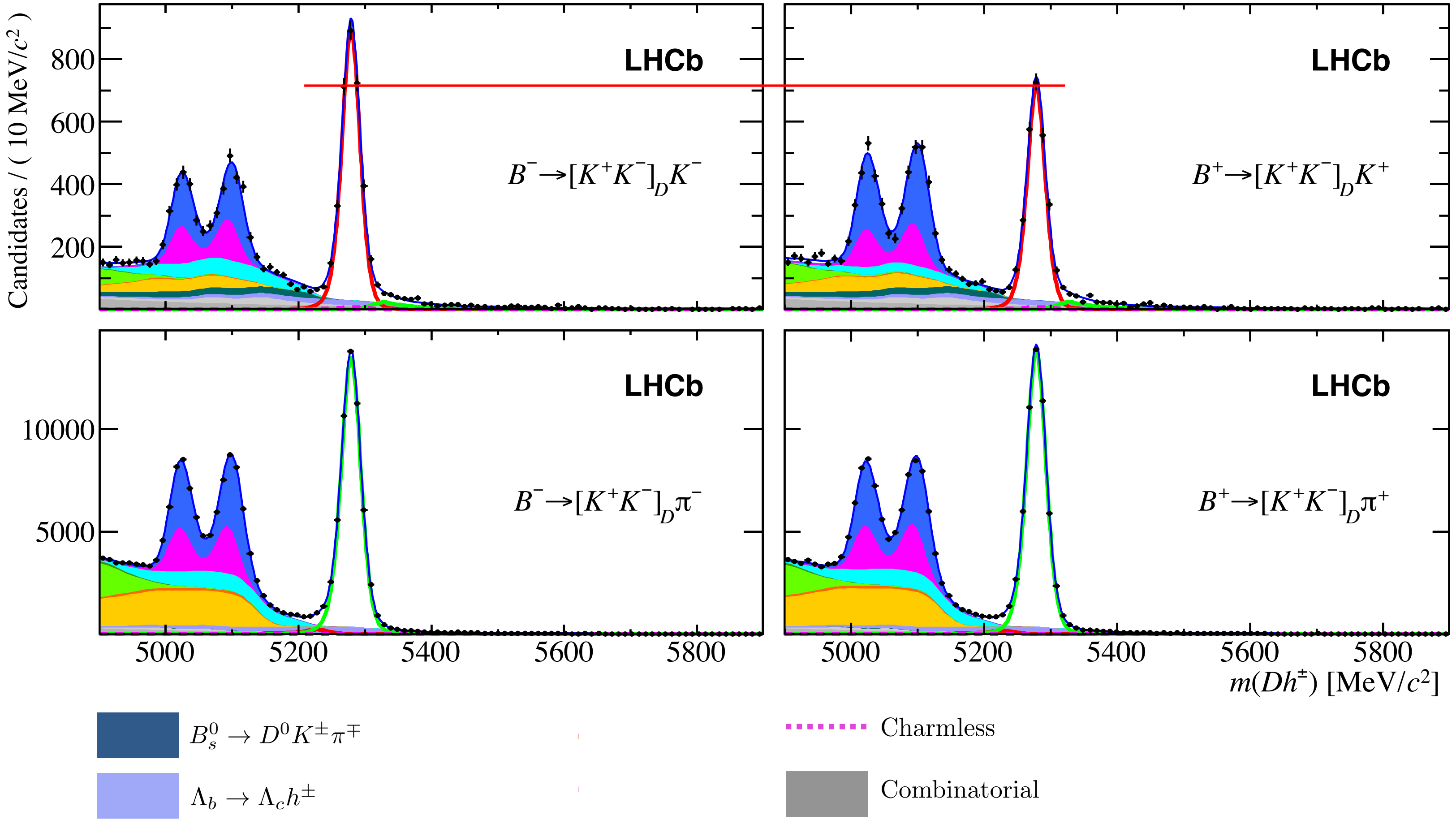
$R^{KK} = 0.988 \pm 0.015 \pm 0.011$

$R^{CP,\gamma} = 0.902 \pm 0.087 \pm 0.112$

$R^{CP,\pi^0} = 1.138 \pm 0.029 \pm 0.016$

$B^{\pm} \to D^{(*)}K^{\pm}$ GLW analysis (5 fb^{-1}) [Phys. Lett. B 777, (2018) 16-30]

- $D \to K^+K^-$ results:

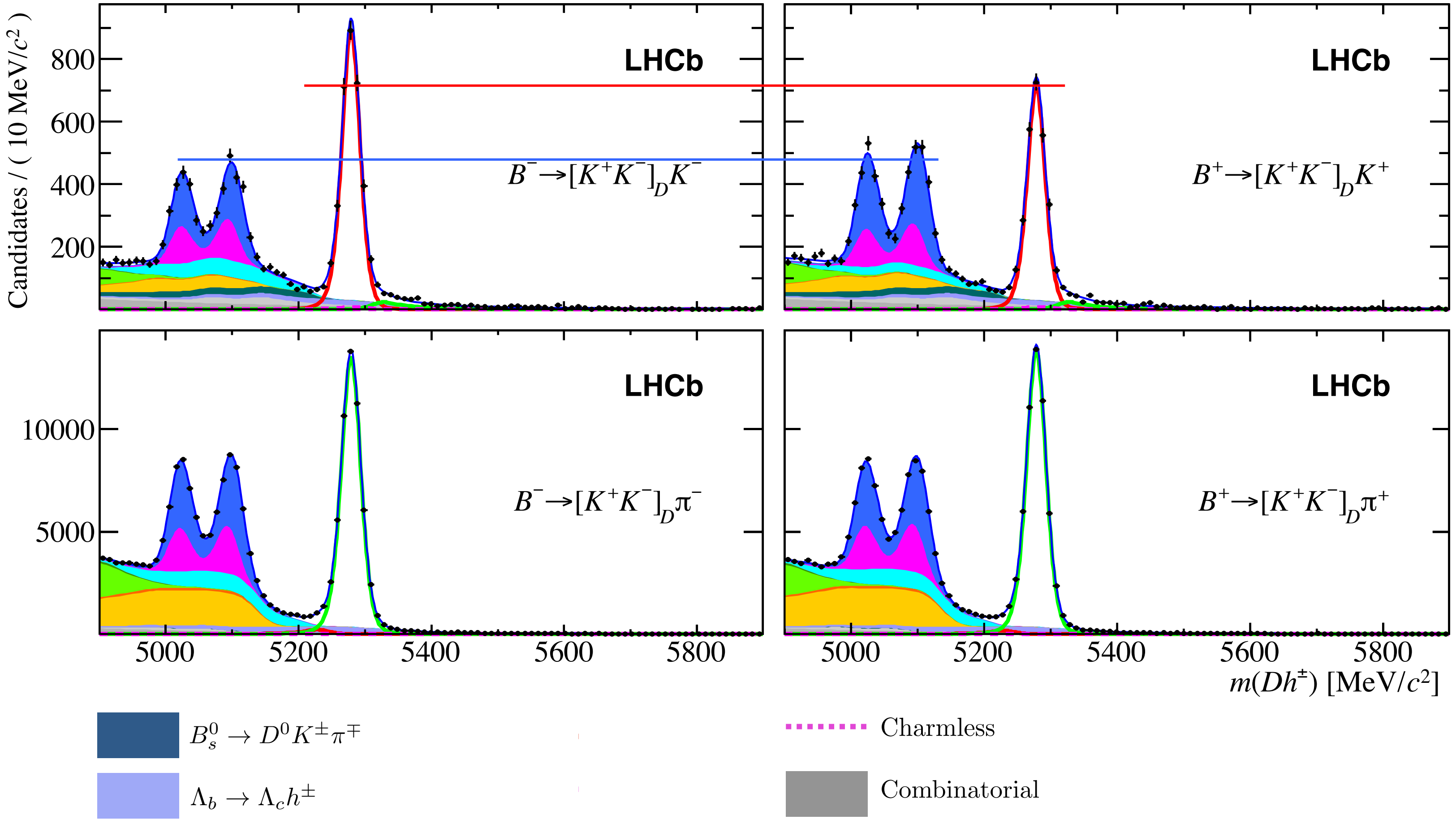


$A^{KK} = +0.126 \pm 0.014 \pm 0.002$
$A^{CP,\gamma} = +0.276 \pm 0.094 \pm 0.047$
$A^{CP,\pi^0} = -0.151 \pm 0.033 \pm 0.011$

$R^{KK} = 0.988 \pm 0.015 \pm 0.011$
$R^{CP,\gamma} = 0.902 \pm 0.087 \pm 0.112$
$R^{CP,\pi^0} = 1.138 \pm 0.029 \pm 0.016$

$B^{\pm} \to D^{(*)}K^{\pm}$ GLW analysis (5 fb^{-1}) [Phys. Lett. B 777, (2018) 16-30]

- $D \to K^+K^-$ results:



$A^{KK} = +0.126 \pm 0.014 \pm 0.002$

$A^{CP,\gamma} = +0.276 \pm 0.094 \pm 0.047$

$A^{CP,\pi^0} = -0.151 \pm 0.033 \pm 0.011$

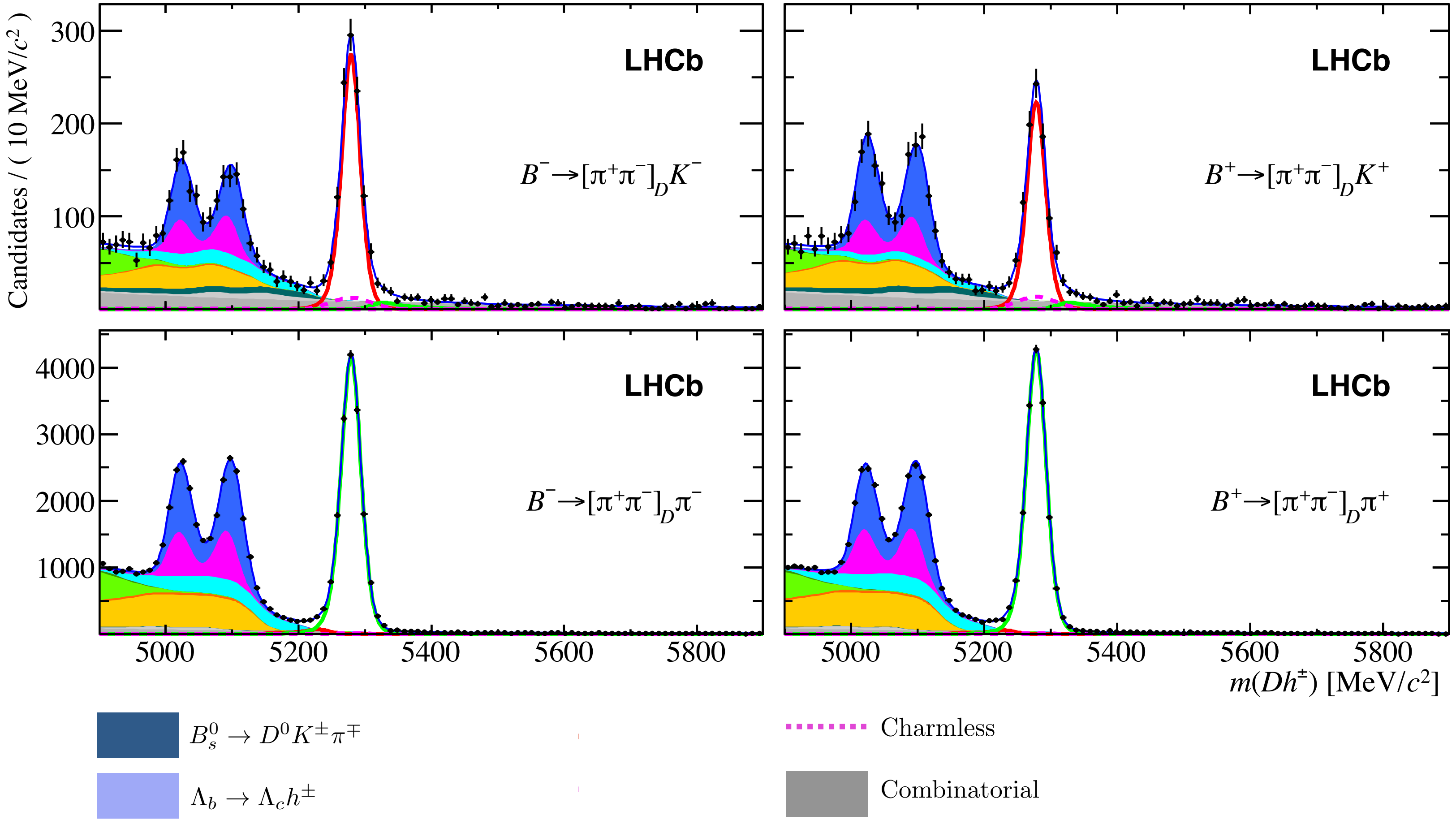
$R^{KK} = 0.988 \pm 0.015 \pm 0.011$

$R^{CP,\gamma} = 0.902 \pm 0.087 \pm 0.112$

$R^{CP,\pi^0} = 1.138 \pm 0.029 \pm 0.016$

$B^{\pm} \rightarrow D^{(*)}K^{\pm}$ GLW analysis (5 fb^{-1}) [Phys. Lett. B 777, (2018) 16-30]

- $D \rightarrow \pi^+\pi^-$ results:



$A^{\pi\pi} = +0.115 \pm 0.025 \pm 0.007$

$A^{CP,\gamma} = +0.276 \pm 0.094 \pm 0.047$

$A^{CP,\pi^0} = -0.151 \pm 0.033 \pm 0.011$

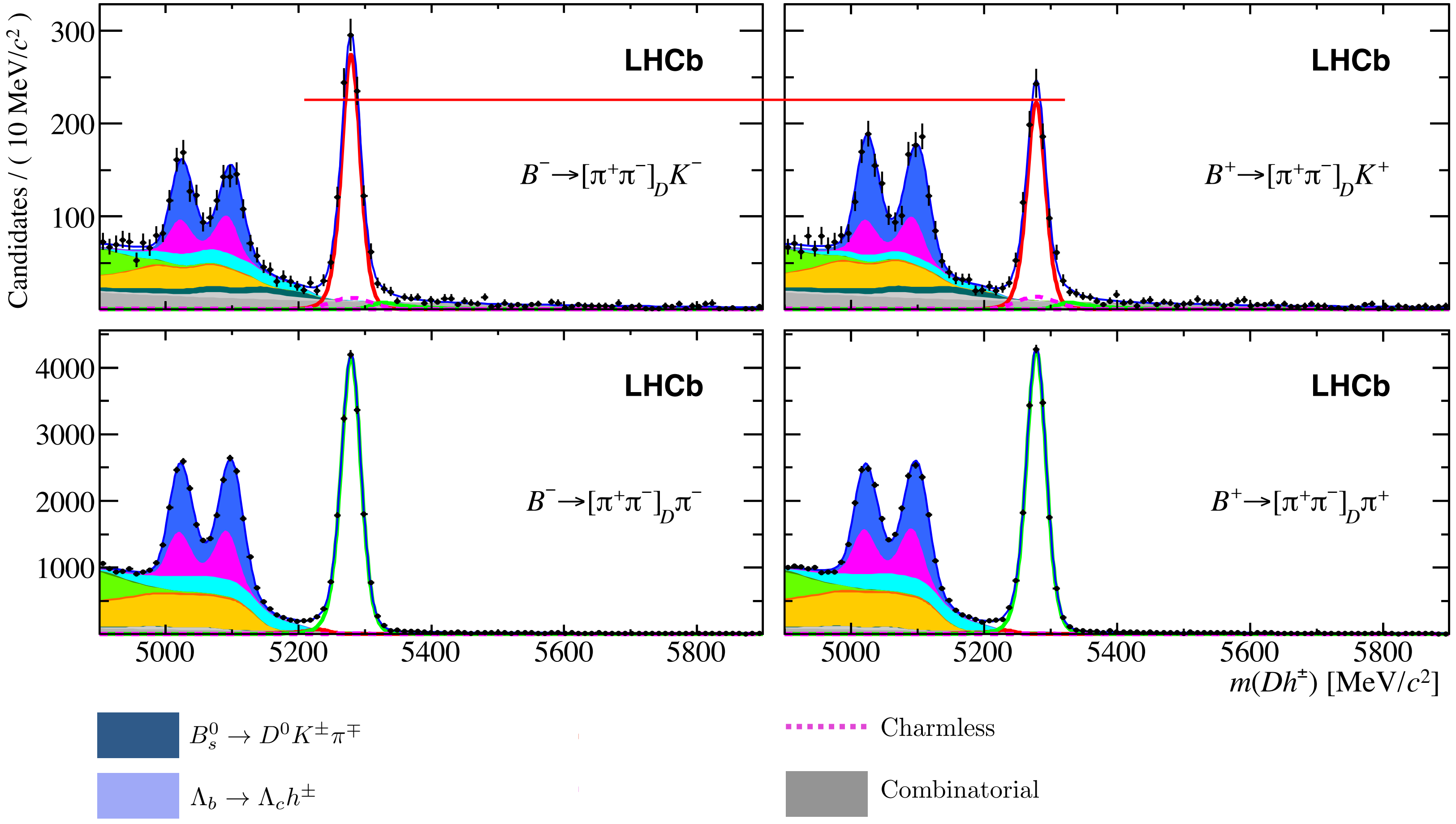
$R^{\pi\pi} = 0.992 \pm 0.027 \pm 0.051$

$R^{CP,\gamma} = 0.902 \pm 0.087 \pm 0.112$

$R^{CP,\pi^0} = 1.138 \pm 0.029 \pm 0.016$

$B^\pm \to D^{(*)}K^\pm$ GLW analysis (5 fb^{-1}) [Phys. Lett. B 777, (2018) 16-30]

- $D \to \pi^+\pi^-$ results:

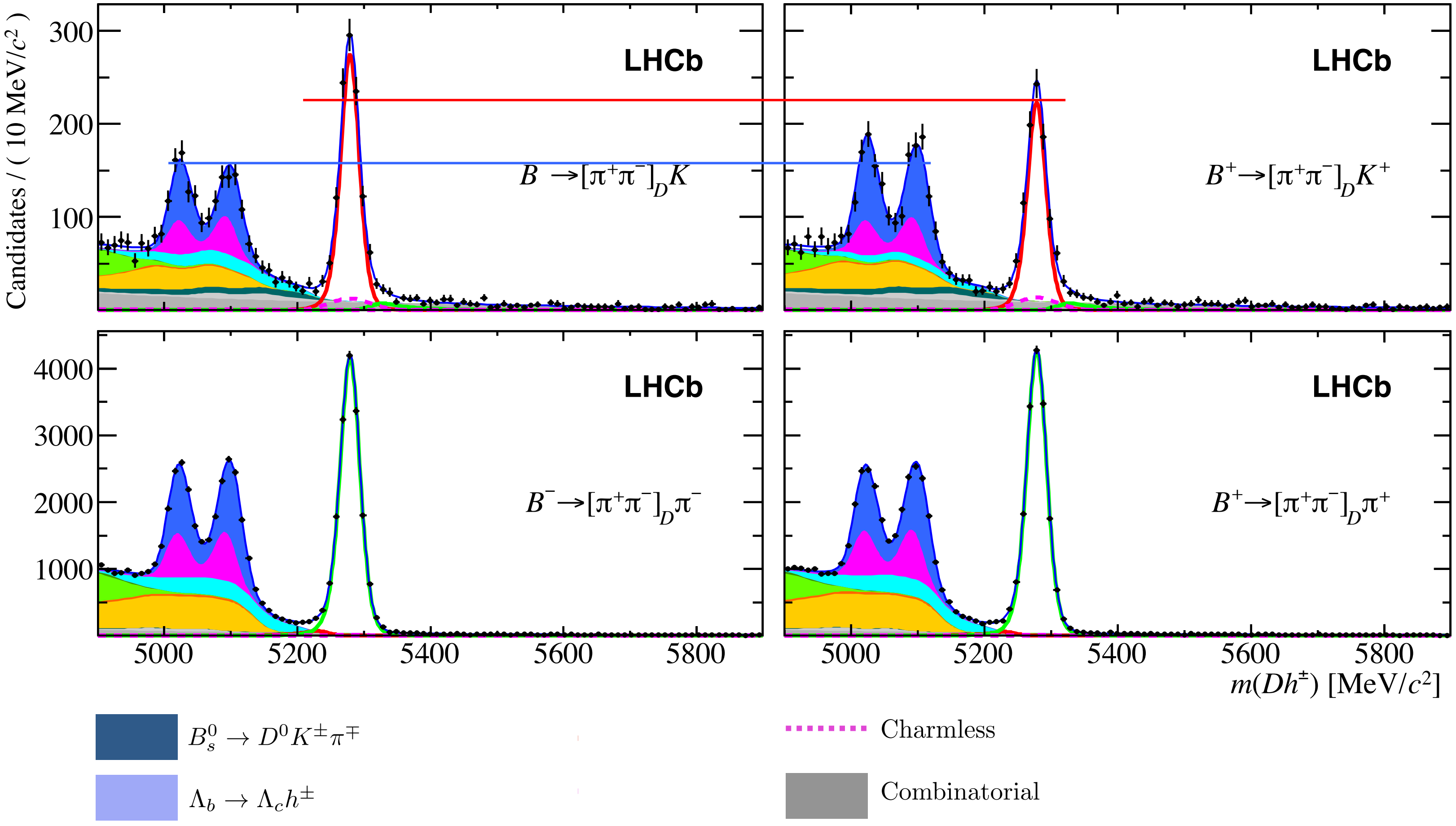


$$A^{\pi\pi} = +0.115 \pm 0.025 \pm 0.007$$
$$A^{CP,\gamma} = +0.276 \pm 0.094 \pm 0.047$$
$$A^{CP,\pi^0} = -0.151 \pm 0.033 \pm 0.011$$

$$R^{\pi\pi} = 0.992 \pm 0.027 \pm 0.051$$
$$R^{CP,\gamma} = 0.902 \pm 0.087 \pm 0.112$$
$$R^{CP,\pi^0} = 1.138 \pm 0.029 \pm 0.016$$

$B^{\pm} \to D^{(*)}K^{\pm}$ GLW analysis (5 fb^{-1}) [Phys. Lett. B 777, (2018) 16-30]

- $D \to \pi^+\pi^-$ results:

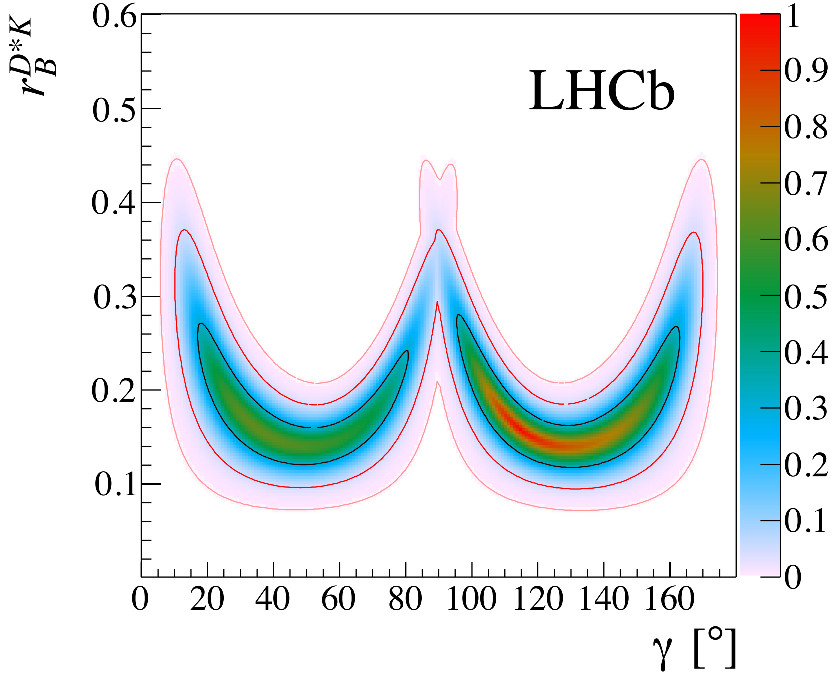


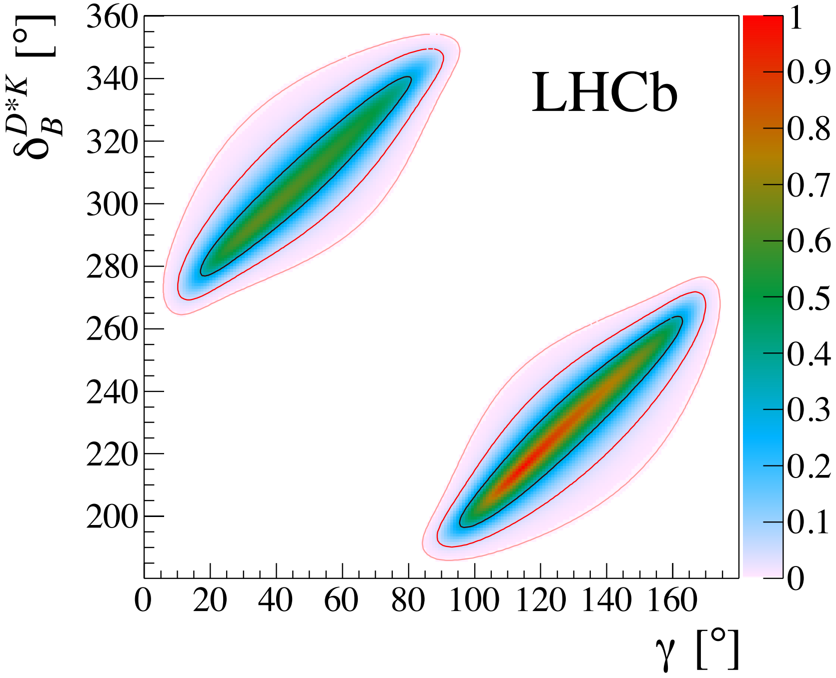
$$A^{\pi\pi} = +0.115 \pm 0.025 \pm 0.007$$
$$A^{CP,\gamma} = +0.276 \pm 0.094 \pm 0.047$$
$$A^{CP,\pi^0} = -0.151 \pm 0.033 \pm 0.011$$

$$R^{\pi\pi} = 0.992 \pm 0.027 \pm 0.051$$
$$R^{CP,\gamma} = 0.902 \pm 0.087 \pm 0.112$$
$$R^{CP,\pi^0} = 1.138 \pm 0.029 \pm 0.016$$

$B^{\pm} \to D^{(*)}K^{\pm}$ GLW analysis (5 fb^{-1}) [Phys. Lett. B 777, (2018) 16-30]

- The observables give constraints on γ, along with the amplitude ratio $r_B^{D^{(*)}K}$ and strong phase difference $\delta_B^{D^{(*)}K}$:





LHCb and Belle II luminosity scenarios

			Milestone I	Milestone II	Milestone III
Year		2012	2020	2024	2030
LHCb	$\mathcal{L}[\text{fb}^{-1}]$	3	8	22	30
	$n(b\bar{b})$	0.3×10^{12}	1.1×10^{12}	37×10^{12}	87×10^{12}
	$\sqrt{s}$	7/8 TeV	13 TeV	14 TeV	14 TeV
Belle (II)	$\mathcal{L}[\text{ab}^{-1}]$	0.7	5	50	-
	$n(B\bar{B})$	0.1×10^{10}	0.54×10^{10}	5.4×10^{10}	-
	$\sqrt{s}$	10.58 GeV	10.58 GeV	10.58 GeV	-

[arXiv:1709.10308v5]

GLW mode predictions at LHCb & Belle II

	$\int \mathcal{L}\, dt$	$B^\pm \to (D^* \to D\gamma)\pi^\pm$		$B^\pm \to (D^* \to D\pi^0)\pi^\pm$	
		$D \to K^+K^-$	$D \to \pi^+\pi^-$	$D \to K^+K^-$	$D \to \pi^+\pi^-$
Run I	3 fb^{-1}	$\sim$ 120 events	$\sim$ 42 events	$\sim$ 110 events	$\sim$ 38 events
Run I & II	6 fb^{-1}	$\sim$ 600 events	$\sim$ 210 events	$\sim$ 550 events	$\sim$ 190 events

Scaled to KK mode: $\frac{\mathcal{BF}(B^\pm \to D^* K^\pm)}{\mathcal{BF}(B^\pm \to D^* \pi^\pm)} \times \frac{\mathcal{BF}(D^0 \to K^+K^-)}{\mathcal{BF}(D^0 \to K^+\pi^-)} = 8.3 \times 10^{-3}$

Scaled to ππ mode: $\frac{\mathcal{BF}(B^\pm \to D^* K^\pm)}{\mathcal{BF}(B^\pm \to D^* \pi^\pm)} \times \frac{\mathcal{BF}(D^0 \to \pi^+\pi^-)}{\mathcal{BF}(D^0 \to K^+\pi^-)} = 2.9 \times 10^{-3}$

	$n(B\bar{B})$	$B^\pm \to (D^* \to D\gamma)\pi^\pm$		$B^\pm \to (D^* \to D\pi^0)\pi^\pm$	
		$D \to K^+K^-$	$D \to \pi^+\pi^-$	$D \to K^+K^-$	$D \to \pi^+\pi^-$
2010: BaBar [arXiv:0807.2408]	383×10^6	62 ± 12 events	15 ± 6 events	101 ± 14 events	31 ± 8 events
2020: Belle II	0.54×10^{10}	$\sim$ 870 events	$\sim$ 210 events	$\sim$ 1420 events	$\sim$ 440 events

γ combination at LHCb

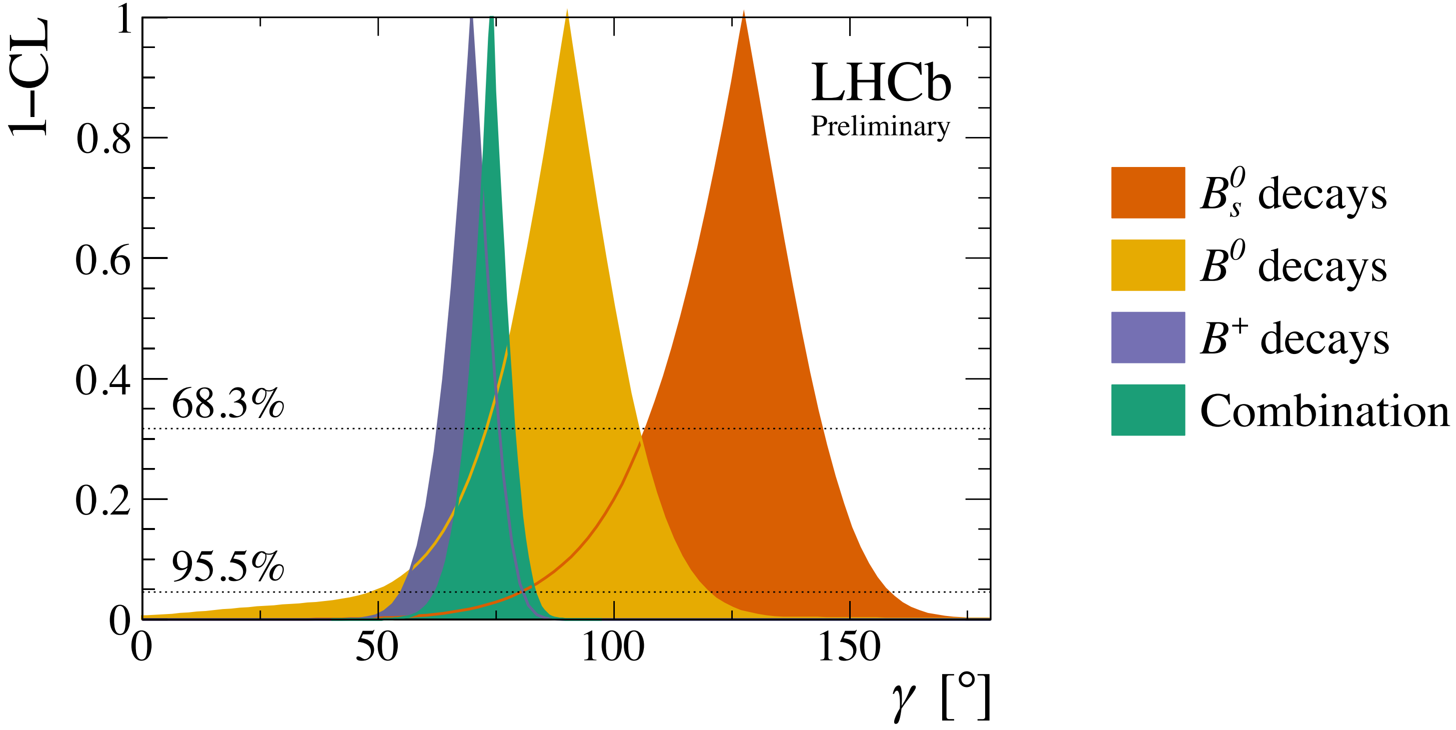
- World average dominated by the LHCb measurement: $\gamma = \left(74.0^{+5.0}_{-5.8}\right)^{\circ}$:

Run I:	• 3 fb^{-1} of data at $\sqrt{s}$ = 7/8 TeV	• $B^- \to DK^-$ ADS & GLS • $B^- \to DK^+\pi^-\pi^+$ GLW & ADS • $B^0 \to DK^{*0}$ ADS & GLW • $B^0 \to DK^+\pi^-$ GLW-Dalitz • $B_s^0 \to D_s^{\mp}K^{\pm}$ TD • $B^0 \to D^{\pm}\pi^{\mp}$ TD
Run I & Run II:	• 3 fb^{-1} of data at $\sqrt{s}$ = 7/8 TeV • 6 fb^{-1} of data at $\sqrt{s}$ = 13 TeV	• $B^- \to DK^-$ GLW & GGSZ • $B^- \to D^*K^-$ GLW • $B^- \to DK^{*-}$ GLW & ADS

[LHCb-CONF-2018-002]

γ combination at LHCb

- World average dominated by the LHCb measurement: $\gamma = \left(74.0^{+5.0}_{-5.8}\right)^{\circ}$:



[LHCb-CONF-2018-002]

γ combination at LHCb in the upgrade era

- 4° with Run II data ($\sim$ 9 fb^{-1}) [arXiv:1709.10308v5]
- 1.5° by the end of Run III ($\sim$ 22 fb^{-1}, 2024) [arXiv:1709.10308v5]
- $< 1^{\circ}$ by the end of Run IV ($\sim$ 50 fb^{-1}, 2029) [arXiv:1709.10308v5]
- $\sim 0.4^{\circ}$ in Phase II upgrade ($\sim$ 300 fb^{-1}, 2034) [CERN-LHCC-2017-003]