Time-integrated CP violation measurements in B→DD and B→DKK decays at LHCb

Wenbin Qian
University of Chinese Academy of Sciences

On behalf of the LHCb collaboration

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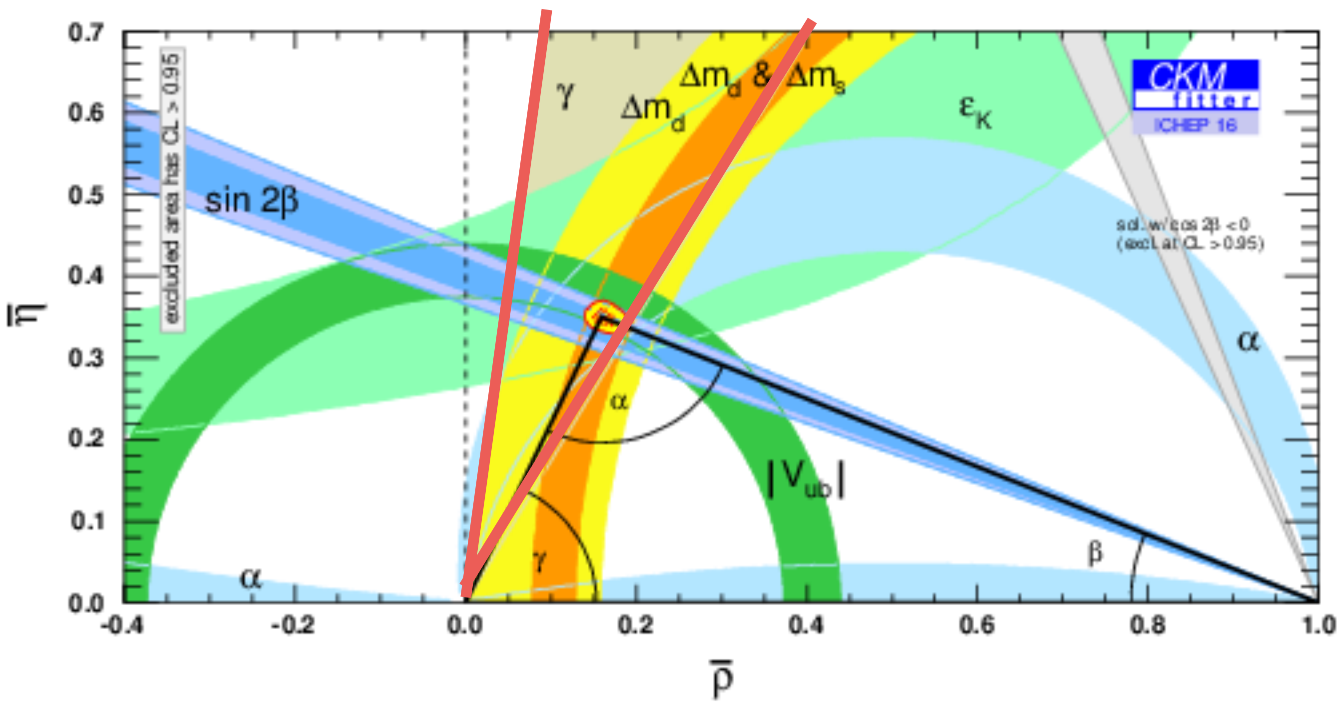
Outlines

- **CKM angle γ measurements**
- **First observation of $B_s \to \overline{D}^0 KK$** LHCb-PAPER-2018-014
- **Studies of the $B_{(s)} \to \overline{D}^{(*)} \phi$ system** LHCb-PAPER-2018-015
- **Search for B_c^+ decays to two charmed mesons** LHCb-PAPER-2017-045
- **CPV measurements in $B^- \to D_s^- D^0$ and $B^- \to D^- D^0$ decays** LHCb-PAPER-2018-007
- **Conclusion**

CKM angle γ

➢ **Least well known CKM parameter**

$$\gamma = \arg\left[-V_{ud}V_{ub}^{*}/(V_{cd}V_{cb}^{*})\right]$$



Direct: $\gamma = (73.5^{+4.3}_{-5.0})^{\circ}$

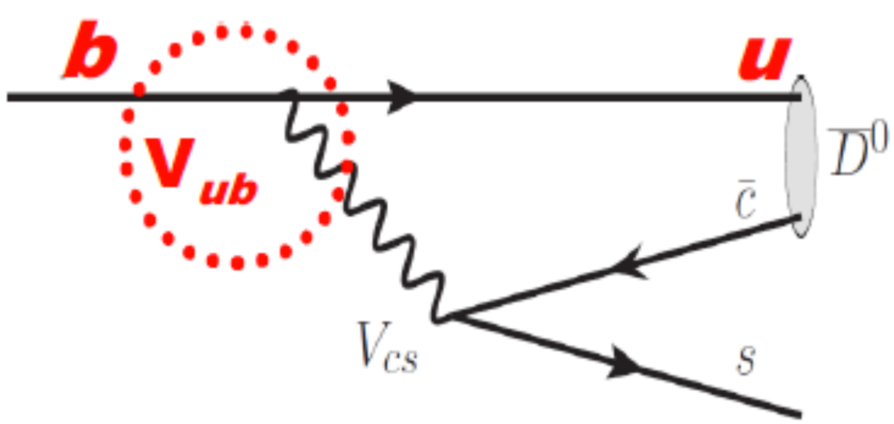
VS

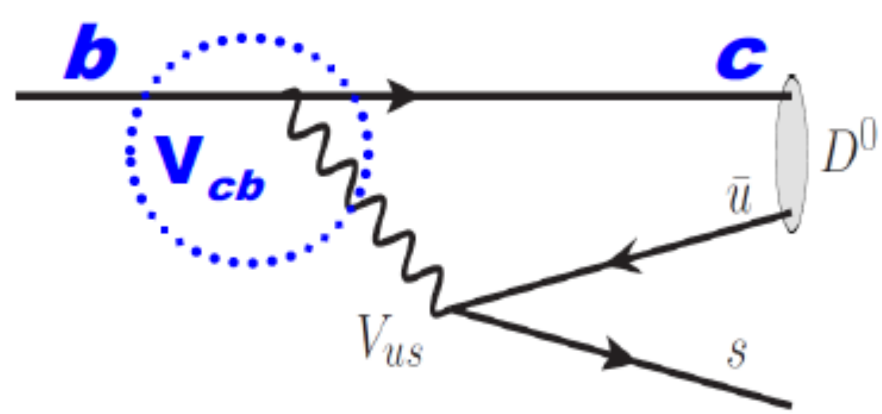
Indirect: $\gamma = (65.3^{+1.0}_{-2.5})^{\circ}$

New Physics?

➢ **γ at tree level: clean theory prediction $\delta\gamma/\gamma \sim 10^{-7}$**

JHEP 1401 (2014) 051





Methodology for γ measurement

- **Sensitive channels with small BFs: need to combine many channels**

  GLW: D = CP eigenstates, e.g. KK, ππ — **PLB 253 (1991) 483**, **PLB 265 (1991) 172**

  ADS: D = quasi-flavour-specific states e.g. Kπ — **PRL 78 (1997) 3257**

  GGSZ: D = self-conjugate multi(3)-body states e.g. $K_s\pi\pi$ — **PRD 68 (2003) 054018**

  GLS: ADS variant with singly Cabbibo-suppressed decay $D\rightarrow K_sK\pi$ — **PRD 67 (2003) 071301**

  time-dependent $B_s\rightarrow D_sK$, $B^0\rightarrow D\pi$ etc **(see talks from Alex Birnkraut)** — **Nucl. phys. B 672 (2003) 459**

  Dalitz (GW) method: $B^0\rightarrow DK\pi$ — **PRD 79 (2009) 051301**

- **Global fit needed to extract γ** **(see talks from Mark Whitehead)**

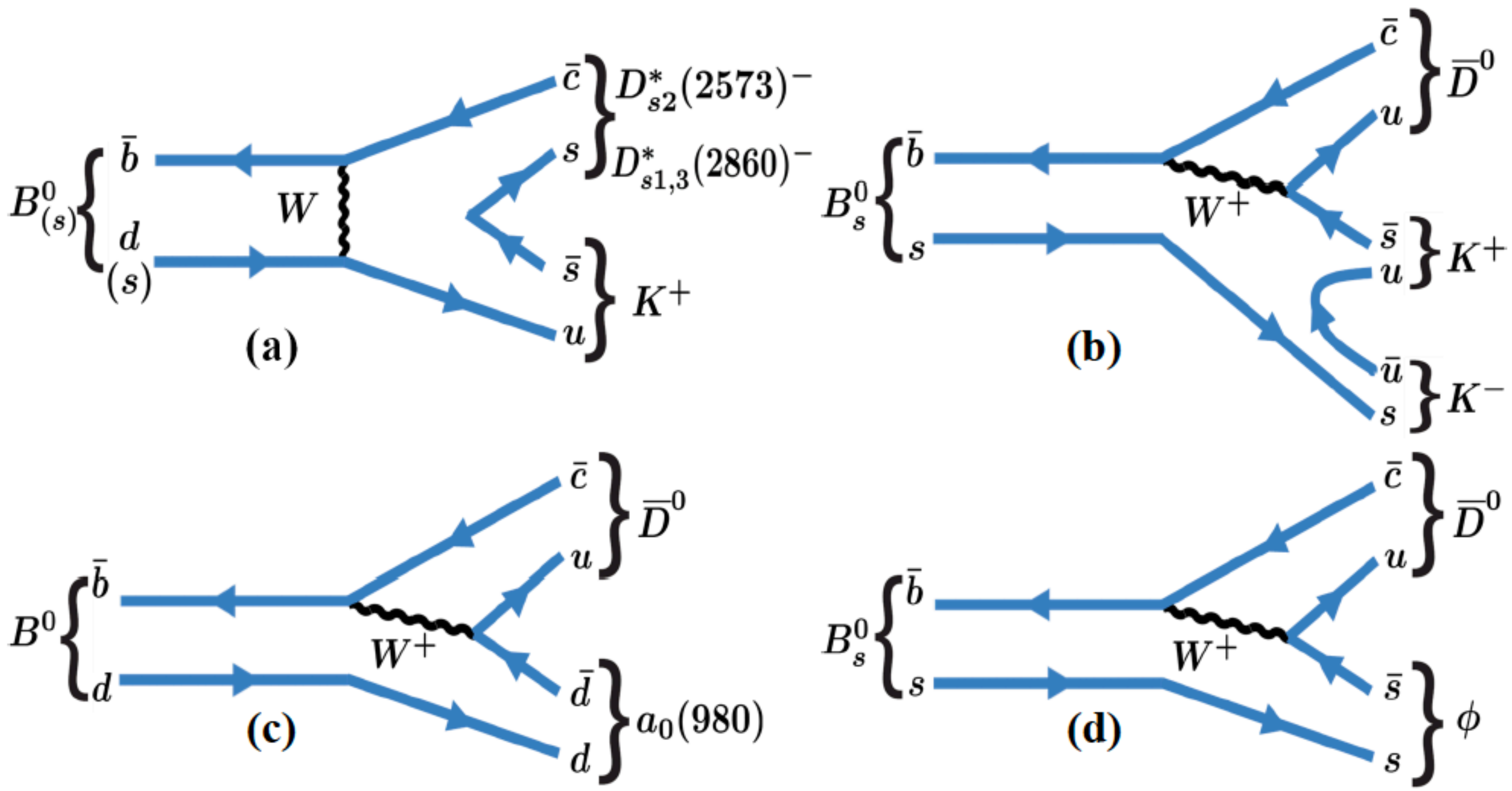
- **Investigation of new methods important**

Physics with $B_{(s)} \to \overline{D}^0 KK$

- ➢ **Time-Dependent Dalitz analyses can be used to access CKM angle γ and $\beta_{(s)}$**

PRD 85 (2012) 114015

- ➢ **Dalitz structures are interesting for charm spectroscopy studies**



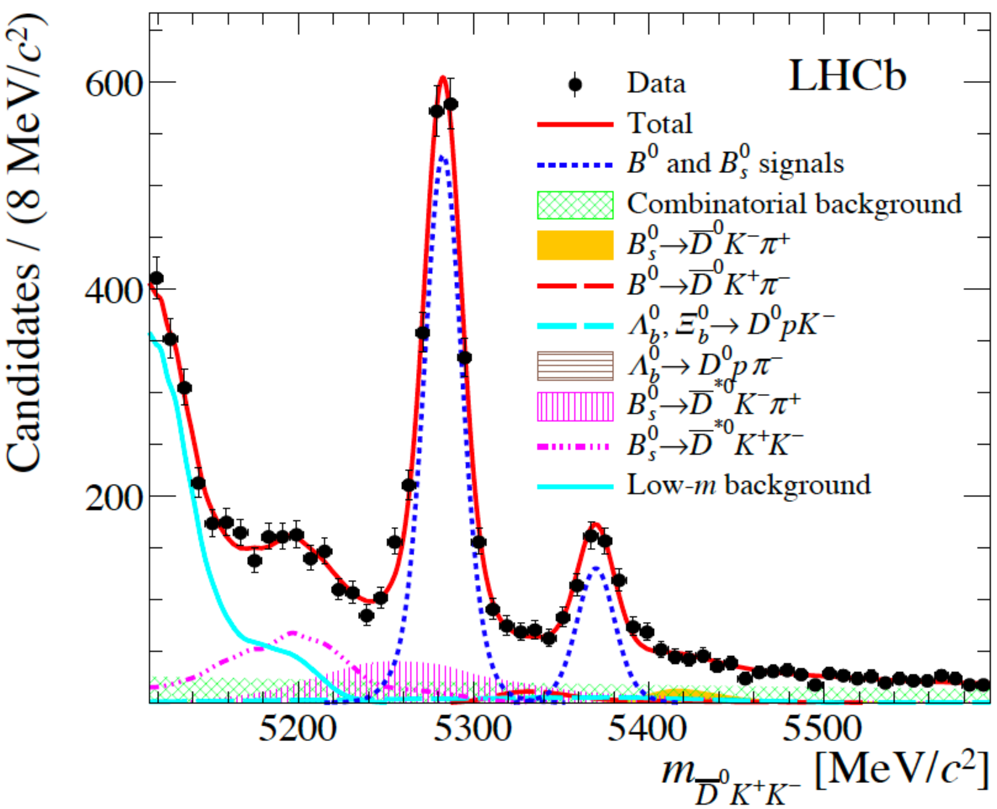
PRL 109 (2012) 131801

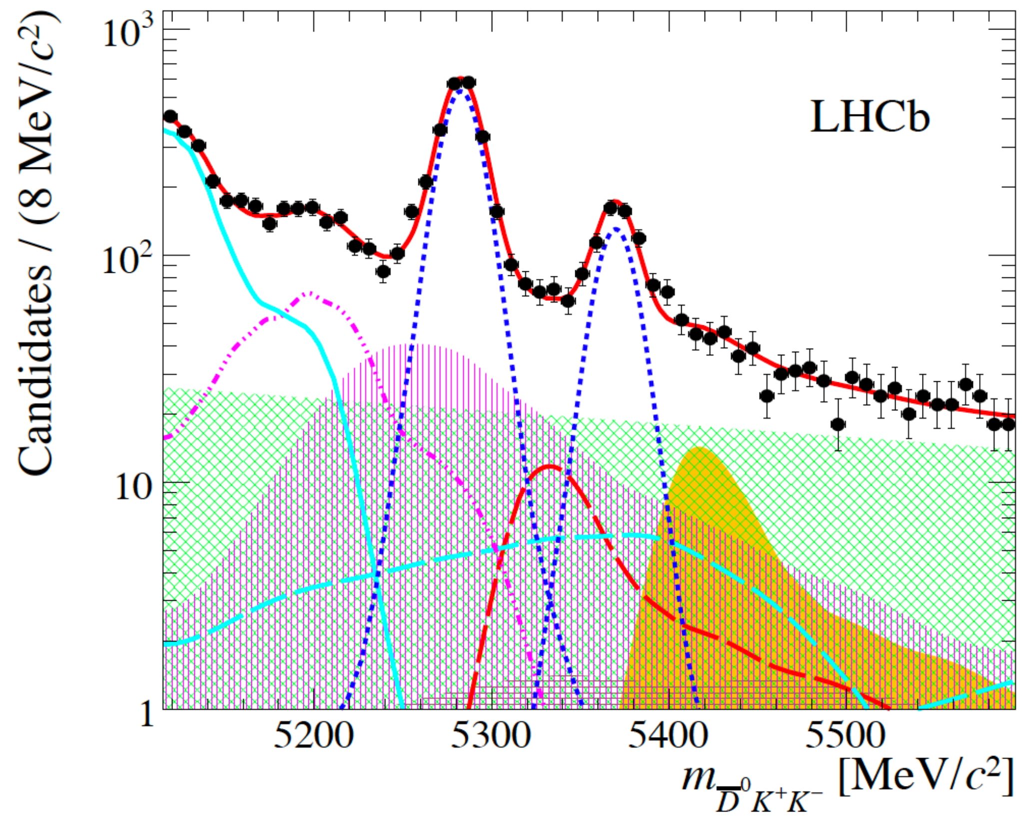
- ➢ **Analysis has been performed with 0.62 fb^{-1} in 2012 by the LHCb collaboration**
➔ observation of B^0 channel and evidence for B_s channel

- ➢ **Updated measurements performed with 3 fb^{-1} Run 1 data**

Observation of $B_{(s)} \to \overline{D}^0 KK$

- ➢ Signals: 2 crystal ball function; Background: exponential
- ➢ Peaking background from simulation with corrections to match data





- ➢ Around 1918±74 $B^0 \to \overline{D}^0 KK$ and 473±33 $B_s \to \overline{D}^0 KK$ observed

$$\frac{\mathcal{B}(B^0 \to \overline{D}^0 K^+ K^-)}{\mathcal{B}(B^0 \to \overline{D}^0 \pi^+ \pi^-)} = (6.9 \pm 0.4 \pm 0.3)\%$$

stat. sys.

$$\frac{\mathcal{B}(B_s^0 \to \overline{D}^0 K^+ K^-)}{\mathcal{B}(B^0 \to \overline{D}^0 K^+ K^-)} = (93.0 \pm 8.9 \pm 6.9)\%,$$

stat. sys.

$$\mathcal{B}(B^0 \to \overline{D}^0 K^+ K^-) = (6.1 \pm 0.4 \pm 0.3 \pm 0.3) \times 10^{-5},$$

stat. sys. normalize

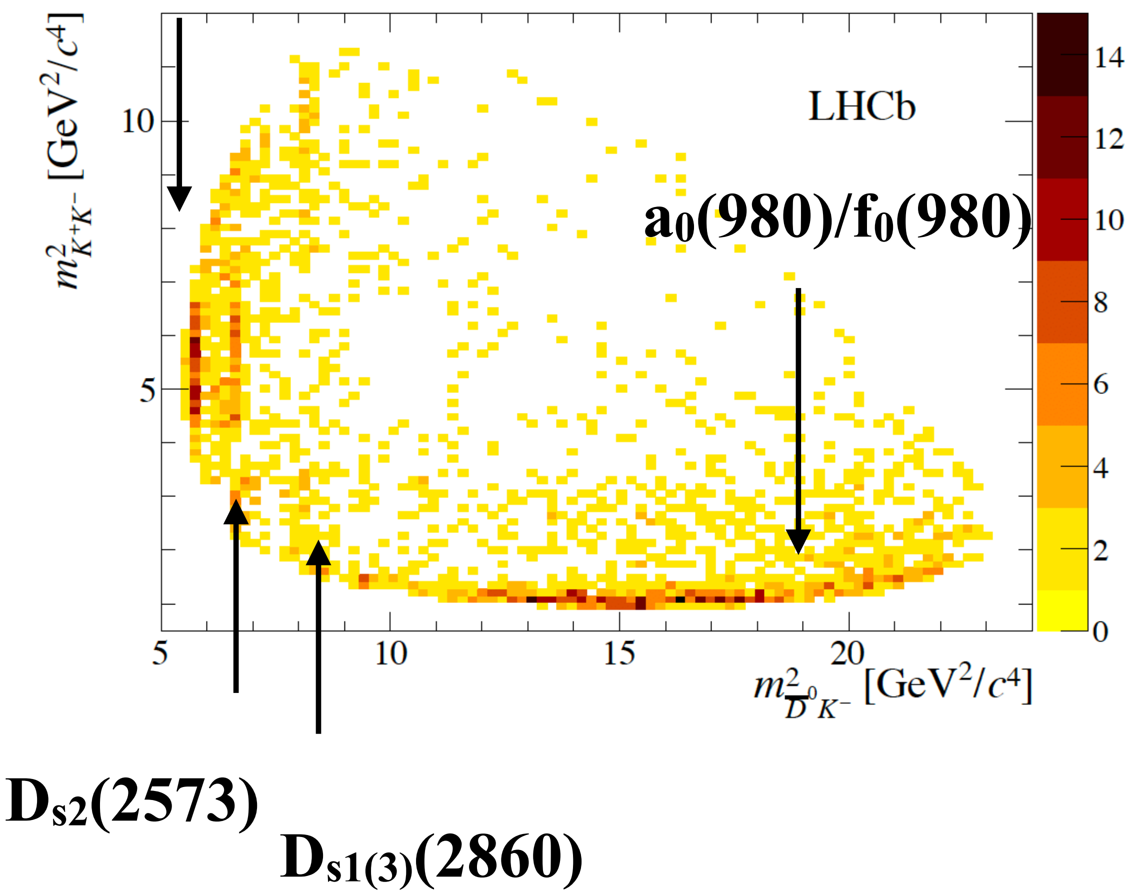
$$\mathcal{B}(B_s^0 \to \overline{D}^0 K^+ K^-) = (5.7 \pm 0.5 \pm 0.4 \pm 0.5) \times 10^{-5},$$

stat. sys. normalize

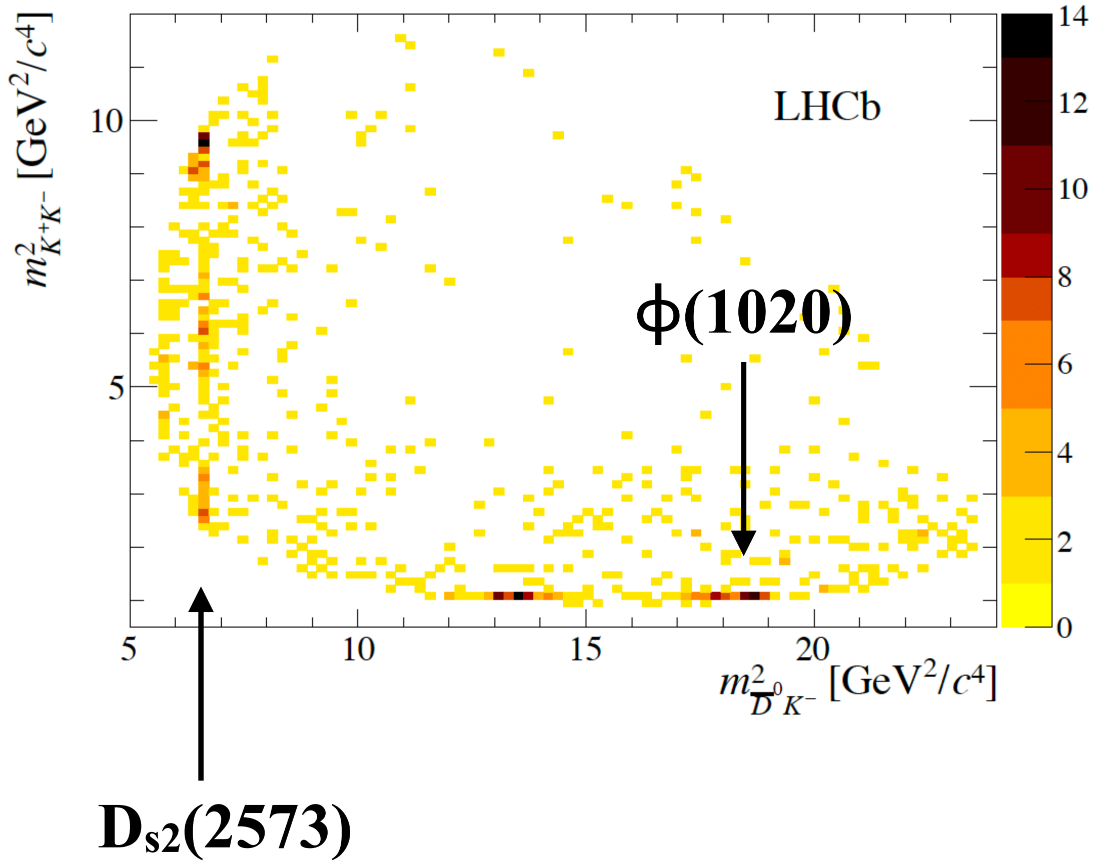
Inspection of Dalitz plot

$B^0 \to \overline{D}^0 KK$: [5240, 5320] MeV

Background: $D_{s1}(2536)$



$B_s \to \overline{D}^0 KK$: [5340, 5400] MeV

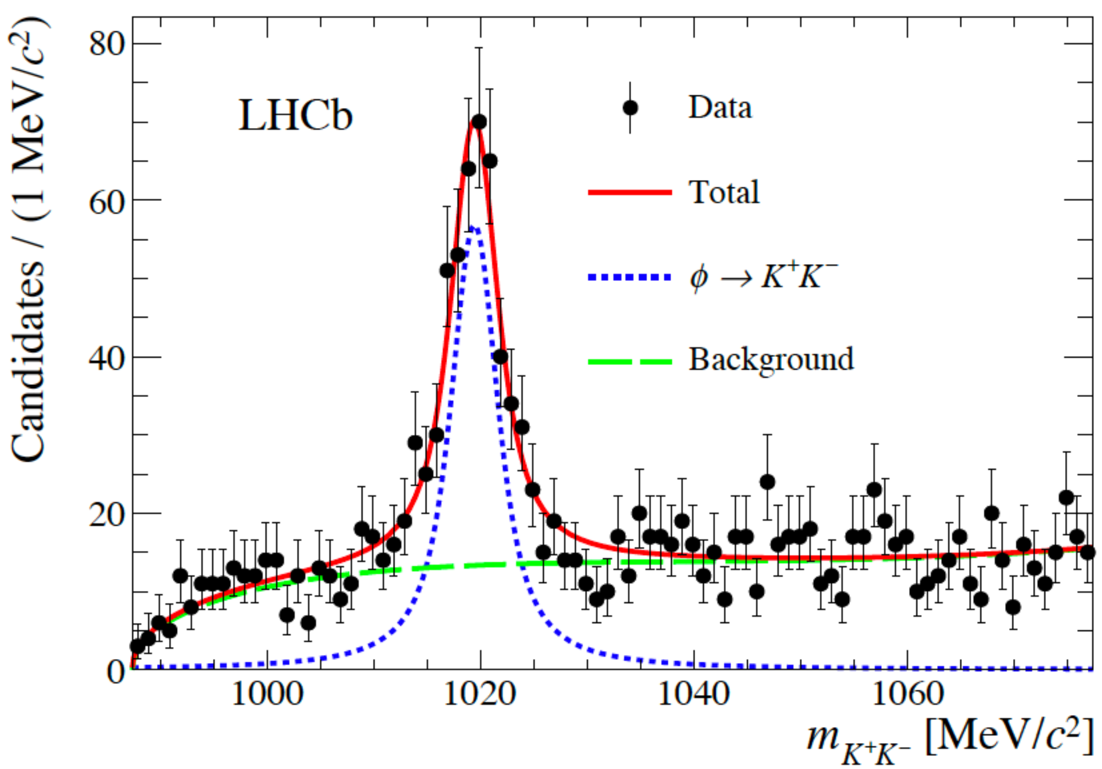


➢ **Resonant structures motivate future Dalitz plot analyses**

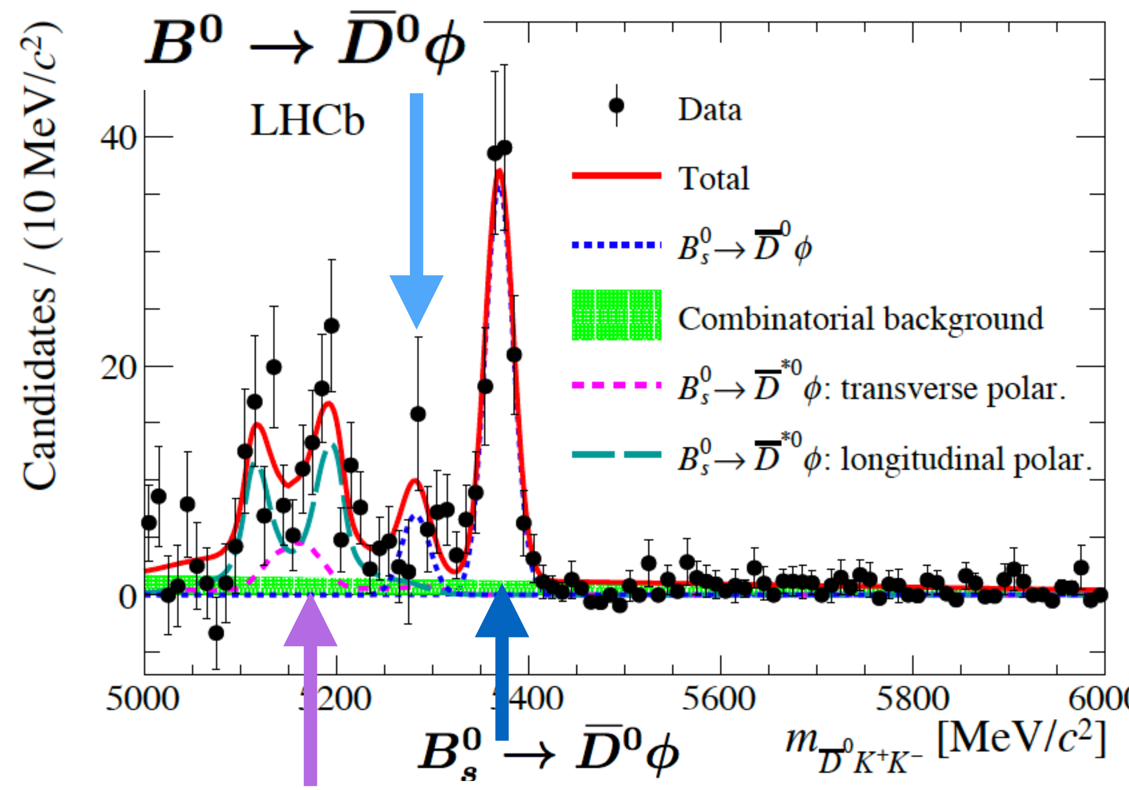
$D^{(*)0}\phi$ studies

➢ ϕ(1020) is a very narrow resonance and permits us to do clean studies on $D^{(*)}\phi$ channels

Little correlations between m_{KK} and m_{DKK} for each components



ϕ peak: RBW ⊗ Gaussian;



$B_s^0 \to \overline{D}^{*0}\phi$ (Partially reconstructed, Two components for different polarizations)

➢ Mass shapes of B^0 and B_s decaying to $\overline{D^0}\phi$ modeled with Gaussian

➢ $D^*\phi$ shape determined from MC: $D^* \to D^0\gamma/\pi^0$ branching fraction fixed from PDG; polarization as free parameter; efficiency determined from MC

Results on $B_s \to \overline{D}^{(*)0}\phi$

$$\frac{\mathcal{B}(B^0_{(s)} \to \overline{D}^{(*)0}\phi)}{\mathcal{B}(B^0 \to \overline{D}^0\pi^+\pi^-)} = \frac{N_{B^0_{(s)}\to\overline{D}^{(*)0}\phi} \times \varepsilon(B^0 \to \overline{D}^0\pi^+\pi^-)}{N_{B^0\to\overline{D}^0\pi^+\pi^-} \times \varepsilon(B^0_{(s)} \to \overline{D}^{(*)0}\phi)} \times \frac{f_d/f_s}{\mathcal{B}(\phi \to K^+K^-)},$$

$$\frac{\mathcal{B}(B^0_s \to \overline{D}^0\phi)}{\mathcal{B}(B^0 \to \overline{D}^0\pi^+\pi^-)} = (3.4 \pm 0.4 \pm 0.2)\%$$

stat. sys.

$$\frac{\mathcal{B}(B^0_s \to \overline{D}^{*0}\phi)}{\mathcal{B}(B^0 \to \overline{D}^0\pi^+\pi^-)} = (4.2 \pm 0.5 \pm 0.4)\%$$

stat. sys.

$$\mathcal{B}(B^0_s \to \overline{D}^0\phi) = (3.0 \pm 0.3 \pm 0.2 \pm 0.2) \times 10^{-5}$$

stat. sys. normalize

$$\mathcal{B}(B^0_s \to \overline{D}^{*0}\phi) = (3.7 \pm 0.5 \pm 0.3 \pm 0.2) \times 10^{-5}$$

stat. sys. normalize

- **Both channels can be used to constrain angle γ** (LHCb-PUB-2010-005)

PLB 727 (2013), 403

- **Previous branching fraction measurement of $B_s \to \overline{D}^0\phi$ with 1 fb^{-1} data, normalized to $B_s \to \overline{D}^0 K^*$**

$$\mathcal{B}(B^0_s \to \overline{D}^0\phi) = (2.3 \pm 0.4 \pm 0.2 \pm 0.2 \pm 0.3) \times 10^{-5}$$

stat. sys. fs/fd normalize

Updated to $(3.0 \pm 0.8) \times 10^{-5}$ in PDG

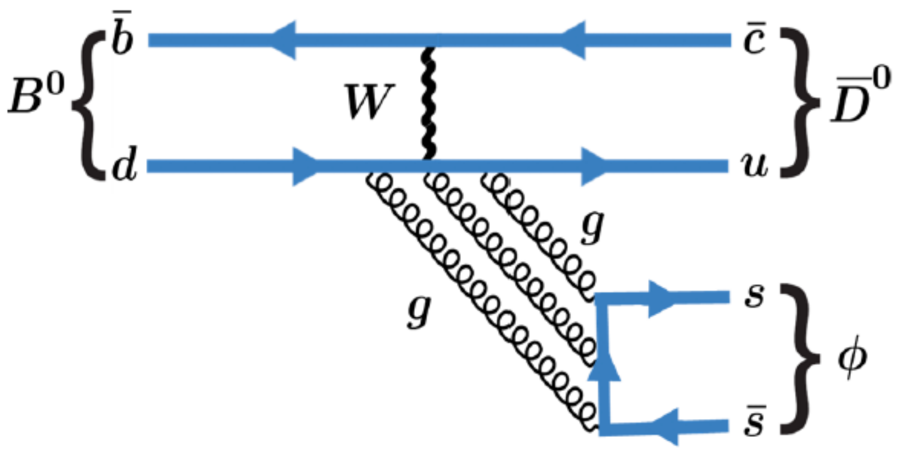
- **First observation of $B_s \to \overline{D}^*\phi$ decay with more than 7σ significance**

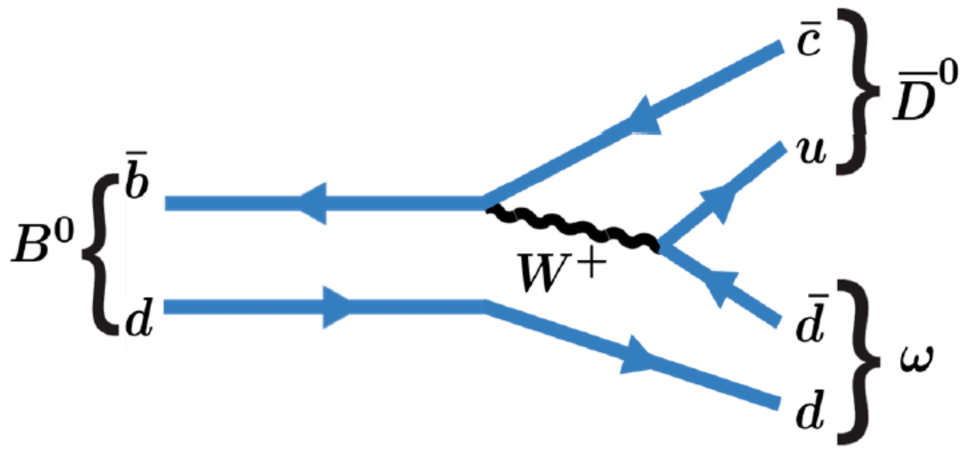
- **The longitudinal fraction of $B_s \to \overline{D}^*\phi$ also measured,** $f_L = (73 \pm 15 \pm 3)\ \%$ **consistent with what measured in $B^0 \to \overline{D}^*\omega$ by BaBar**

PRD 84 (2011) 112007 Erratum PRD 87 (2013) 039901

Search for $B^0 \to \overline{D}^0 \phi$

- Exchange diagram + OZI suppression or through ω-ϕ mixing





- No significant $B^0 \to \overline{D}^0 \phi$ found (~ 2σ significance)

$$\frac{\mathcal{B}(B^0 \to \overline{D}^0 \phi)}{\mathcal{B}(B^0 \to \overline{D}^0 \pi^+ \pi^-)} = (1.2 \pm \underbrace{0.7}_{\text{stat.}} \pm \underbrace{0.3}_{\text{sys.}}) \times 10^{-3}$$

$$\mathcal{B}(B^0 \to \overline{D}^0 \phi) = (1.1 \pm \underbrace{0.6}_{\text{stat.}} \pm \underbrace{0.3}_{\text{sys.}} \pm \underbrace{0.1}_{\text{normalize}}) \times 10^{-6}.$$

- Upper limits set on both branching fractions and mixing angle assuming contributions from ω-ϕ mixing dominated here

$$\mathcal{B}(B^0 \to \overline{D}^0 \phi) < 2.0\ (2.2) \times 10^{-6}$$

90 (95)%

Mixing angle: $|\delta| < 5.2^\circ\ (5.5^\circ)$

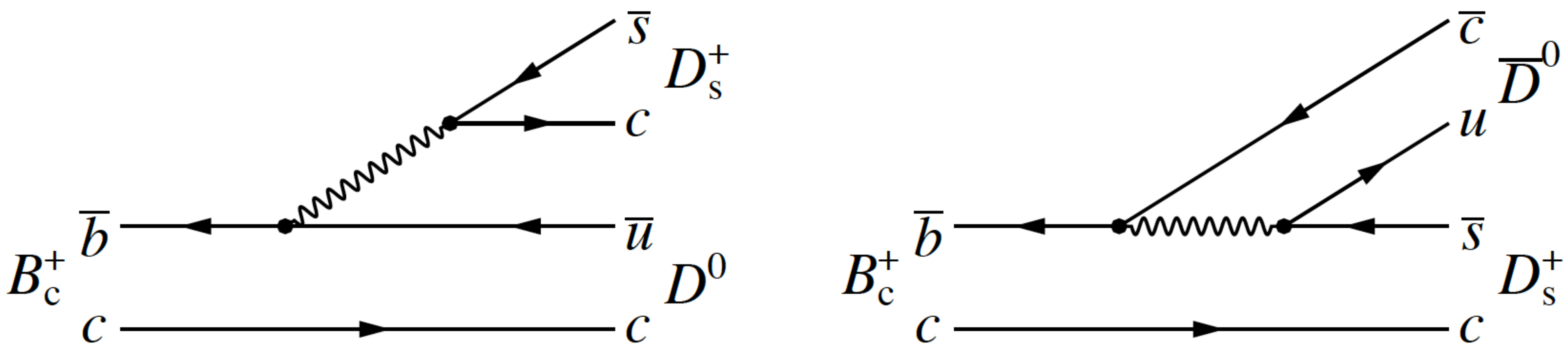
90 (95)%

γ measurement in B_c decays

- **Massive B_c^+ produced in LHCb: ~ 30K $B_c^+ \to J/\psi\pi^+$ with Run 1 + Run 2**
- **Branching fraction of $B_c^+ \to J/\psi\pi^+$: $(0.6\text{–}2.9)\times10^{-3}$**

PRD 49 (1994) 3399
PRD 68 (2003) 094020
PRD 89 (2014) 034008

- **Able to access B_c decays with Branching fraction of $10^{-5}\text{–}10^{-6}$**
- **$B_c^+ \to D_{(s)}^+ D^0$ decays sensitive to γ with r_{Ds} ~ 1 and r_D ~ 0.1**



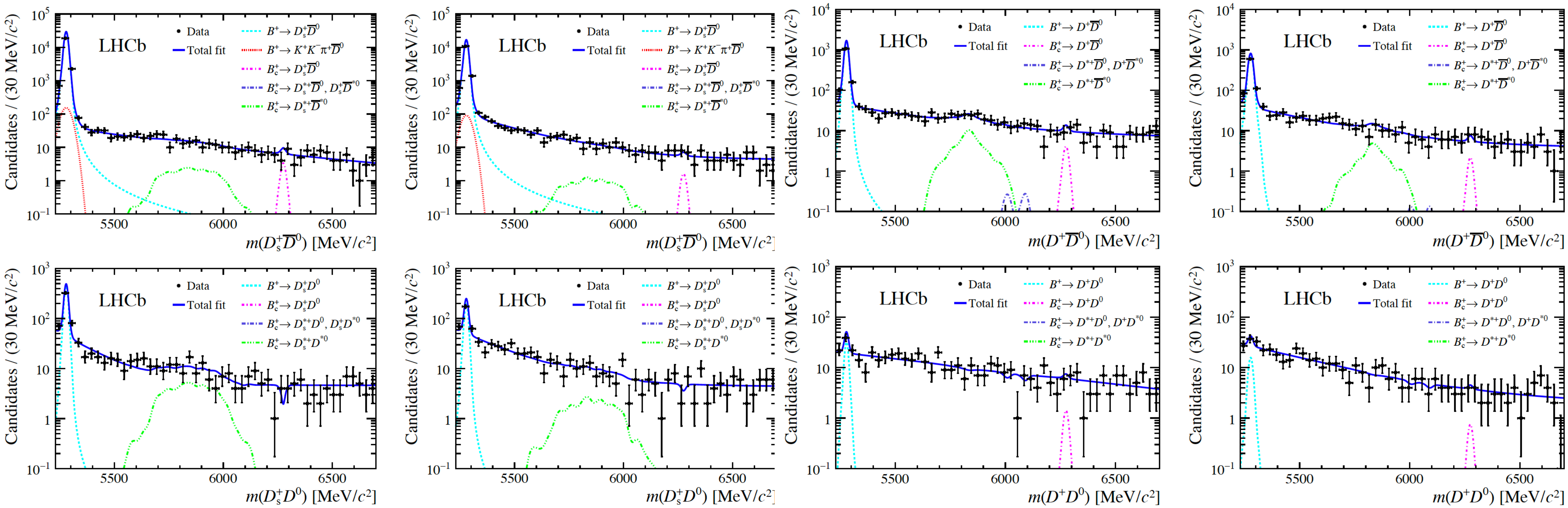
- **The branching fraction is predicted to be**

Channel	Prediction for the branching fraction $[10^{-6}]$ [1]	[2]	[3]	[4]
$B_c^+ \to D_s^+ \overline{D}^0$	2.3 ± 0.5	4.8	1.7	2.1
$B_c^+ \to D_s^+ D^0$	3.0 ± 0.5	6.6	2.5	7.4
$B_c^+ \to D^+ \overline{D}^0$	32 ± 7	53	32	33
$B_c^+ \to D^+ D^0$	0.10 ± 0.02	0.32	0.11	0.32

[1]: PRD 86 (2012) 074019
[2]: arXiv:hep-ph/0211021
[3]: PLB 555 (2013) 189
[4]: PRD73 (2006) 054024

Currently search with Run 1 data: 3 fb^{-1}

Results on $B_c^+ \to D_{(s)}^{(*)+} D^{(*)0}$ search



D_s-D^0, $D^0 \to K\pi$ | **D_s-D^0, $D^0 \to K3\pi$** | **D-D^0, $D^0 \to K\pi$** | **D-D^0, $D^0 \to K3\pi$**

➢ **Nothing observed and upper limits set on these decays**

➢ **Decays with $D_{(s)}^*$ and D^* are searched without reconstructing γ/π^0**

Results on upper limits

Key formula:

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D_{(s)}^+ D)}{\mathcal{B}(B^+\to D_{(s)}^+\overline{D}^0)} = \frac{N(B_c^+\to D_{(s)}^+ D)}{N(B^+\to D_{(s)}^+\overline{D}^0)}\frac{\varepsilon(B^+\to D_{(s)}^+\overline{D}^0)}{\varepsilon(B_c^+\to D_{(s)}^+ D)},$$

$D_{(s)}$-D^0

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D_s^+\overline{D}^0)}{\mathcal{B}(B^+\to D_s^+\overline{D}^0)} = (\ \ 3.0\pm 3.7)\times 10^{-4}\ [< 0.9\,(1.1)\times 10^{-3}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D_s^+ D^0)}{\mathcal{B}(B^+\to D_s^+\overline{D}^0)} = (-3.8\pm 2.6)\times 10^{-4}\ [< 3.7\,(4.7)\times 10^{-4}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D^+\overline{D}^0)}{\mathcal{B}(B^+\to D^+\overline{D}^0)} = (\ \ 8.0\pm 7.5)\times 10^{-3}\ [< 1.9\,(2.2)\times 10^{-2}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D^+ D^0)}{\mathcal{B}(B^+\to D^+\overline{D}^0)} = (\ \ 2.9\pm 5.3)\times 10^{-3}\ [< 1.2\,(1.4)\times 10^{-2}].$$

$D_{(s)}^*$-D^*

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D_s^{*+}\overline{D}^{*0})}{\mathcal{B}(B^+\to D_s^+\overline{D}^0)} = (\ \ 3.2\pm 4.3)\times 10^{-3}\ [< 1.1\,(1.3)\times 10^{-2}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D_s^{*+} D^{*0})}{\mathcal{B}(B^+\to D_s^+\overline{D}^0)} = (\ \ 7.0\pm 9.2)\times 10^{-3}\ [< 2.0\,(2.4)\times 10^{-2}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D^{*+}\overline{D}^{*0})}{\mathcal{B}(B^+\to D^+\overline{D}^0)} = (\ \ 3.4\pm 2.3)\times 10^{-1}\ [< 6.5\,(7.3)\times 10^{-1}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D^{*+} D^{*0})}{\mathcal{B}(B^+\to D^+\overline{D}^0)} = (-4.1\pm 9.1)\times 10^{-2}\ [< 1.3\,(1.6)\times 10^{-1}].$$

$D_{(s)}^*$-D^0 + $D_{(s)}$-D^*

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D_s^{*+}\overline{D}^0)+\mathcal{B}(B_c^+\to D_s^+\overline{D}^{*0})}{\mathcal{B}(B^+\to D_s^+\overline{D}^0)} = (-0.1\pm 1.5)\times 10^{-3}\ [< 2.8\,(3.4)\times 10^{-3}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to D_s^{*+} D^0)+\mathcal{B}(B_c^+\to D_s^+ D^{*0})}{\mathcal{B}(B^+\to D_s^+\overline{D}^0)} = (-0.3\pm 1.9)\times 10^{-3}\ [< 3.0\,(3.6)\times 10^{-3}],$$

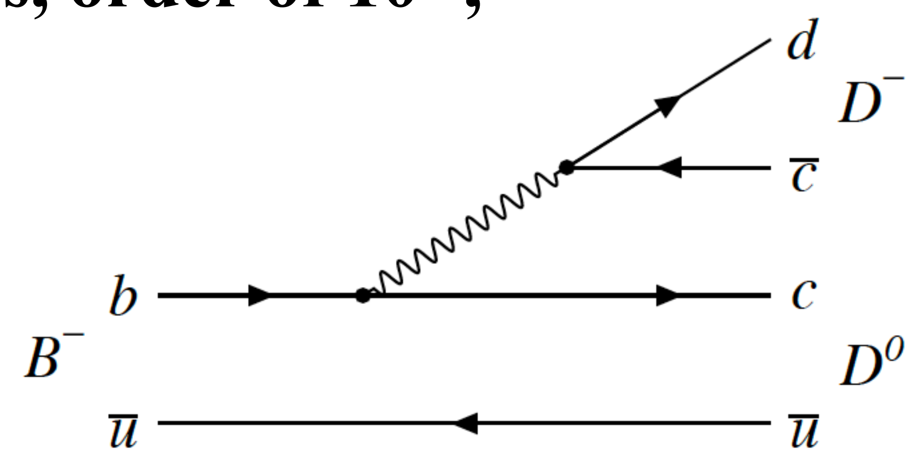
$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to (D^{*+}\to D^+\pi^0,\gamma)\overline{D}^0)+\mathcal{B}(B_c^+\to D^+\overline{D}^{*0})}{\mathcal{B}(B^+\to D^+\overline{D}^0)} = (\ \ 0.2\pm 3.2)\times 10^{-2}\ [< 5.5\,(6.6)\times 10^{-2}],$$

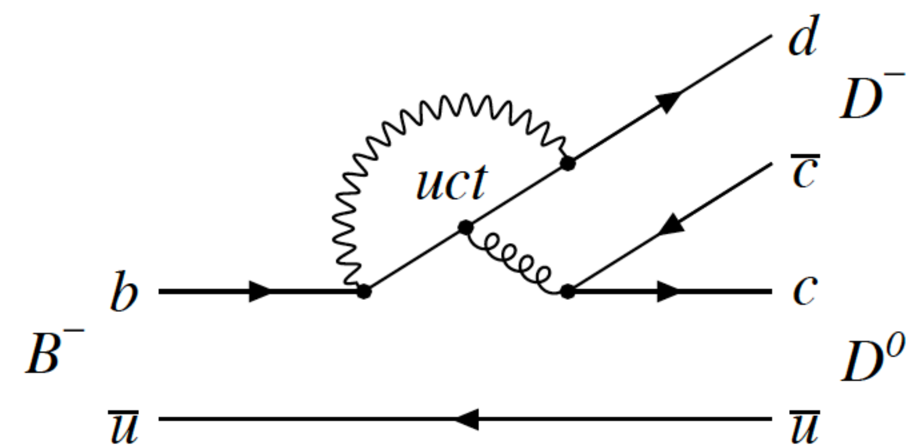
$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+\to (D^{*+}\to D^+\pi^0,\gamma)D^0)+\mathcal{B}(B_c^+\to D^+ D^{*0})}{\mathcal{B}(B^+\to D^+\overline{D}^0)} = (-1.5\pm 1.7)\times 10^{-2}\ [< 2.2\,(2.8)\times 10^{-2}].$$

- **Absolute Branching fraction upper limits at level of 10^{-4}–10^{-3}, consistent with expectations in previous slides**

A^{CP} measurements for $B^- \to D_{(s)}^- D^0$

- Nonzero CPV expected due to interference between tree-level and loop-level diagrams, order of 10^{-2};





- A^{CP} of $B^- \to D^- D^0$ measured by BaBar and Belle collaborations

Belle: PRD 77 (2008) 091101

$$\mathcal{A}^{CP} = (0 \pm 8 \pm 2)\%$$

BaBar: PRD 73 (2016) 112004

$$\mathcal{A}^{CP} = (-13 \pm 14 \pm 2)\%$$

- A^{CP} in LHCb determined using the following formalism:

$$\mathcal{A}^{CP}(B^- \to D_{(s)}^- D^0) \equiv \frac{\Gamma(B^- \to D_{(s)}^- D^0) - \Gamma(B^+ \to D_{(s)}^+ \overline{D}^0)}{\Gamma(B^- \to D_{(s)}^- D^0) + \Gamma(B^+ \to D_{(s)}^+ \overline{D}^0)} = A_{\rm raw} - A_P - A_D,$$

$$A_P \equiv \frac{\sigma(B^-) - \sigma(B^+)}{\sigma(B^-) + \sigma(B^+)}, \qquad A_D \equiv \frac{\varepsilon(B^- \to D_{(s)}^- D^0) - \varepsilon(B^+ \to D_{(s)}^+ \overline{D}^0)}{\varepsilon(B^- \to D_{(s)}^- D^0) + \varepsilon(B^+ \to D_{(s)}^+ \overline{D}^0)}.$$

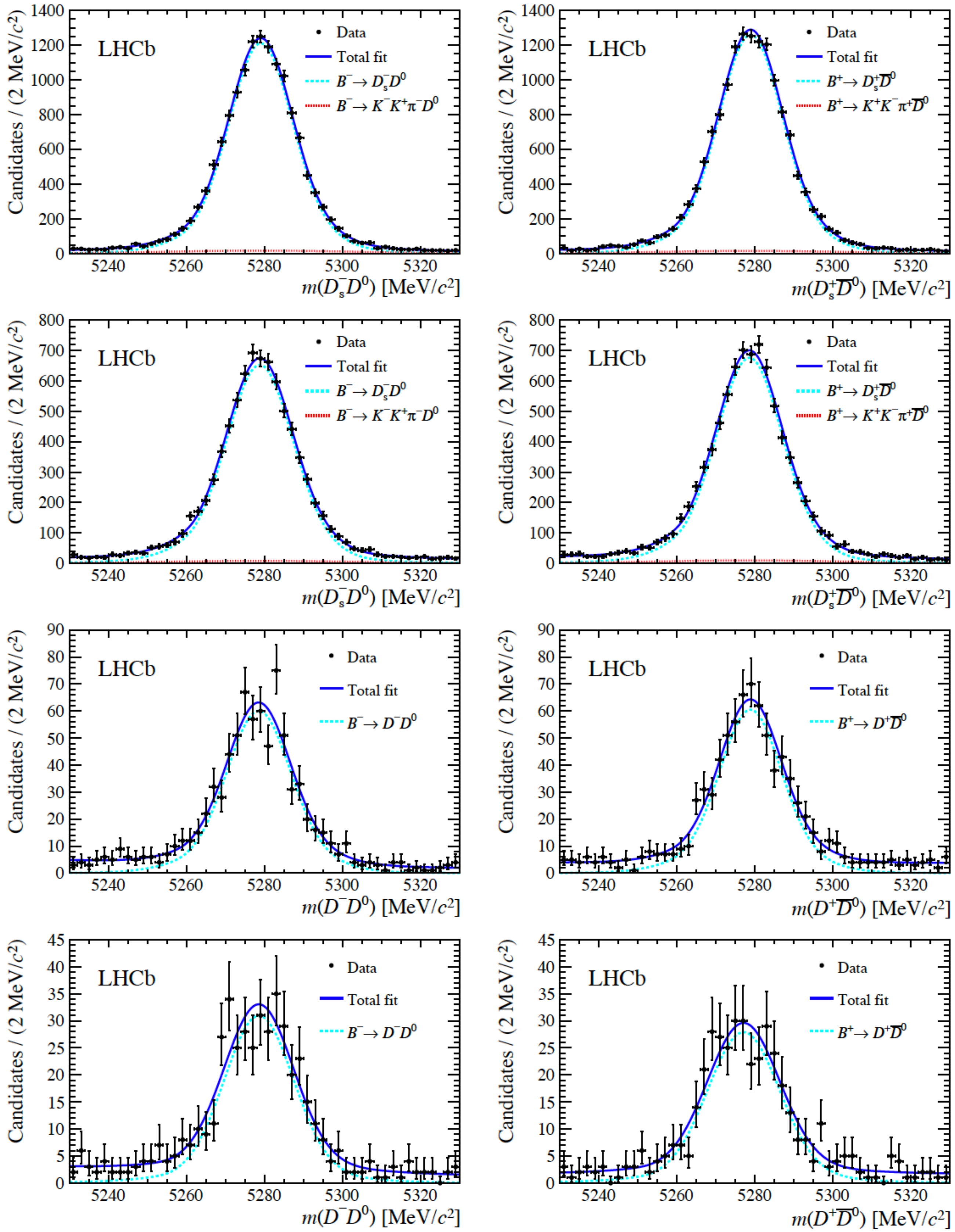
$A_P + A_D$:

$(-1.4 \pm 0.5)\%$ D_s-D^0

$(-0.3 \pm 0.4)\%$ D-D^0

Production asymmetry measured by LHCb : PRD 95 (2017) 052005

Results on A_{CP} measurements



B- B+

$D_s^- D^0$, $D^0 \to K\pi$

Consistent with no CPV

$D_s^- D^0$, $D^0 \to K3\pi$

First measurements

$$\mathcal{A}^{CP}(B^- \to D_s^- D^0) = (-0.4 \pm 0.5 \pm 0.5)\%,$$

$$\mathcal{A}^{CP}(B^- \to D^- D^0) = (\ \ 2.3 \pm 2.7 \pm 0.4)\%,$$

$D^- D^0$, $D^0 \to K\pi$

Uncertainties reduced by a factor of two

$D^- D^0$, $D^0 \to K3\pi$

Conclusion

➢ **LHCb experiments are continuously exploring its potential in γ measurements**

➢ **New channels are searched/discovered and stay tuned for updates on γ measurements with these decays**

Thank You for Your Attention