

# Time-integrated measurements of the Unitary Triangle angle $\gamma$

EPS-HEP Conference 2019

Alexandra Rollings on behalf of the LHCb Collaboration

University of Oxford

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1. Introduction to time independent  $\gamma$  measurements
2. How  $\gamma$  is measured using tree-level decays
3. The 2018 LHCb combination
4. Update of the  $B^0 \rightarrow DK^{*0}$  ADS/GLW analysis - **NEW!**

# The Unitary Triangle angle $\gamma$

- The CKM matrix can be parameterised to have a single irreducible complex phase, which is the only known source of  $CP$  violation within the quark sector:

$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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- The unitary triangle angle  $\gamma = \arg \left( -\frac{v_{ud}v_{ub}^*}{v_{cd}v_{cb}^*} \right)$ 
  - No top coupling
  - No need for box/loop processes
  - Time independent measurements at **tree level!**
  - Particularly clean (assuming no enters NP at tree-level)

# The Unitary Triangle angle $\gamma$

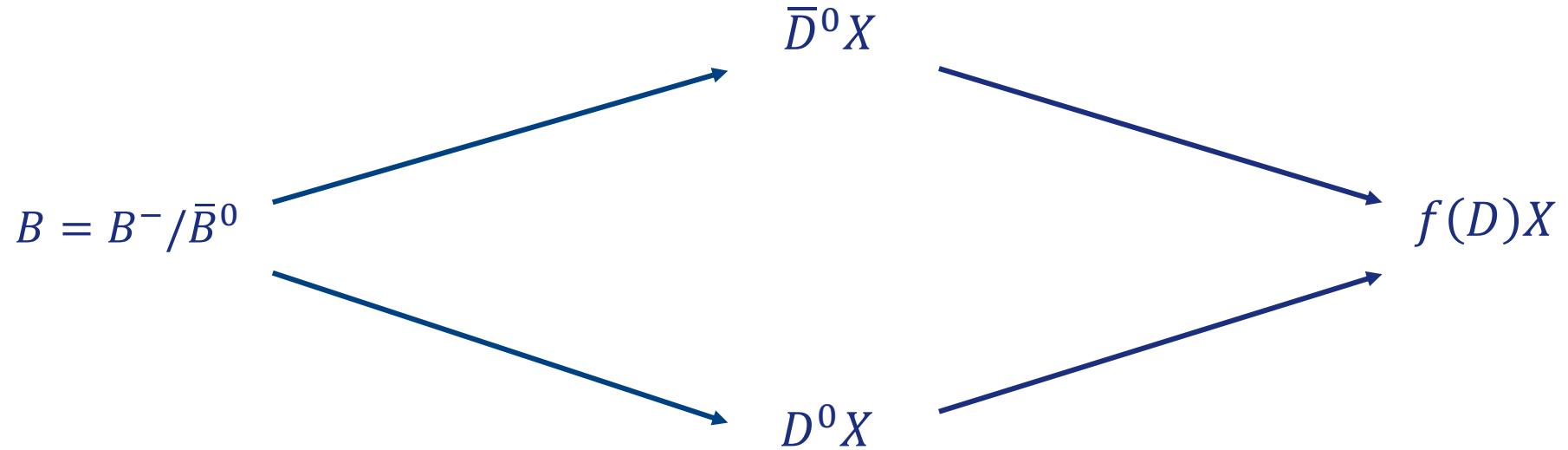
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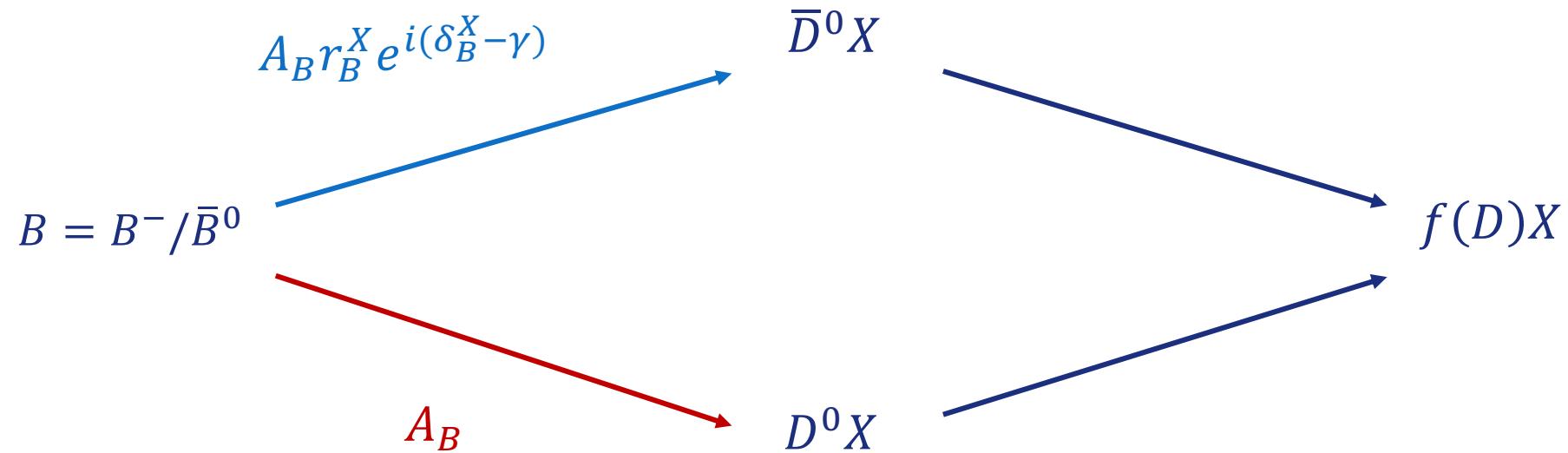
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  - No top coupling
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  - Time independent measurements at **tree level!**
  - Particularly clean (assuming no enters NP at tree-level)
  - $B \rightarrow DX_s: \frac{\Delta\gamma}{\gamma} \sim 10^{-7}$  [JHEP01(2014)051]

To  $\mathcal{O}(\lambda^3)$ , phase only exists in  $V_{ub}$ :  
access  $\gamma$  using  $b \rightarrow u$  interfering with  
 $b \rightarrow c$  transition

# Accessing $\gamma$ with $B \rightarrow DX$ decays

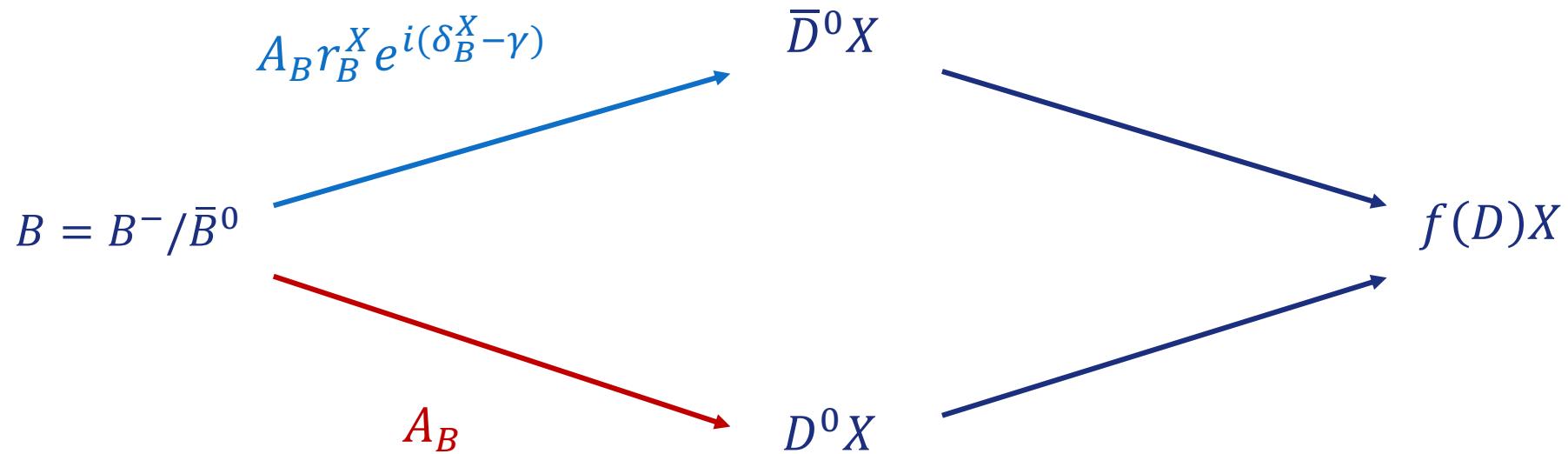


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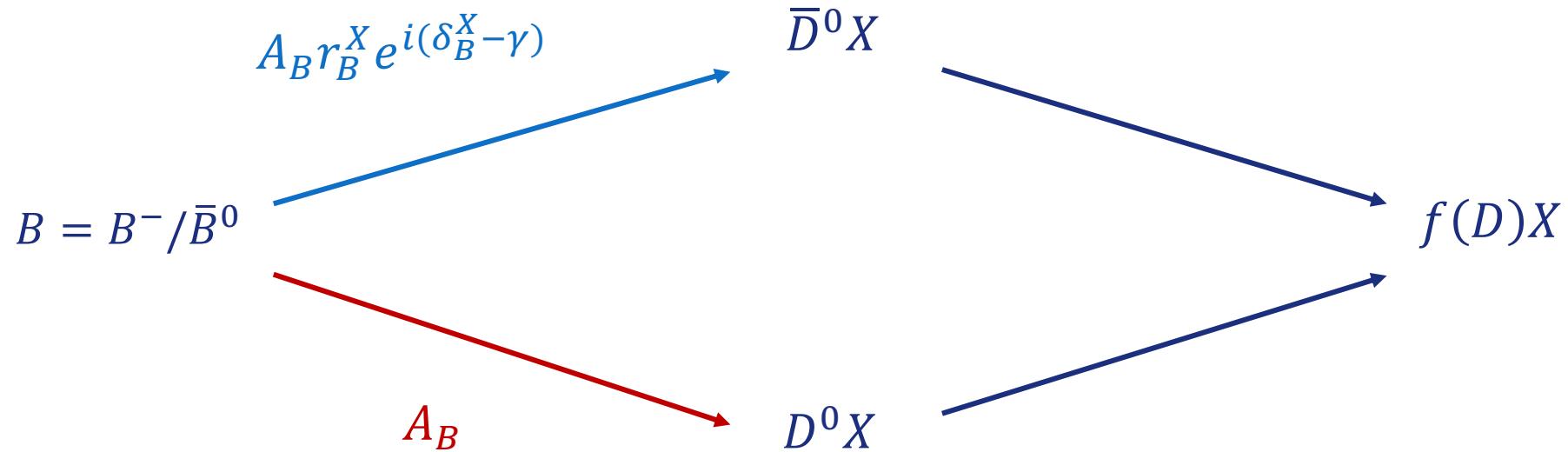
- $b \rightarrow u$  transition in  $B \rightarrow \bar{D}^0 X$  suppressed w.r.t.  $b \rightarrow c$  transition in  $B \rightarrow D^0 X$ 
  - 2 possible paths with amplitude ratio  $r_B^X$ ,  $CP$  conserving phase  $\delta_B^X$  and  $CP$  violating phase  $\gamma$

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- $\gamma$   $CP$  violates  $\rightarrow$  changes sign under charge conjugation
  - Look for differences in decay rates ( $\Gamma \propto |\sum_i A_i|^2$ ) of  $B^- (B^0)$  and  $B^+ (\bar{B}^0)$  mesons

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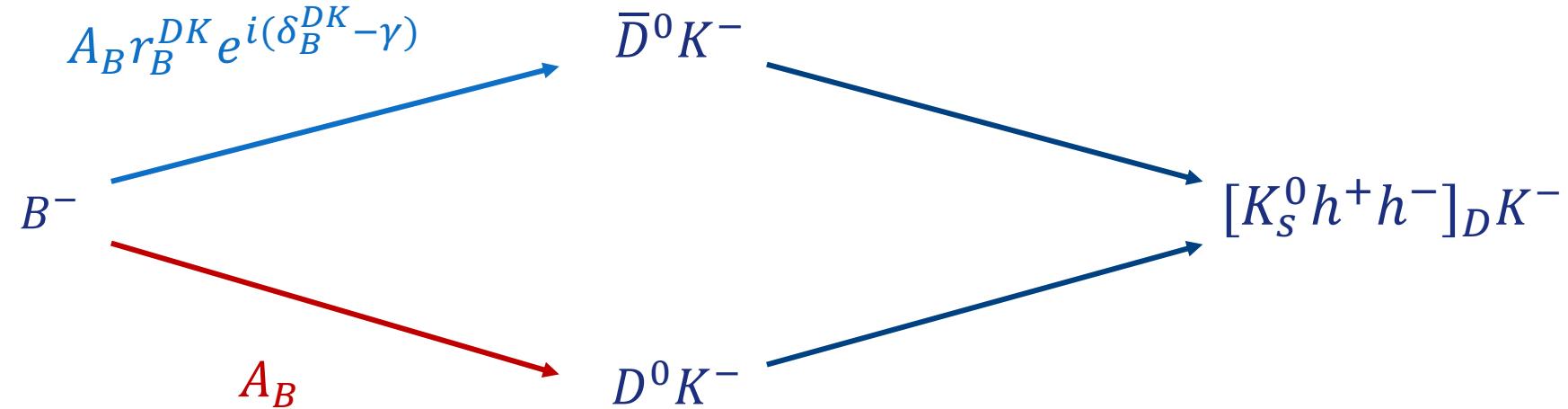


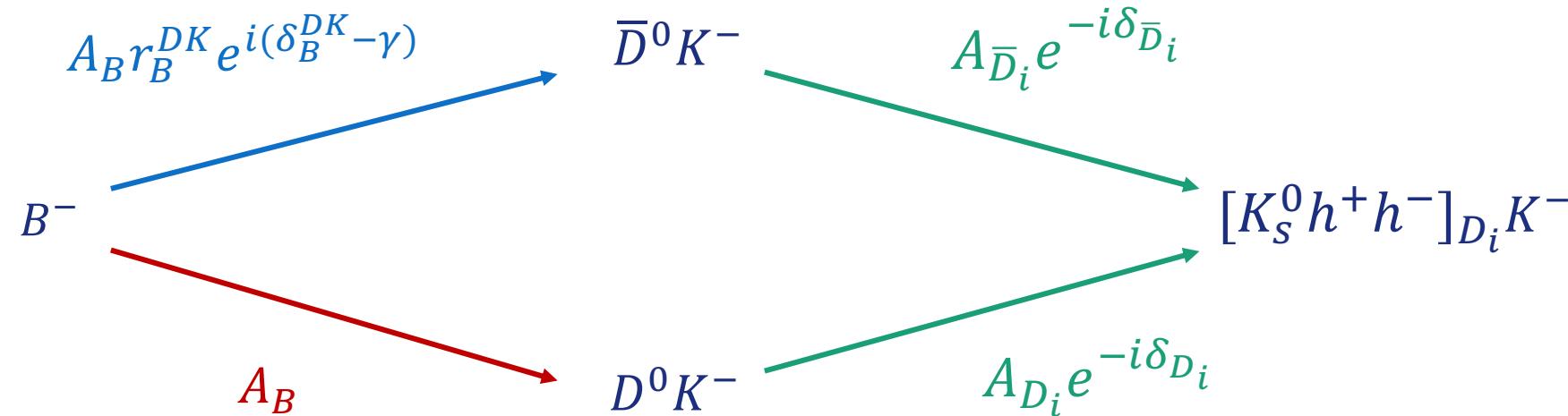
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  - Look for differences in decay rates ( $\Gamma \propto |\sum_i A_i|^2$ ) of  $B^- (B^0)$  and  $B^+ (\bar{B}^0)$  mesons
- Different decay modes have different  $r_B^X, \delta_B^X$ , but **the same  $\gamma$ !**

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

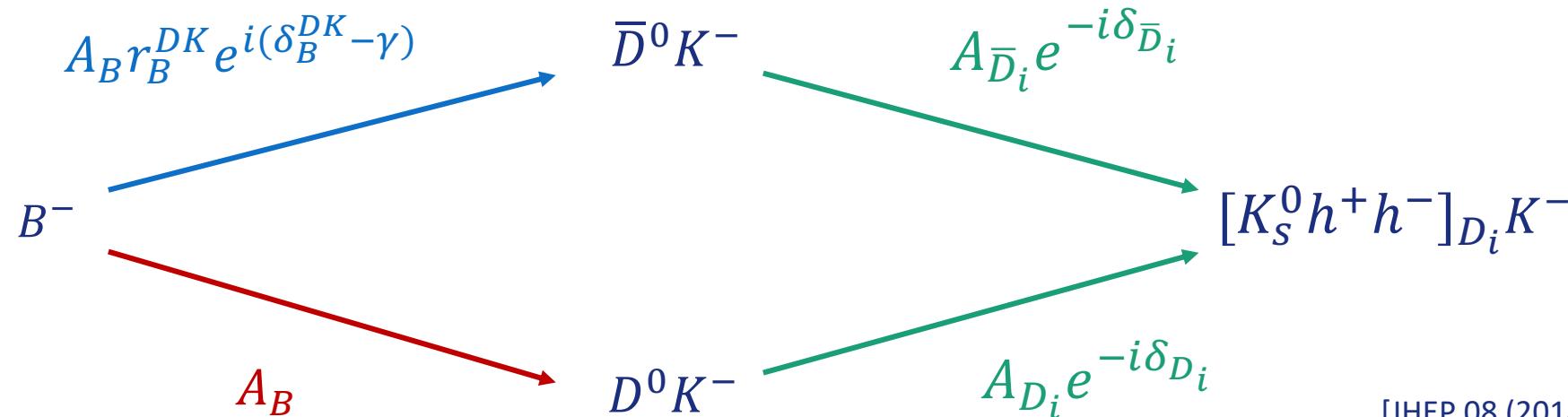
- There are several classes of analysis, depending on the final state the  $D$  meson is reconstructed in:
  1. **GLW:**  $D \rightarrow KK, \pi\pi, \pi\pi\pi\pi, KK\pi^0, \pi\pi\pi^0$  [Phys. Lett. B253 (1991) 483]  $\rightarrow CP$  or  $CP$ -like eigenstates
  2. **ADS:**  $D \rightarrow \pi K, \pi K \pi\pi, \pi K \pi^0$  [Phys. Lett. D63 (2001) 036005]  $\rightarrow CF$  or DCS final state
  3. **GGSZ:**  $D \rightarrow K_S^0 \pi\pi, K_S^0 KK$  [Phys. Lett. D68 (2003) 054018]  $\rightarrow$  3-body final state
  4. **GLS:**  $D \rightarrow K_S^0 K\pi$  [Phys. Lett. D67 (2003) 071301]  $\rightarrow SCS$  final state

# $B^- \rightarrow [K_s^0 h^+ h^-]_D K^-$ ( $h = \pi/K$ ): the GGSZ Method



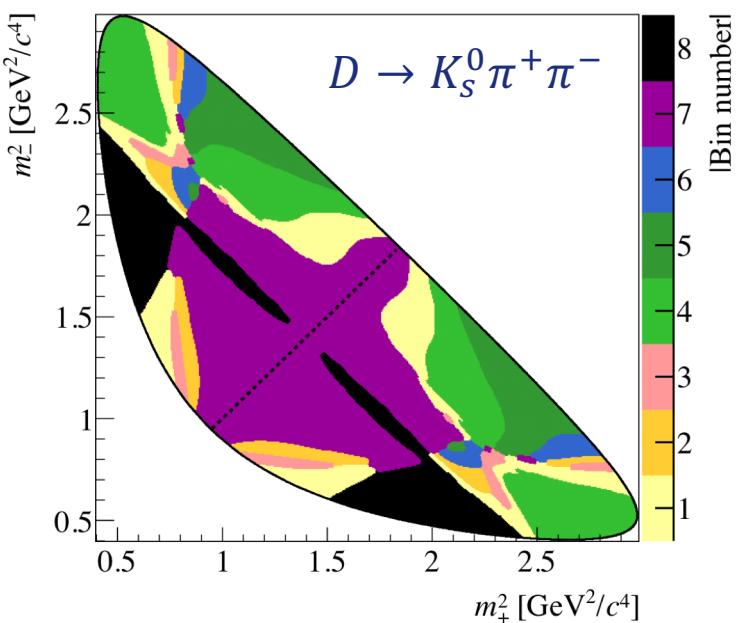


- $D = D^0/\bar{D}^0$  decaying to the same final state have different amplitudes and strong phases
- 3-body  $D$  decay  $\rightarrow$  measure  $B^+$  and  $B^-$  yields in **Dalitz bins**, with axes  $m_\pm^2 = m^2(K_s^0, h^\pm)$
- Strong phase difference,  $\Delta\delta_{D_i} = \delta_{\bar{D}_i} - \delta_{D_i}$  varies across the Dalitz plane



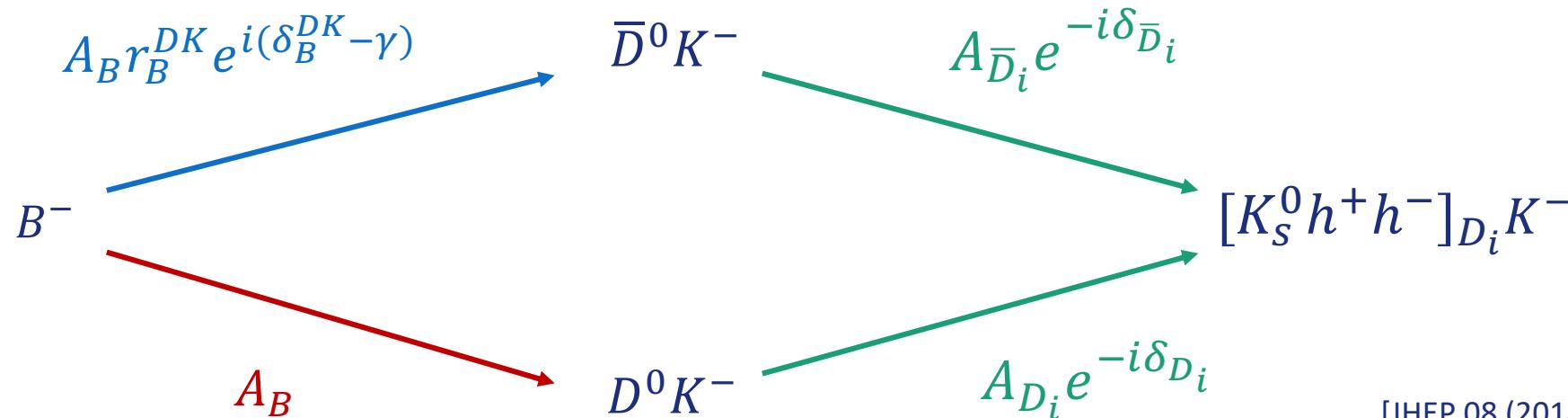
[JHEP 08 (2018) 176]

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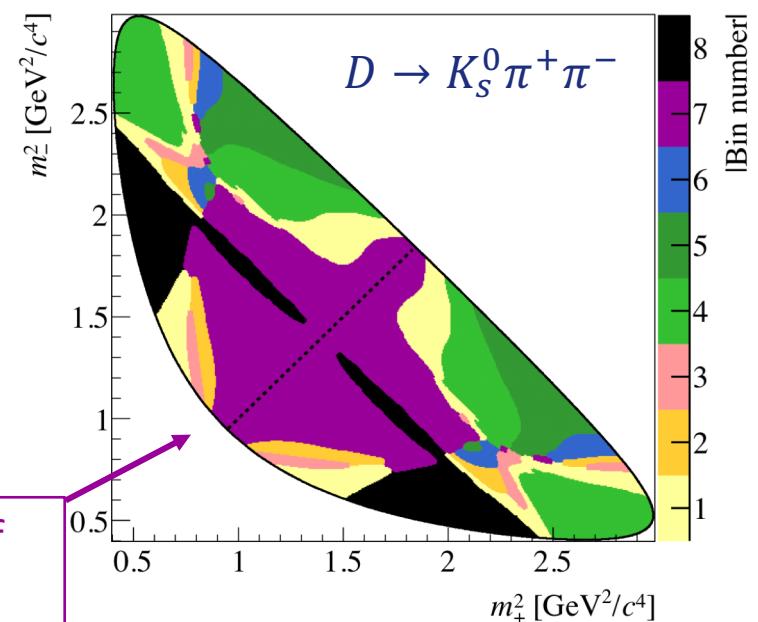
LHCb  
FCC



[JHEP 08 (2018) 176]

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$D_i$  sits on one side of the  $y = x$  axis of symmetry,  $\bar{D}_i$  on the other



# The model independent GGSZ method

- Look for differences between  $B^+$  and  $B^-$  yields in each bin  $\pm i$ :

$$N_{\pm i}^- \propto F_{\pm i} + (x_-^2 + y_-^2)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i})$$
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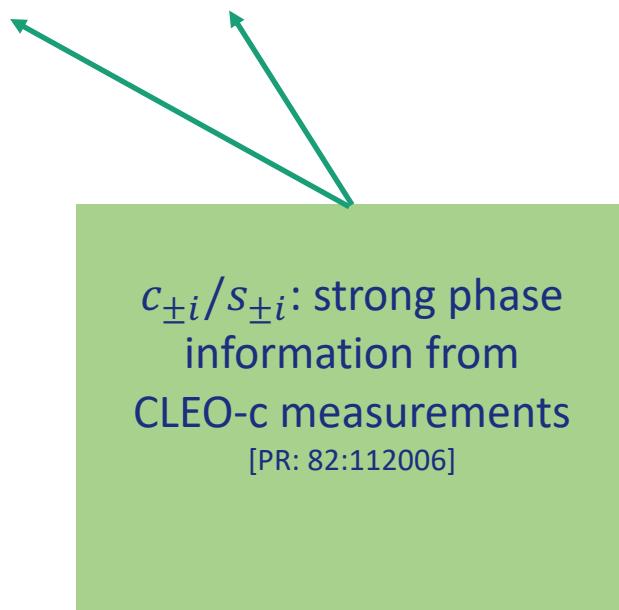
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$$c_i = \frac{\int_i |A_{\bar{D}_i}| |A_{D_i}| \cos[\delta_{\bar{D}_i} - \delta_{D_i}]}{\sqrt{\int_i |A_{\bar{D}_i}|^2 \int_i |A_{D_i}|^2}}$$

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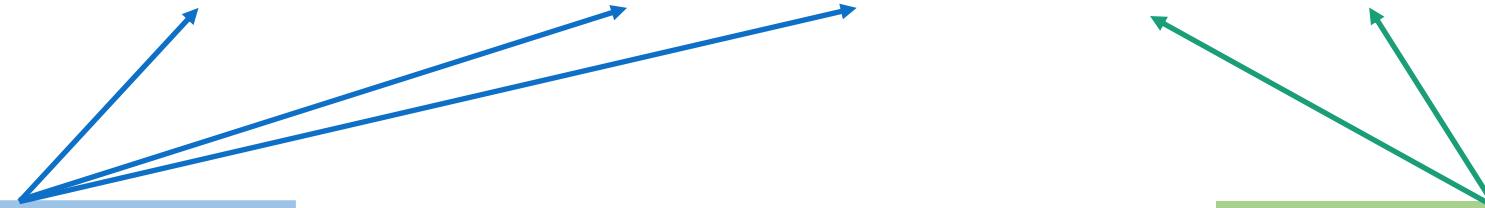
$c_{\pm i}/s_{\pm i}$ : strong phase information from CLEO-c measurements  
[PR: 82:112006]

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$F_{\pm i}$ : Fractional yield of flavour tagged  $D$  in bin  $\pm i$

Measured using control channel:



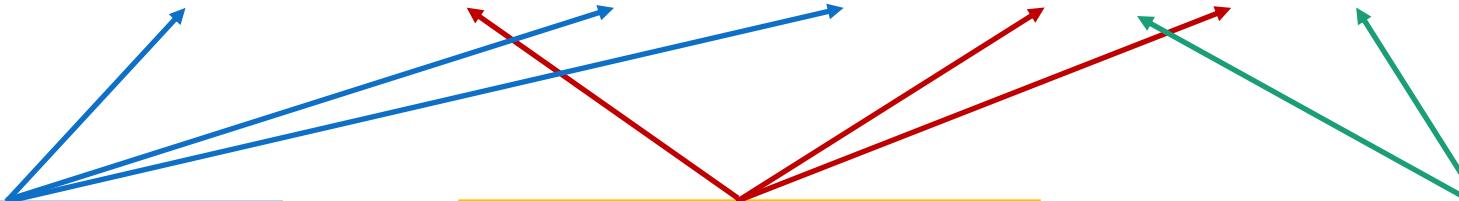
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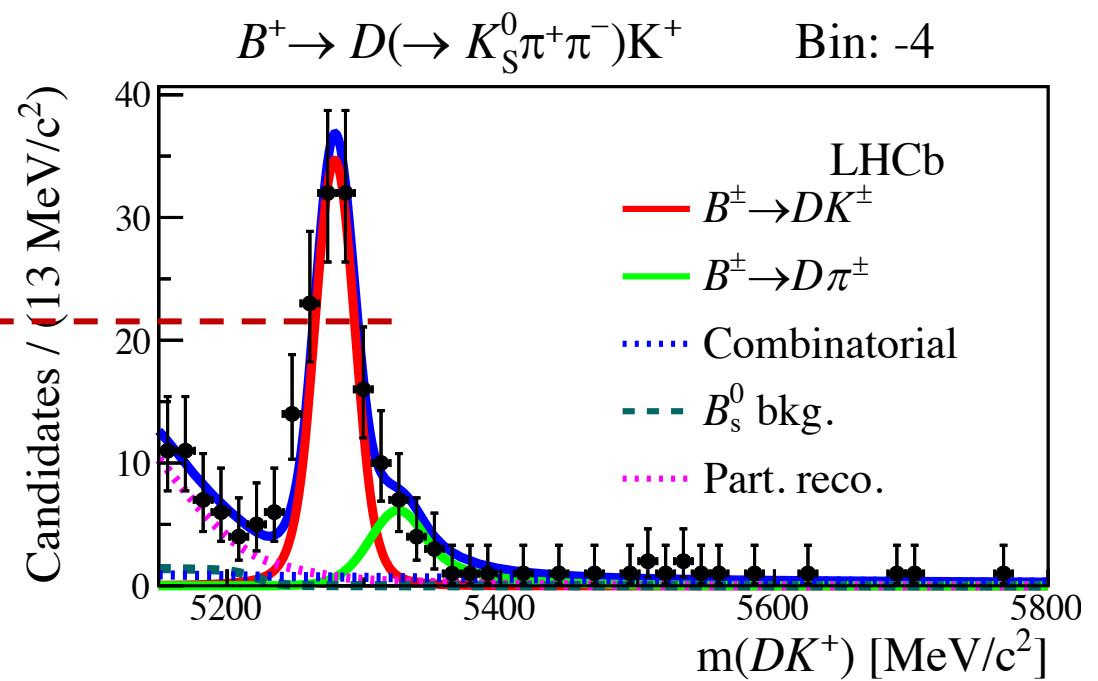
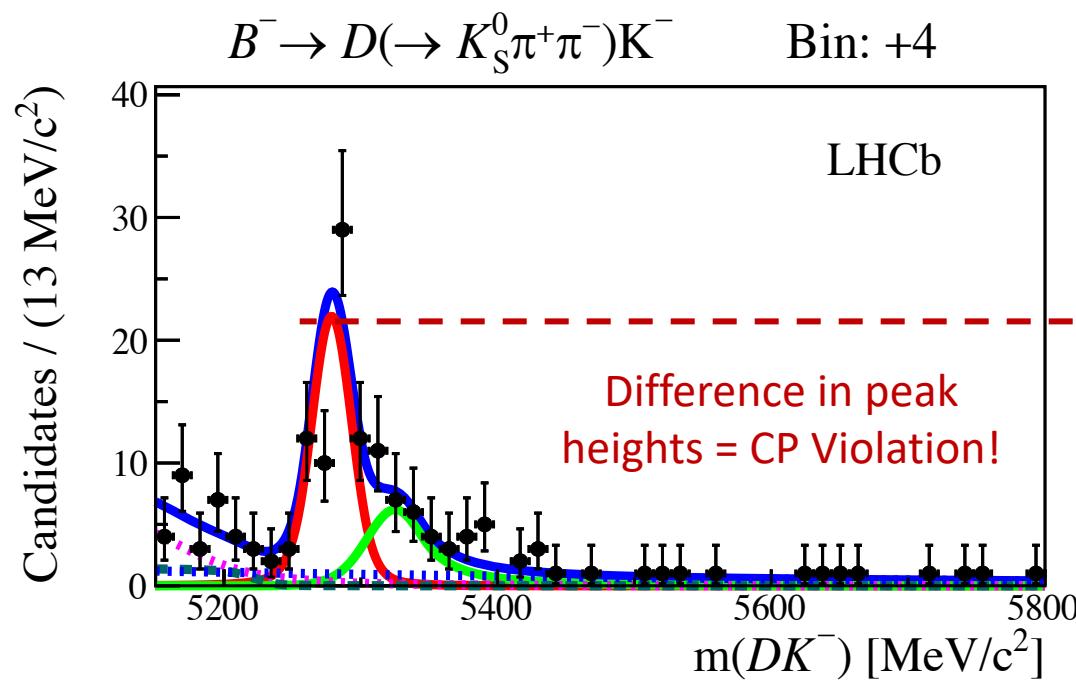
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 $\bar{B}^0 \rightarrow D^{*+} \mu^- \nu_\mu X$

$CP$  violating parameters:

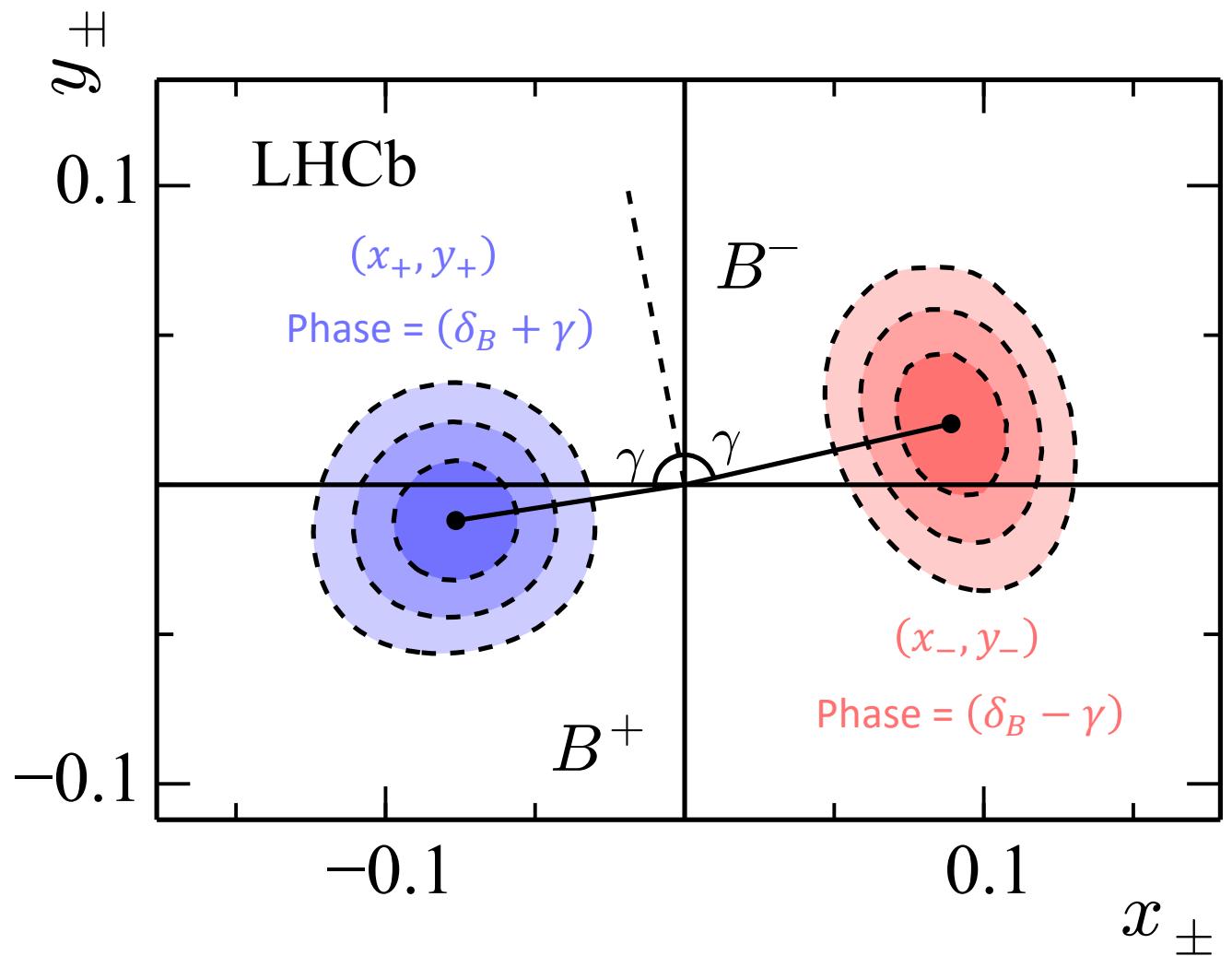
$$x_{\pm} = r_B^{DK} \cos(\delta_B \pm \gamma)$$
$$y_{\pm} = r_B^{DK} \sin(\delta_B \pm \gamma)$$

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[PR: 82:112006]

- Analysis used 2015 + 2016 data ( $= 2 \text{ fb}^{-1}$ )
- Compare  $B^-$  yields in bin  $+i$  to  $B^+$  yields in bin  $-i$  (reflection in Dalitz axis of symmetry)



- 16 bins for  $B^+$  and  $B^-$  means **32 observables** to measure **4 parameters**
- Over-constrained system **removes ambiguities** present in single-mode analyses (ADS/GLW)
- Opening angle between  $(x_+, y_+)$  and  $(x_-, y_-)$  gives  $\gamma = (87^{+11}_{-12})^\circ$



- The GGSZ results for  $(x_{\pm}, y_{\pm})$  is combined with many other LHCb results to extract a combined value of  $\gamma$
- The world average is currently dominated by the LHCb 2018 combination:  $\gamma = (74.0^{+5.0}_{-5.8})^{\circ}$ 
  - Combined result obtained by minimising a global  $\chi^2$  calculation
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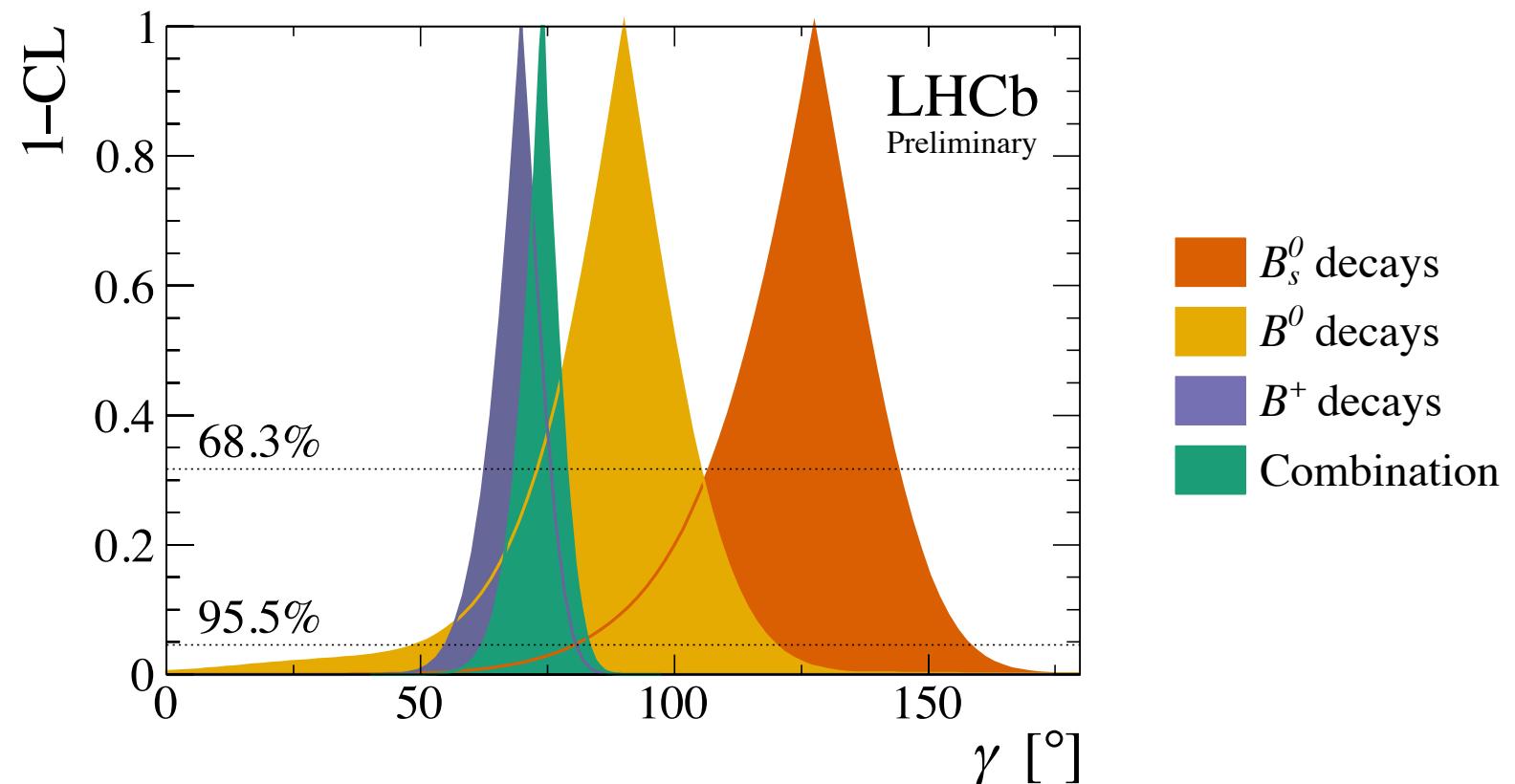
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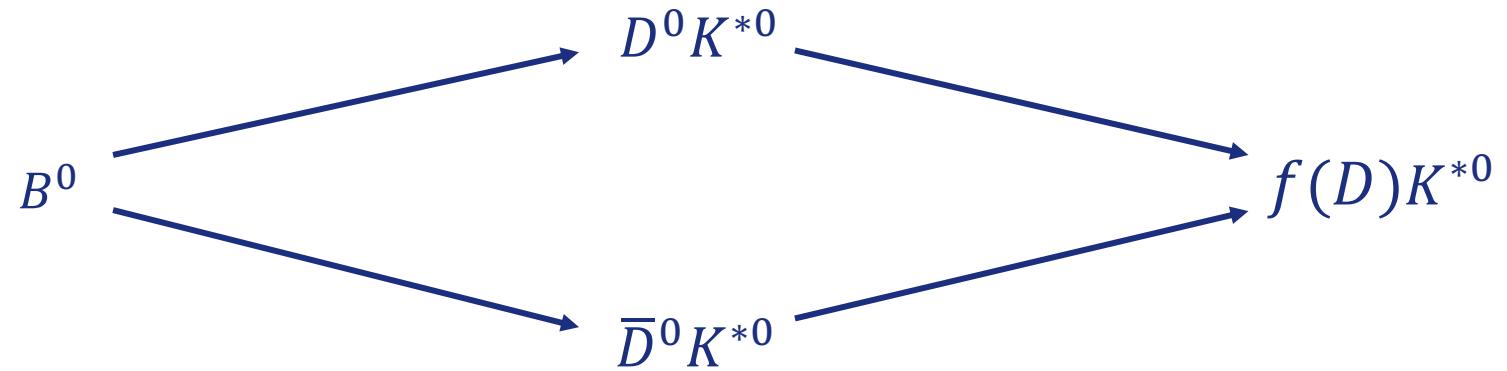
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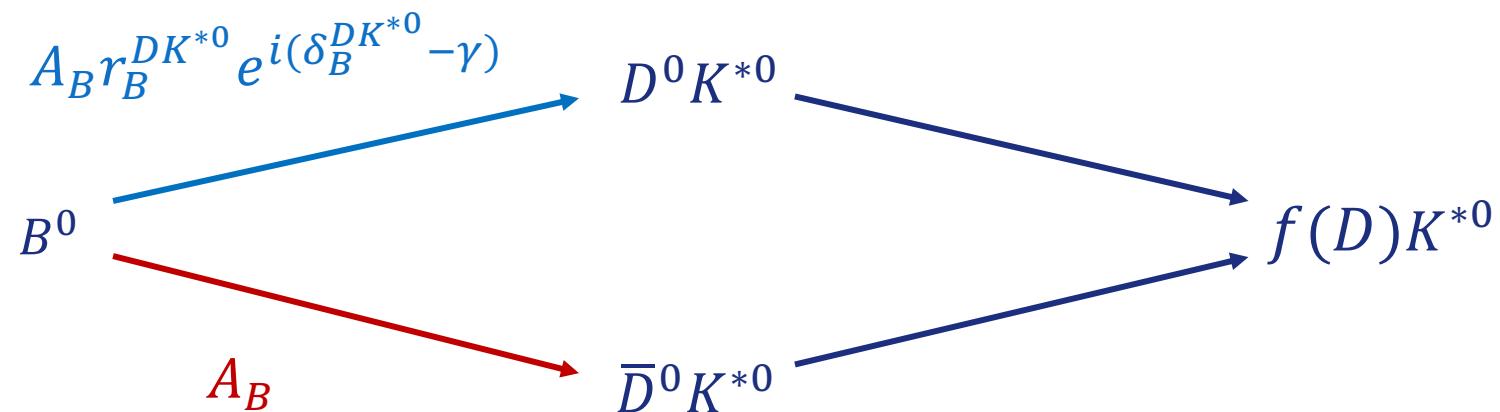
- The combination is currently dominated by analyses of  $B^-$  decays; increasing focus on developing analyses of  $B^0$  (next) and  $B_s^0$  mesons (TD):



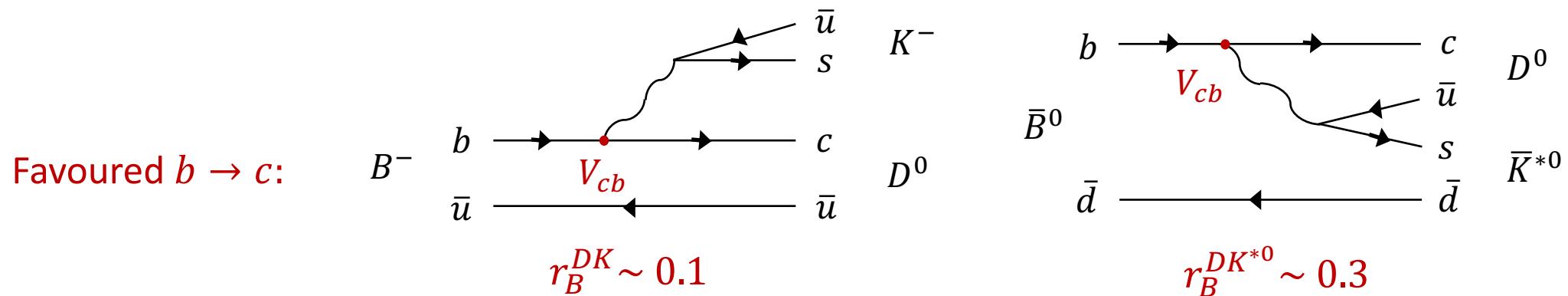
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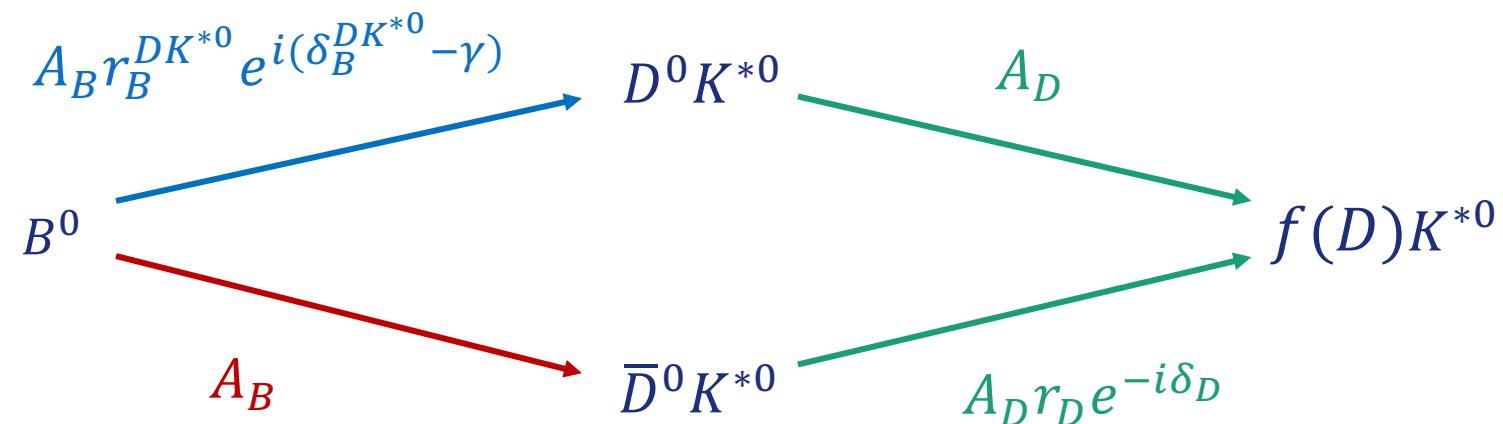


# $B^0 \rightarrow DK^{*0}$ decays



- Both paths are colour suppressed  $\rightarrow$  larger  $r_B$  than in  $B^-$  decays:





- $D = D^0/\bar{D}^0$  decaying 2/4-body final states with amplitude ratio  $r_D$  and phase difference  $\delta_D$ 
  - 2 possible paths proceed at a similar rate → larger interference effect

# The ADS Method

- 2-body:  $D^0 \rightarrow K^+ \pi^-$ ,  $\bar{D}^0 \rightarrow K^+ \pi^-$  and charge conjugates
  - Former is doubly-Cabibbo suppressed w.r.t. the latter ( $r_D \sim 0.06$ )
- Look for differences in decay rates ( $\Gamma \propto |\sum_i A_i|^2$ ) of  $B^0$  and  $\bar{B}^0$  mesons:

$$\Gamma(B^0 \rightarrow D K^{*0}) \propto r_D^2 + r_B^{DK^{*0}2} + 2\kappa r_D r_B^{DK^{*0}} \cos(\delta_B^{DK^{*0}} + \delta_D + \gamma)$$

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Smaller ADS asymmetries than in  $B^- \rightarrow D K^-$ :  
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- Coherence factor,  $\kappa$ , accounts for non- $K^{*0}$  contributions to  $B^0 \rightarrow D K^+ \pi^-$ 
  - $\kappa = 0.958^{+0.005}_{-0.046}$  [PRD 93 (2016) 112018]

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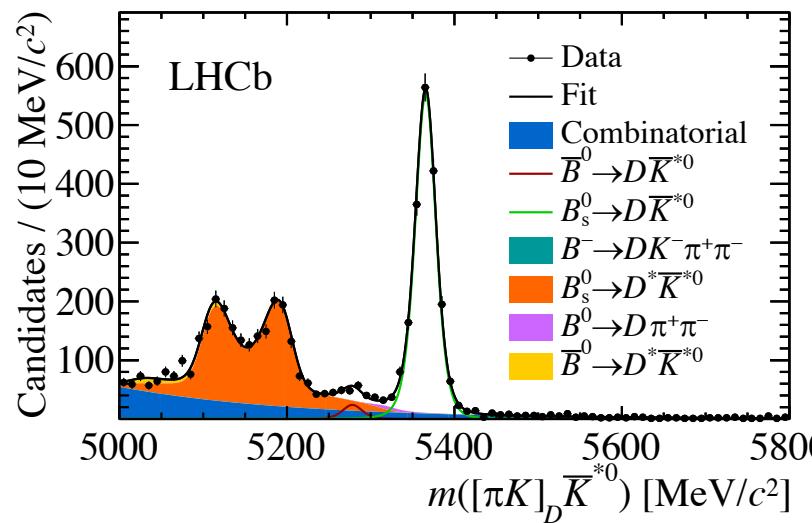
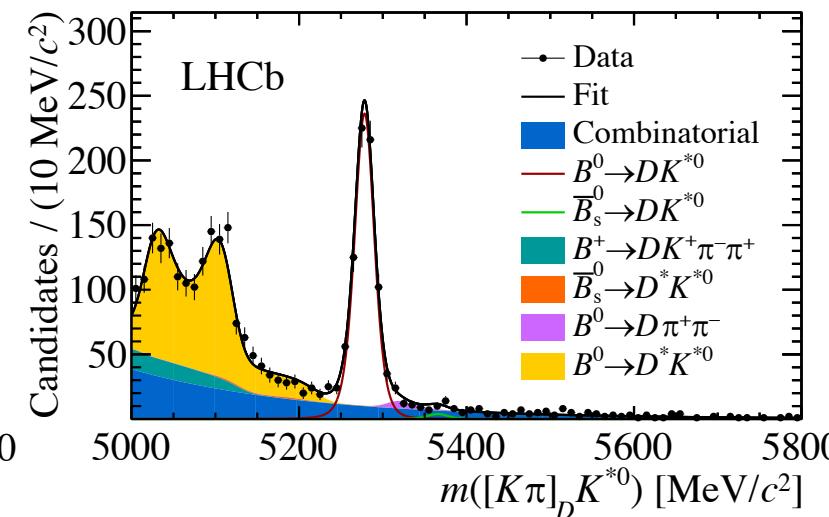
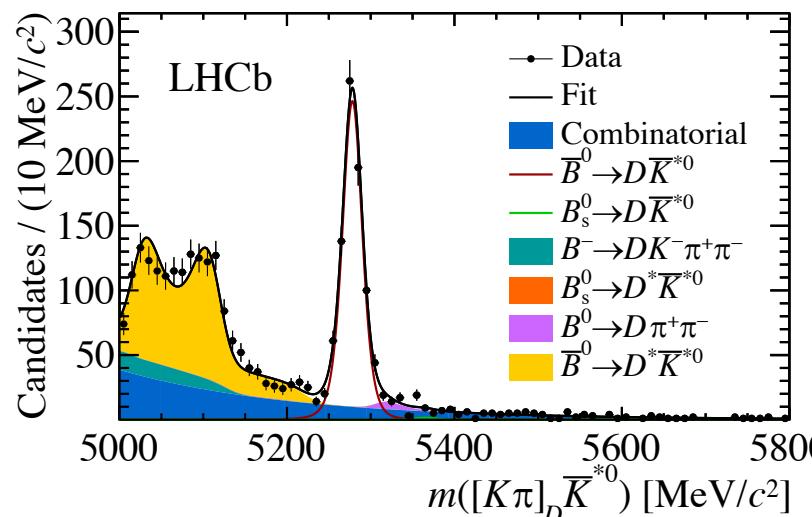
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- Measure ratios of the suppressed decay to their favoured counterparts:

$$\left. \begin{aligned} R_-^{\pi K} &= \frac{\Gamma(\bar{B}^0 \rightarrow [\pi^- K^+]_D \bar{K}^{*0})}{\Gamma(\bar{B}^0 \rightarrow [K^- \pi^+]_D \bar{K}^{*0})} \\ R_+^{\pi K} &= \frac{\Gamma(B^0 \rightarrow [\pi^+ K^-]_D K^{*0})}{\Gamma(B^0 \rightarrow [K^+ \pi^-]_D K^{*0})} \end{aligned} \right\} R_+^{\pi K} \neq R_-^{\pi K} \rightarrow CP \text{ violation!}$$

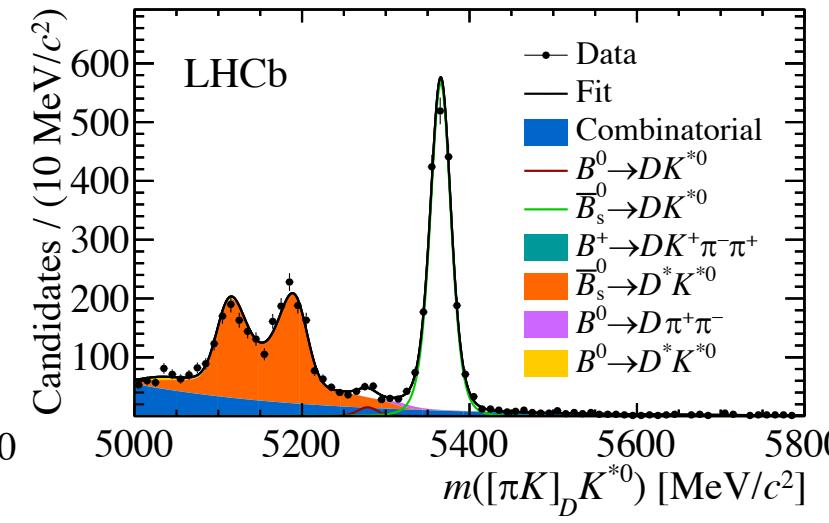
# $B^0 \rightarrow D K^{*0}, D \rightarrow \pi K$ results [LHCb-PAPER-2019-021] – NEW!

LHCb  
PAPER



Favoured yield =  $786 \pm 29$

Suppressed yield =  $76 \pm 16$



Favoured yield =  $754 \pm 29$

Suppressed yield =  $47 \pm 15$

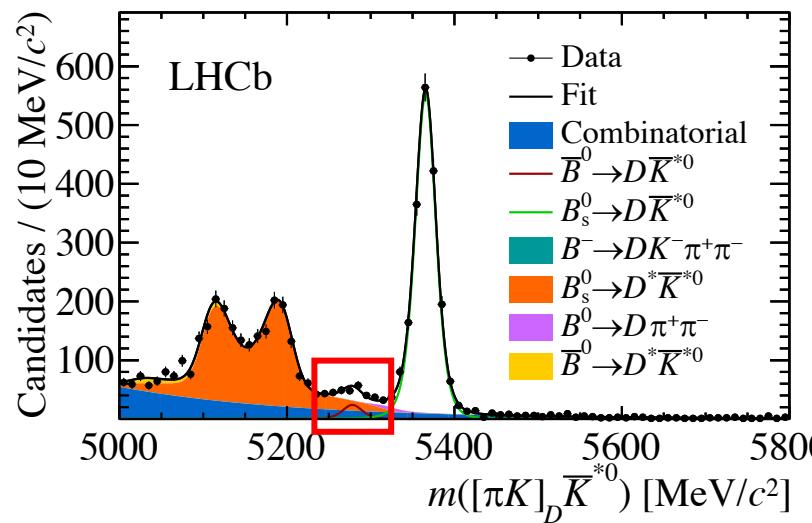
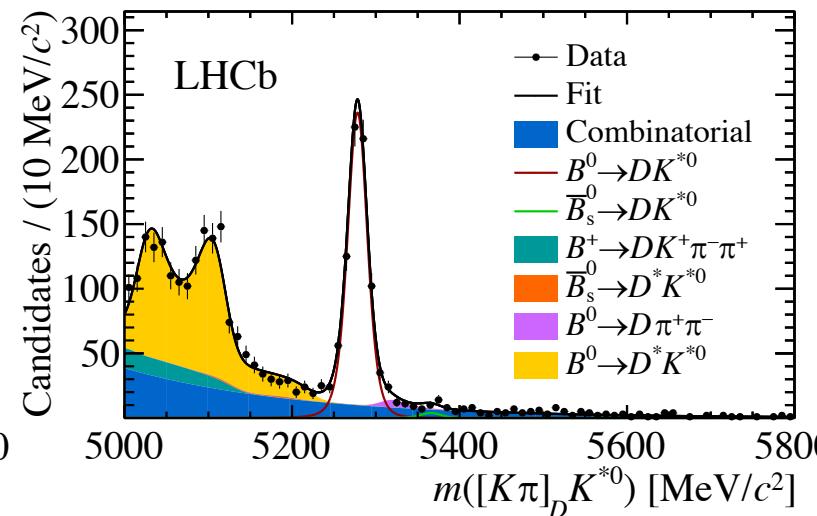
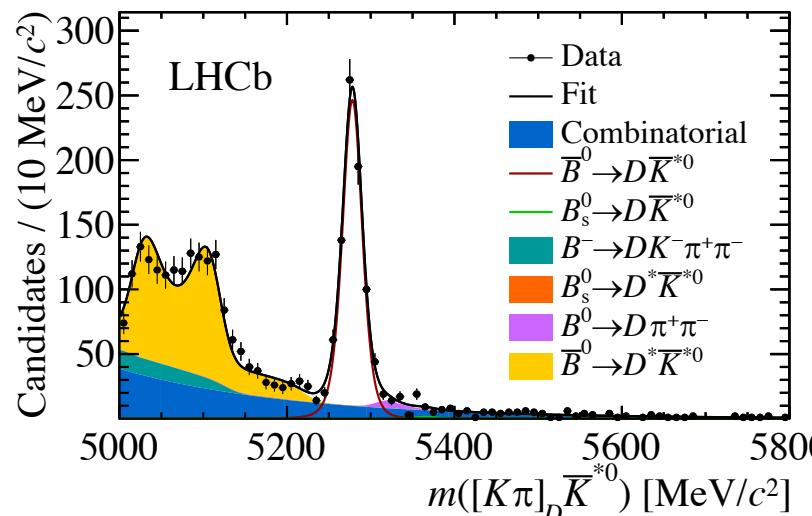
$$R_-^{\pi K} = 0.095 \pm 0.021 \pm 0.003$$

$$R_+^{\pi K} = 0.064 \pm 0.021 \pm 0.002$$

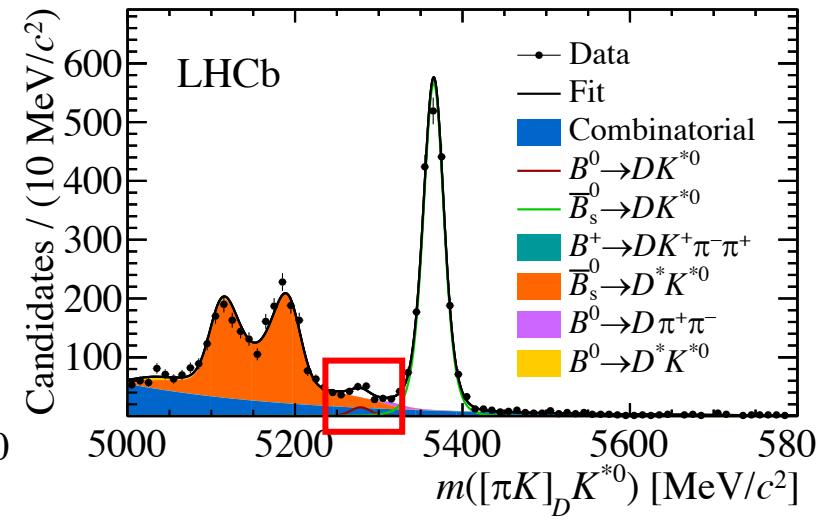
- 2011-2016 data (=  $5 \text{ fb}^{-1}$ )

# $B^0 \rightarrow D K^{*0}, D \rightarrow \pi K$ results [LHCb-PAPER-2019-021] – NEW!

LHCb  
PAPER



Favoured yield =  $786 \pm 29$   
Suppressed yield =  $76 \pm 16$

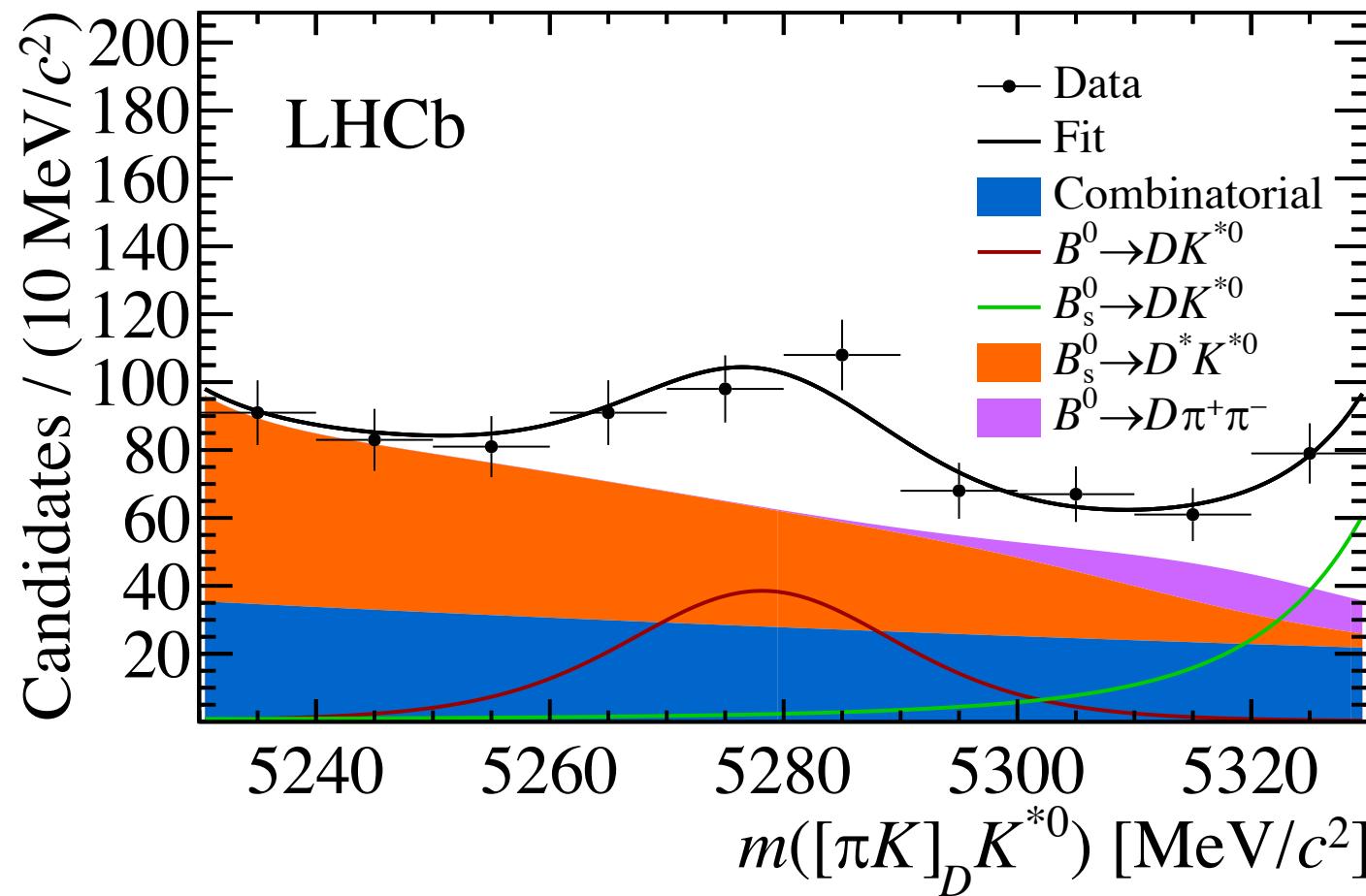


Favoured yield =  $754 \pm 29$   
Suppressed yield =  $47 \pm 15$

$$R_-^{\pi K} = 0.095 \pm 0.021 \pm 0.003$$

$$R_+^{\pi K} = 0.064 \pm 0.021 \pm 0.002$$

- 2011-2016 data (=  $5 \text{ fb}^{-1}$ )
- Suppressed mode significance:  
 $5.8\sigma$  - first observation!

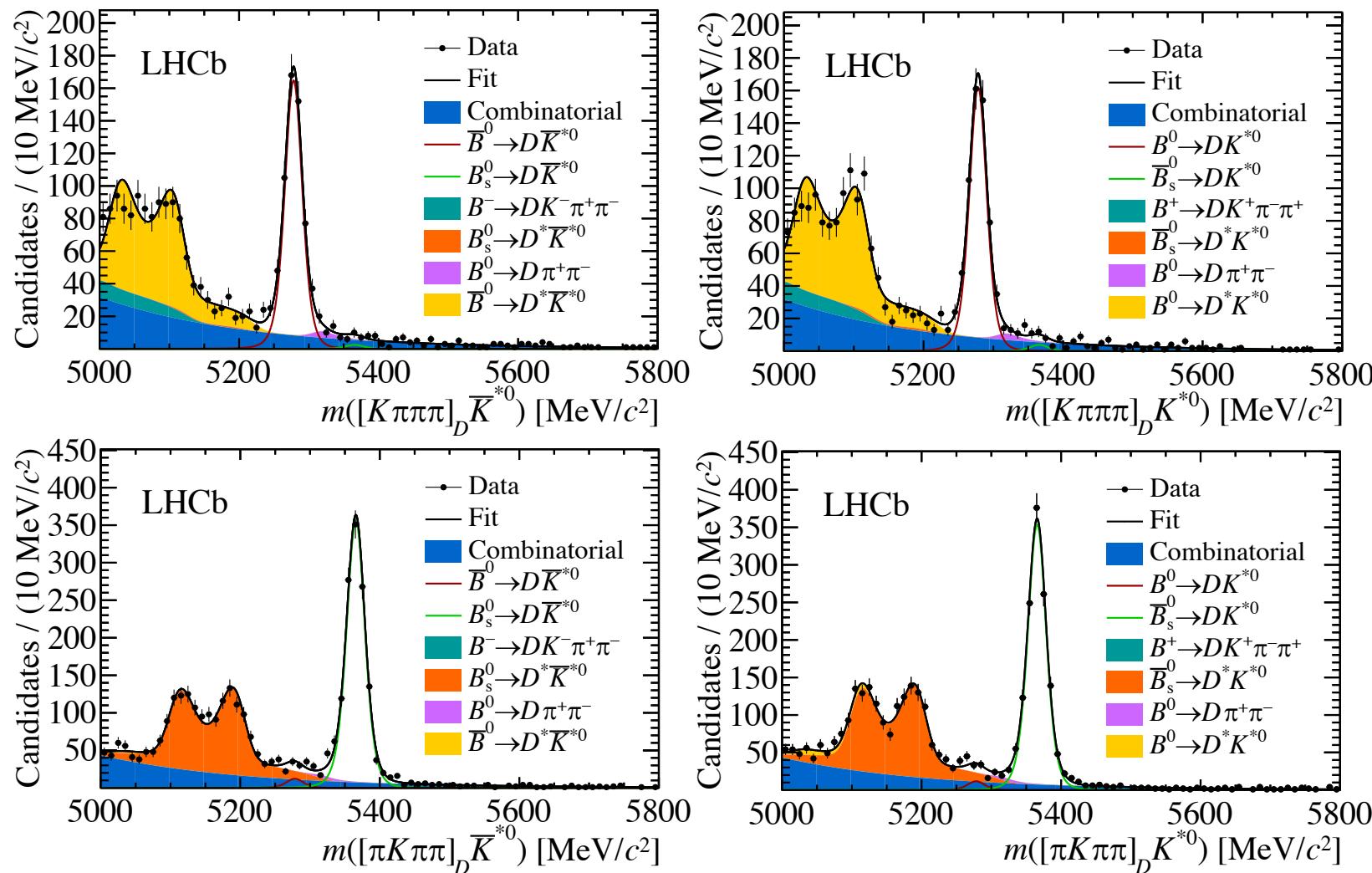


$$R_-^{\pi K} = 0.095 \pm 0.021 \pm 0.003$$
$$R_+^{\pi K} = 0.064 \pm 0.021 \pm 0.002$$

- 2011-2016 data (= 5 fb $^{-1}$ )
- Suppressed mode significance:  
 $5.8\sigma$  - first observation!

# $B^0 \rightarrow D K^{*0}, D \rightarrow \pi K \pi \pi$ results [LHCb-PAPER-2019-021] – NEW!

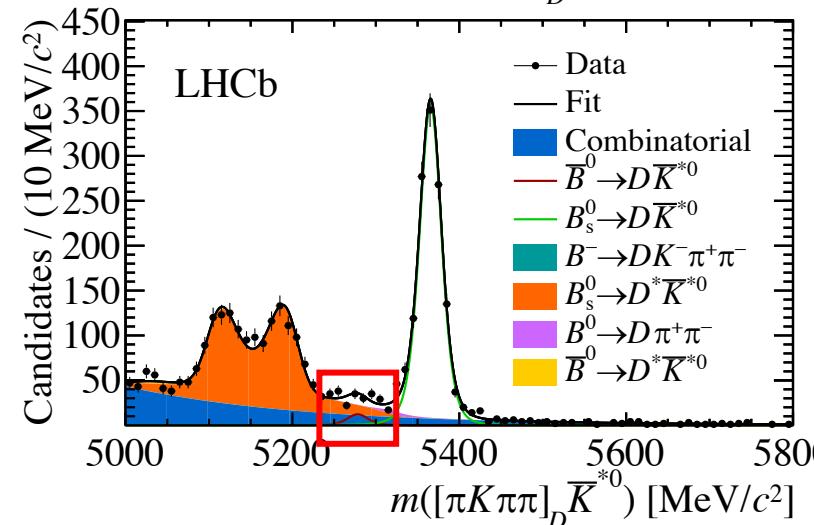
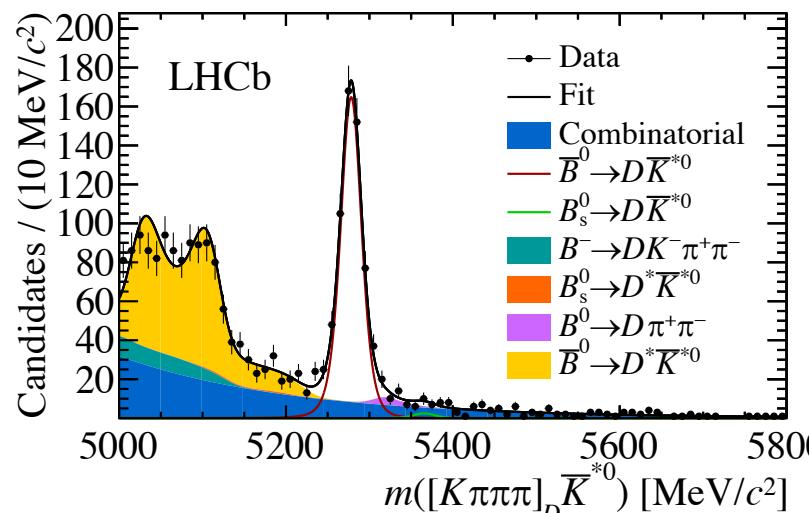
LHCb  
PAPERS



- 4-body: coherence factor  $\kappa_D^{K3\pi}$  enters as a pre-factor to the interference term [PLB 757 (2016) 520]. Different  $r_D^{K3\pi}$  and  $\delta_D^{K3\pi}$
- 2011-2016 data ( $= 5 \text{ fb}^{-1}$ )

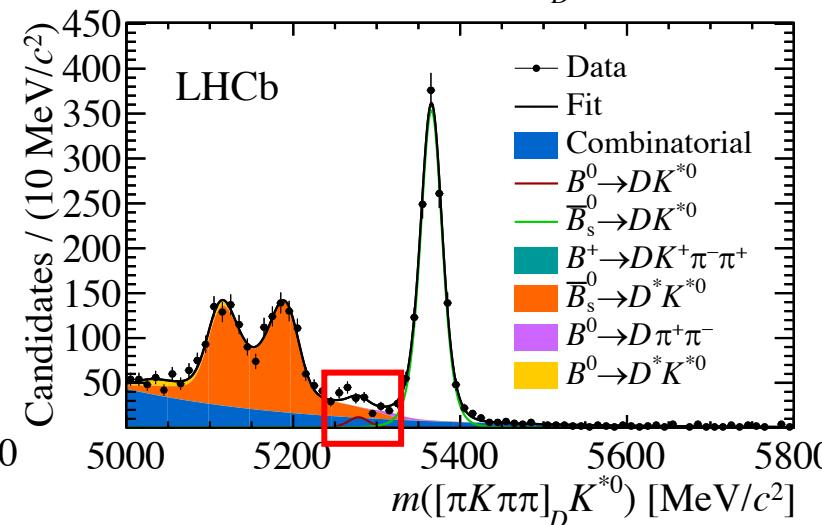
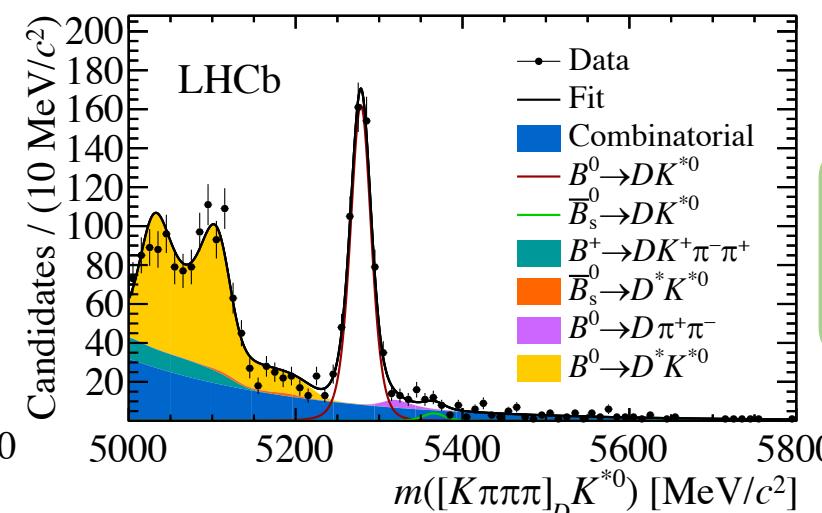
# $B^0 \rightarrow D K^{*0}, D \rightarrow \pi K \pi \pi$ results [LHCb-PAPER-2019-021] – NEW!

LHCb  
PAPER



Favoured yield =  $557 \pm 25$

Suppressed yield =  $41 \pm 14$



Favoured yield =  $548 \pm 25$

Suppressed yield =  $40 \pm 14$

$$R_-^{\pi K \pi \pi} = 0.072 \pm 0.025 \pm 0.003$$

$$R_+^{\pi K \pi \pi} = 0.074 \pm 0.026 \pm 0.002$$

- 4-body: coherence factor  $\kappa_D^{K3\pi}$  enters as a pre-factor to the interference term [PLB 757 (2016) 520]. Different  $r_D^{K3\pi}$  and  $\delta_D^{K3\pi}$
- 2011-2016 data ( $= 5 \text{ fb}^{-1}$ )
- Suppressed mode significance:  $4.4\sigma$

# The GLW Method

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

$$\Gamma(B^0 \rightarrow DK^{*0}) \propto 1 + r_B^{DK^{*0}2} + 2\kappa r_B^{DK^{*0}} \cos(\delta_B^{DK^{*0}} + \gamma)$$

$$\Gamma(\bar{B}^0 \rightarrow D\bar{K}^{*0}) \propto 1 + r_B^{DK^{*0}2} + 2\kappa r_B^{DK^{*0}} \cos(\delta_B^{DK^{*0}} - \gamma)$$



Expect larger interference effect than in  $B^- \rightarrow DK^-$   
decays as  $r_B^{DK^{*0}}$  is closer to 1

# The GLW Method

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$$\Gamma(\bar{B}^0 \rightarrow D\bar{K}^{*0}) \propto 1 + r_B^{DK^{*0}}{}^2 + 2\kappa r_B^{DK^{*0}} \cos(\delta_B^{DK^{*0}} - \gamma)$$

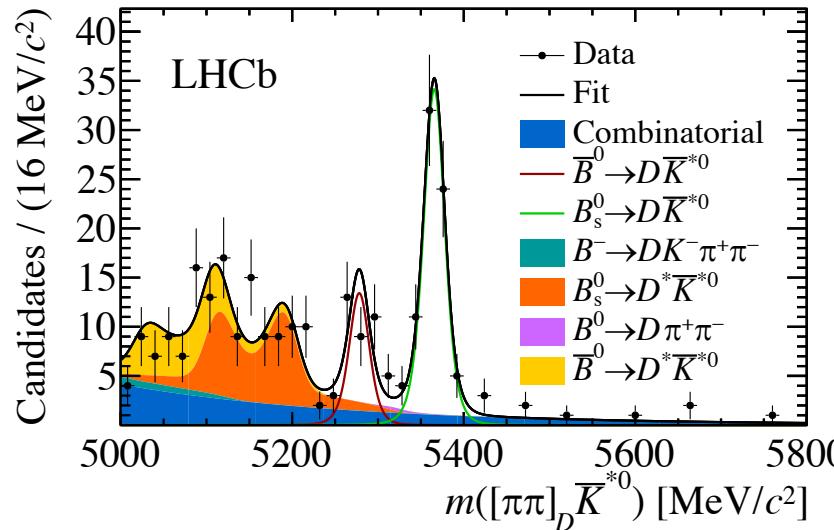
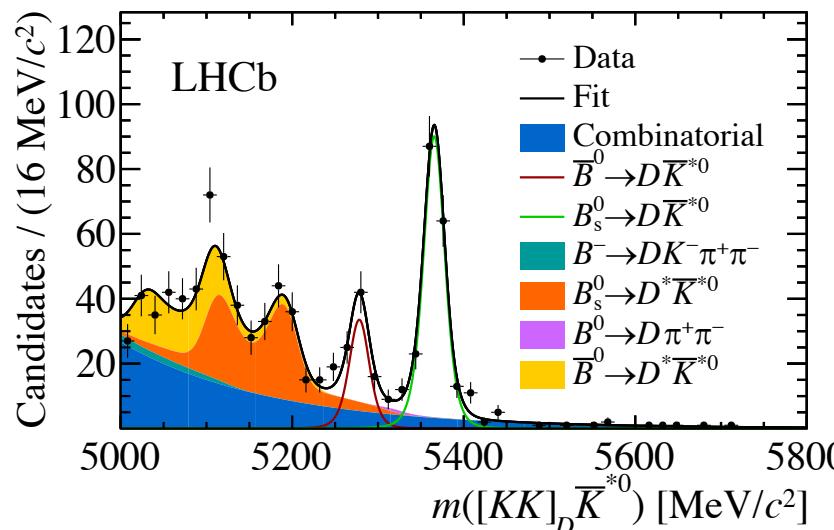
- Build up asymmetries and ratios:

$$A_{CP}^{hh} = \frac{\Gamma(\bar{B}^0 \rightarrow [h^+h^-]_D \bar{K}^{*0}) - \Gamma(B^0 \rightarrow [h^+h^-]_D K^{*0})}{\Gamma(\bar{B}^0 \rightarrow [h^+h^-]_D \bar{K}^{*0}) + \Gamma(B^0 \rightarrow [h^+h^-]_D K^{*0})}$$

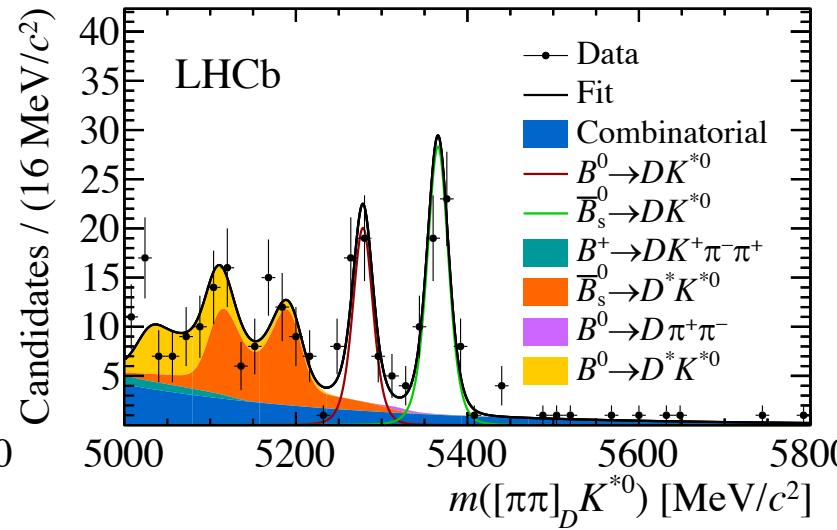
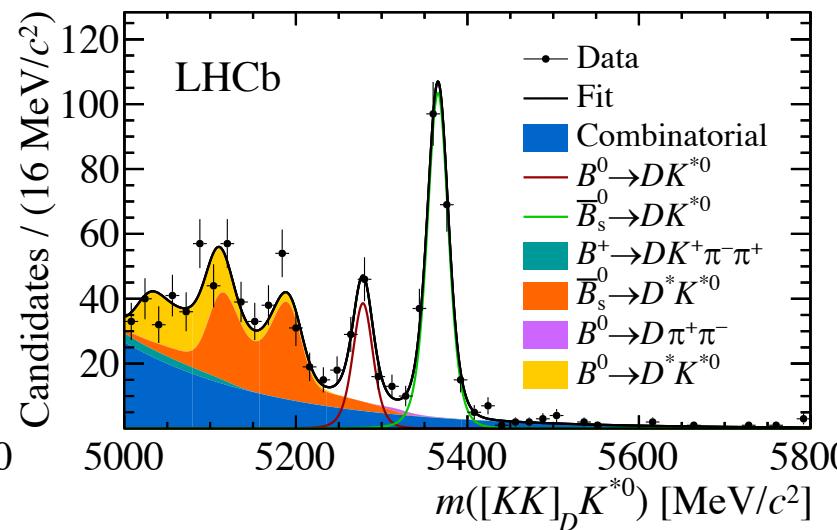
$$R_{CP}^{hh} = \frac{\Gamma(\bar{B}^0 \rightarrow [h^+h^-]_D \bar{K}^{*0}) + \Gamma(B^0 \rightarrow [h^+h^-]_D K^{*0})}{\Gamma(\bar{B}^0 \rightarrow [K^-\pi^+]_D \bar{K}^{*0}) + \Gamma(B^0 \rightarrow [K^+\pi^-]_D K^{*0})} \times \frac{\mathcal{BF}(D^0 \rightarrow K^-\pi^+)}{\mathcal{BF}(D^0 \rightarrow h^+h^-)}$$

# $B^0 \rightarrow DK^{*0}, D \rightarrow h^+ h^-$ results [LHCb-PAPER-2019-021] – NEW!

LHCb  
NEW!



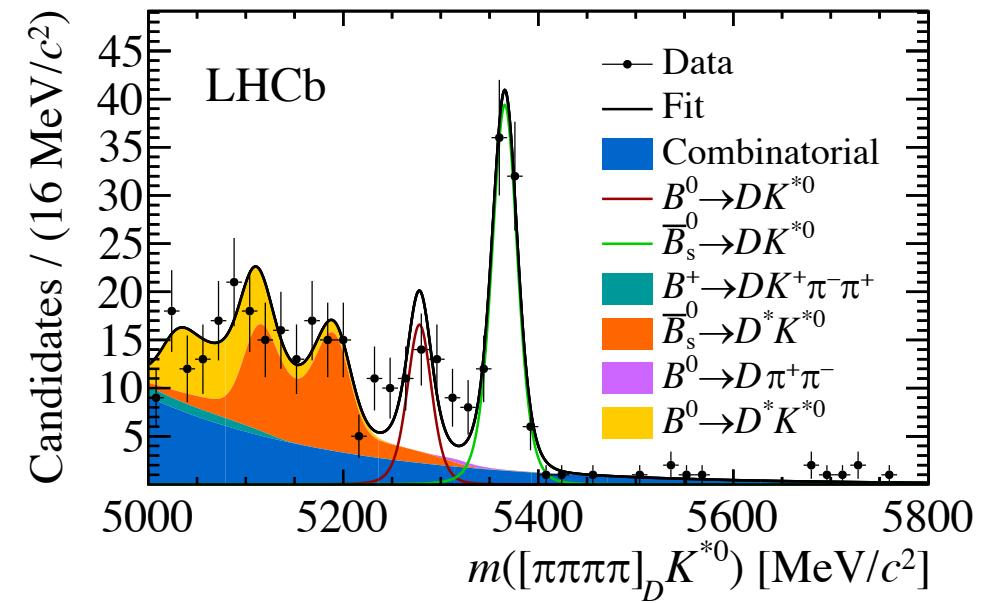
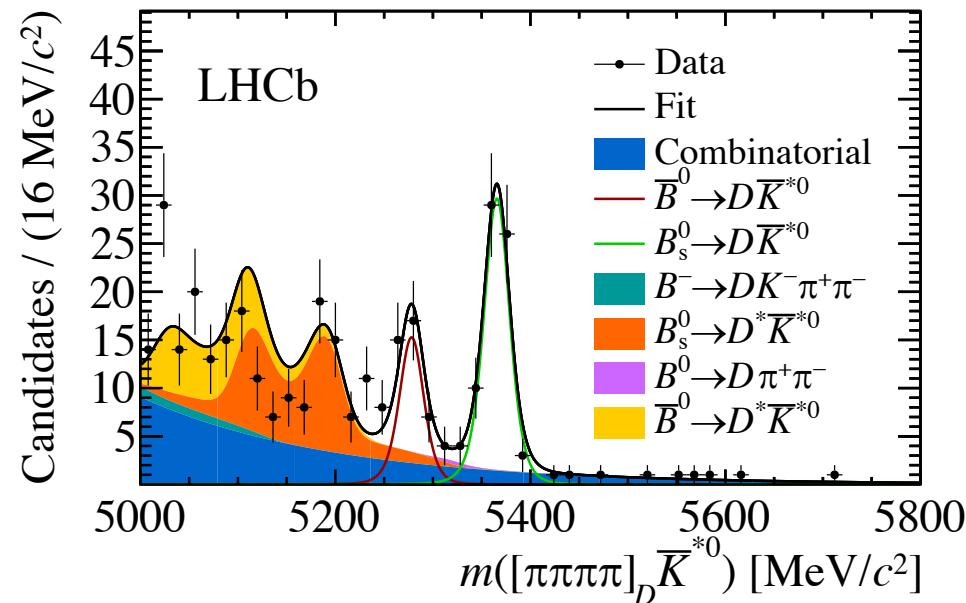
$KK$  yield =  $67 \pm 10$   
 $\pi\pi$  yield =  $26 \pm 6$



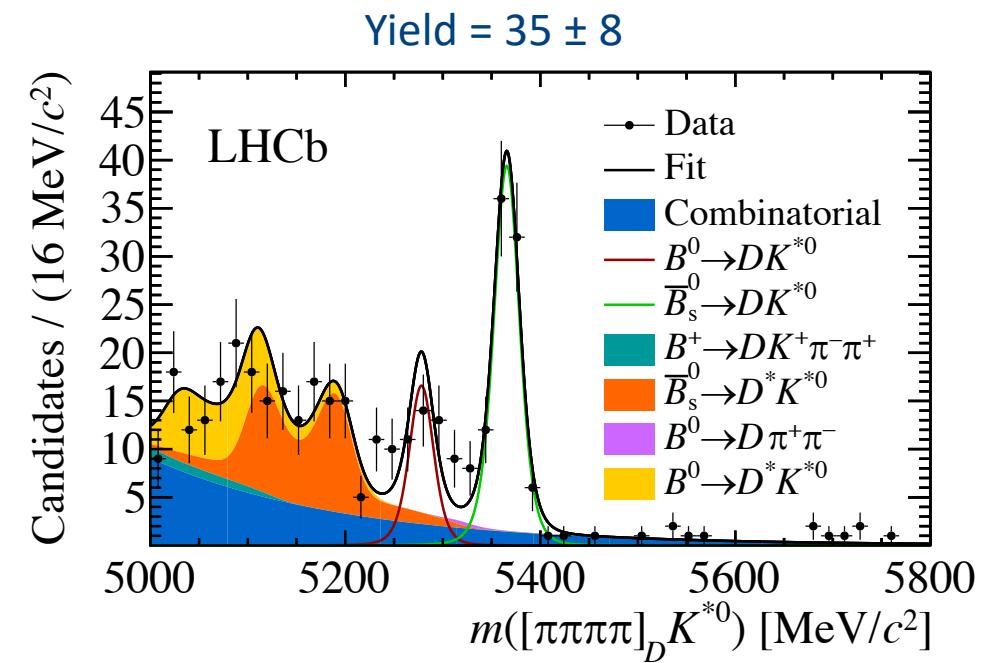
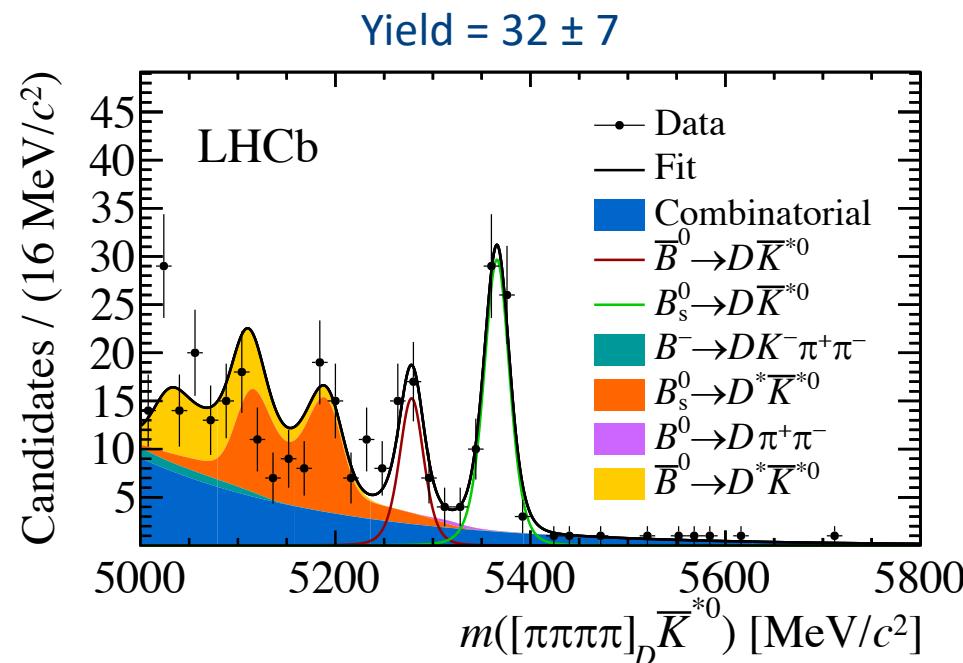
$KK$  yield =  $77 \pm 11$   
 $\pi\pi$  yield =  $40 \pm 7$

2011-2016 data (= 5 fb $^{-1}$ )

$A_{CP}^{KK} = -0.05 \pm 0.10 \pm 0.01$   
 $R_{CP}^{KK} = 0.92 \pm 0.10 \pm 0.02$   
 $A_{CP}^{\pi\pi} = -0.18 \pm 0.14 \pm 0.01$   
 $R_{CP}^{\pi\pi} = 1.32 \pm 0.19 \pm 0.03$



- 4-body: extend method to quasi-GLW mode by reconstructing the  $D$  meson in the final state  $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ 
  - Interference term acquires pre-factor  $(2F_+^{4\pi} - 1)$ , where  $F_+^{4\pi}$  is the fractional  $CP$ -even content of the decay [JHEP 01 (2018) 144]
- Using 2015 + 2016 ( $= 2 \text{ fb}^{-1}$ ) data only

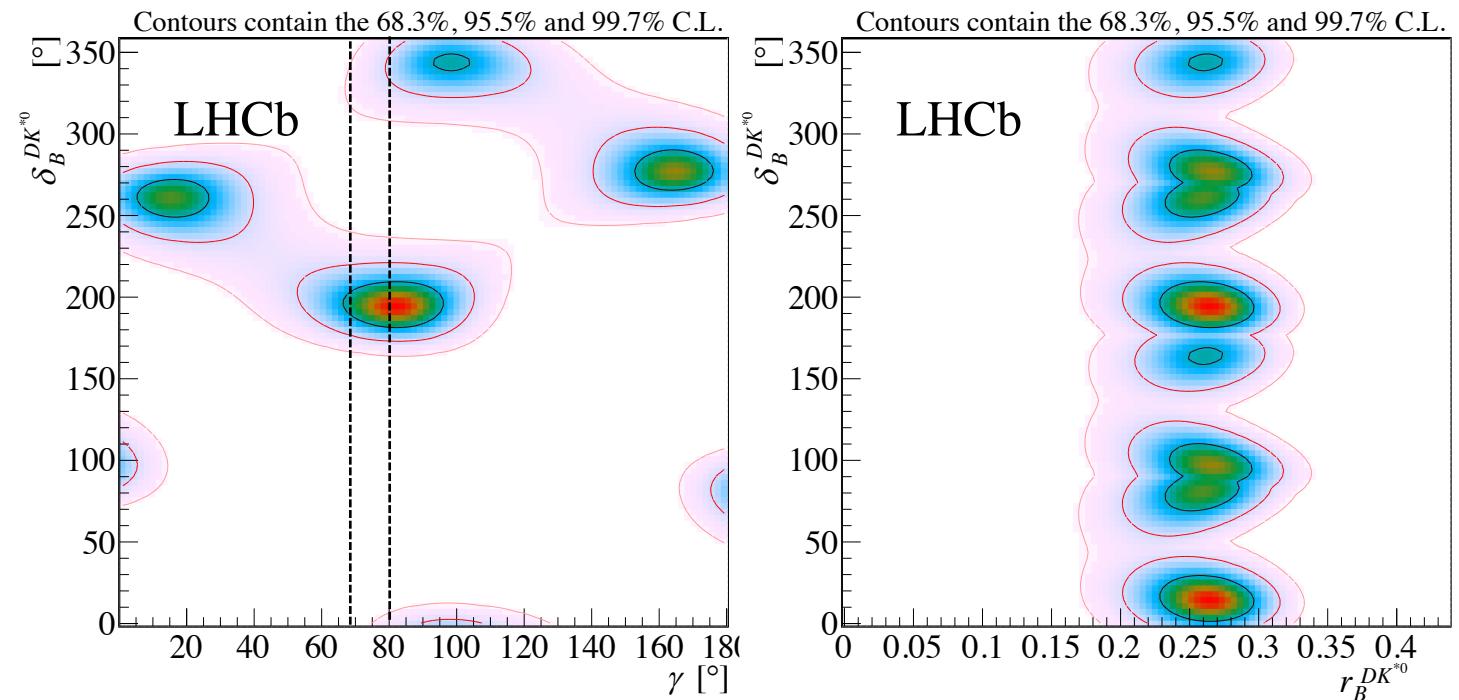


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  - Interference term acquires pre-factor  $(2F_+^{4\pi} - 1)$ , where  $F_+^{4\pi}$  is the fractional  $CP$ -even content of the decay [JHEP 01 (2018) 144]
- Using 2015 + 2016 (=  $2 \text{ fb}^{-1}$ ) data only
- Significance  $8.4\sigma$  – first observation!

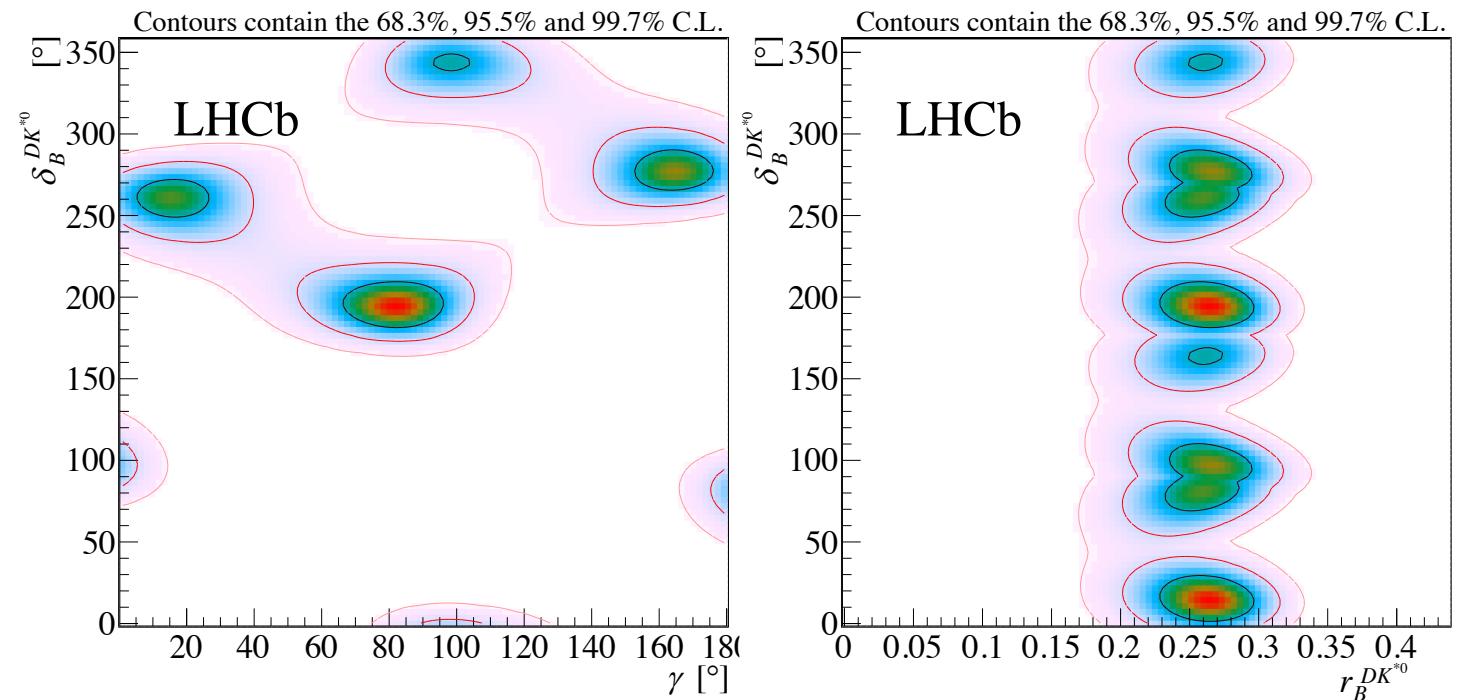
$$A_{CP}^{4\pi} = -0.03 \pm 0.15 \pm 0.01$$

$$R_{CP}^{4\pi} = 1.01 \pm 0.16 \pm 0.04$$

- Two solutions in the  $\gamma - \delta_B^{D K^{*0}}$  space are compatible with current LHCb measurement
  - No strong  $\gamma$  constraint as no significant  $CP$  violation observed
- Combine the measurements to obtain:  $r_B^{D K^{*0}} = 0.265 \pm 0.023$ 
  - The uncertainty has been halved compared to the previous measurement

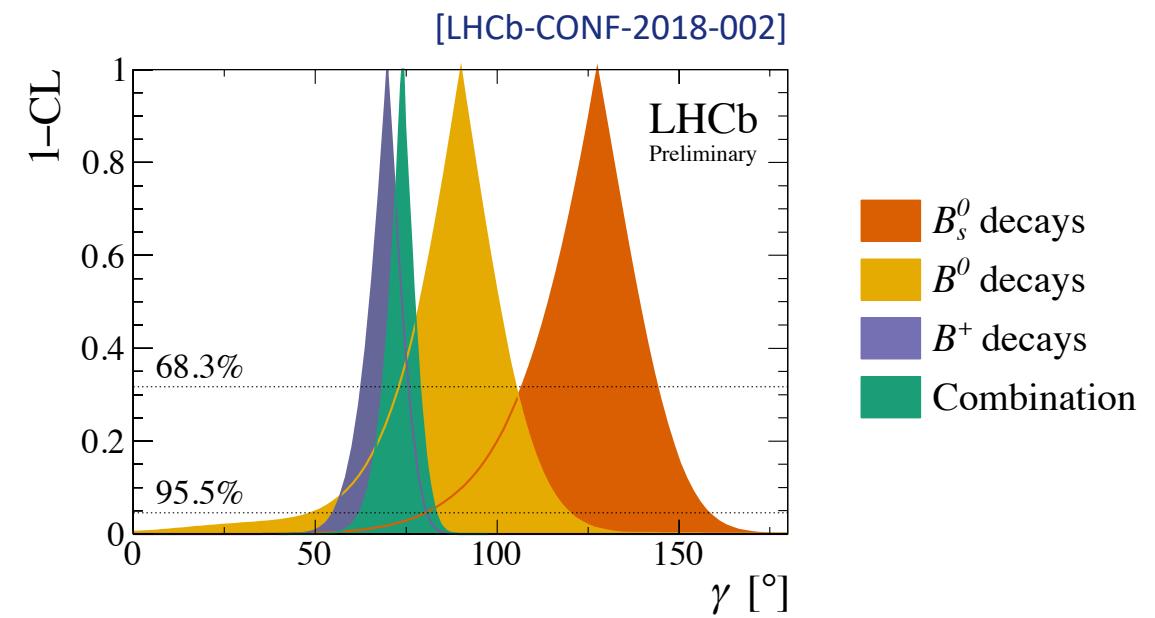


- Two solutions in the  $\gamma - \delta_B^{DK^{*0}}$  space are compatible with current LHCb measurement
  - No strong  $\gamma$  constraint as no significant  $CP$  violation observed
- Combine the measurements to obtain:  $r_B^{DK^{*0}} = 0.265 \pm 0.023$ 
  - The uncertainty has been halved compared to the previous measurement
- Combine with GGSZ analysis of  $B^0 \rightarrow DK^{*0}$ 
  - GLW/ADS has higher stats - more precise  $r_B^{DK^{*0}}$
  - GGSZ has lower stats but removes degeneracy in  $\gamma - \delta_B^{DK^{*0}}$  space



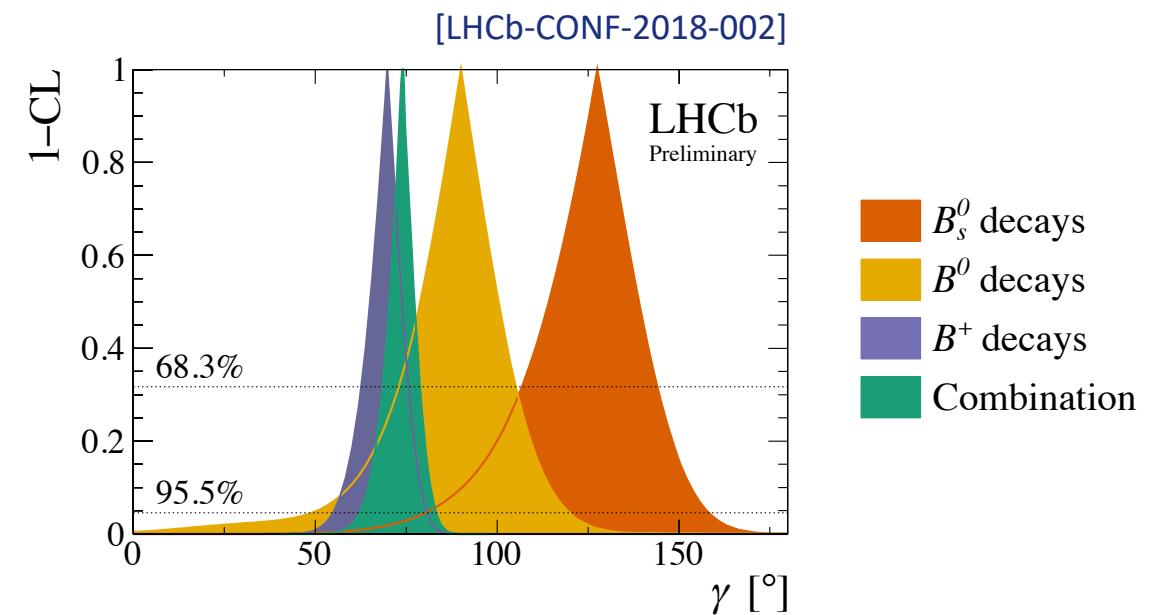
# Summary

- The  $\gamma$  world average is dominated by the 2018 LHCb combination ( $74.0^{+5.0}_{-5.8}$ ) $^\circ$
- New inputs from the ADS/GLW analysis of  $B^0 \rightarrow DK^{*0}$  will be added soon, where the uncertainty on  $r_B^{DK^{*0}}$  has been halved
  - Reduce width of yellow region!



# Summary

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- New inputs from the ADS/GLW analysis of  $B^0 \rightarrow DK^{*0}$  will be added soon, where the **uncertainty on  $r_B^{DK^{*0}}$  has been halved**
  - Reduce width of yellow region!
- Future prospects for  $\gamma$  precision at LHCb:
  - $4^\circ$  with Run 2 data ( $\sim 9 \text{ fb}^{-1}$ )  
[arXiv:1709.10308v5]
  - $1.5^\circ$  by the end of Run 3 ( $\sim 22 \text{ fb}^{-1}$ , 2024)  
[arXiv:1709.10308v5]
  - $< 1^\circ$  by the end of Run 4 ( $\sim 50 \text{ fb}^{-1}$ , 2029)  
[arXiv:1709.10308v5]
  - $\sim 0.4^\circ$  in Phase 2 upgrade ( $\sim 300 \text{ fb}^{-1}$ , 2034)  
[CERN-LHCC-2017-003]

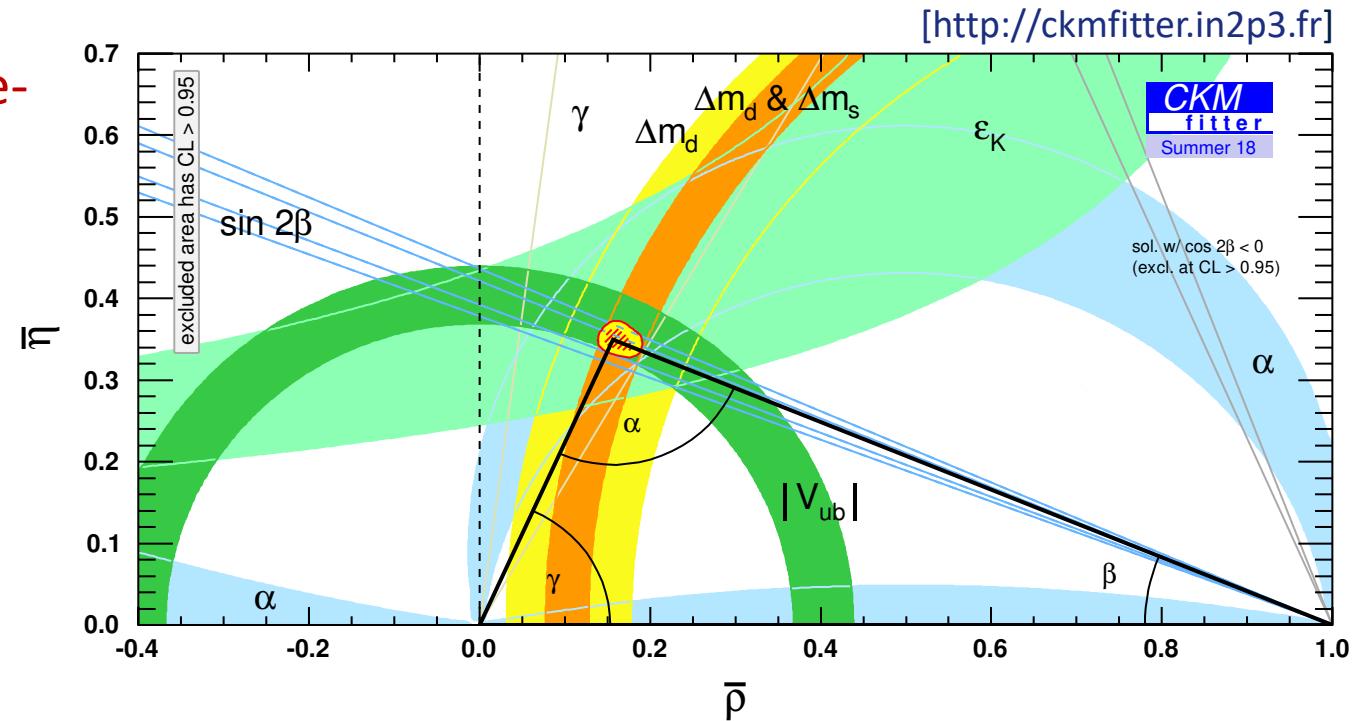


Thank you!

# Back Up

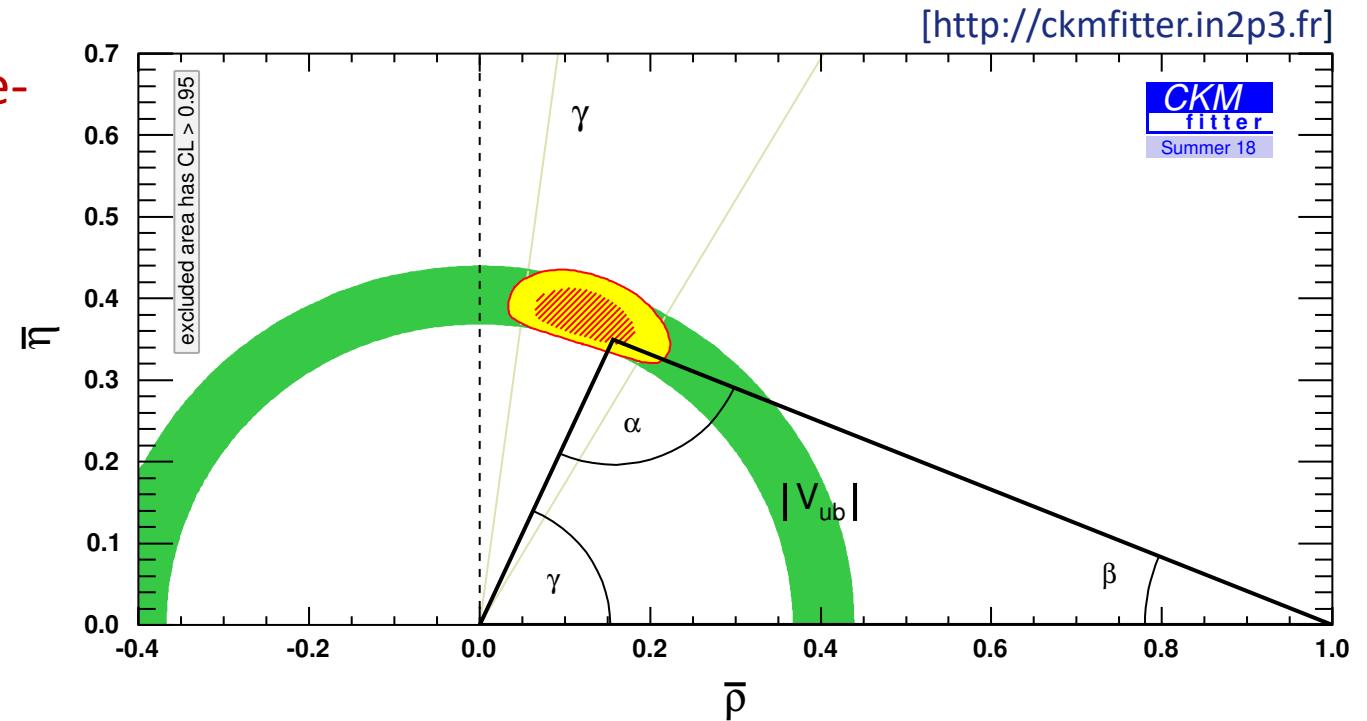
# Measuring $\gamma$ using tree and loop-level decays

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



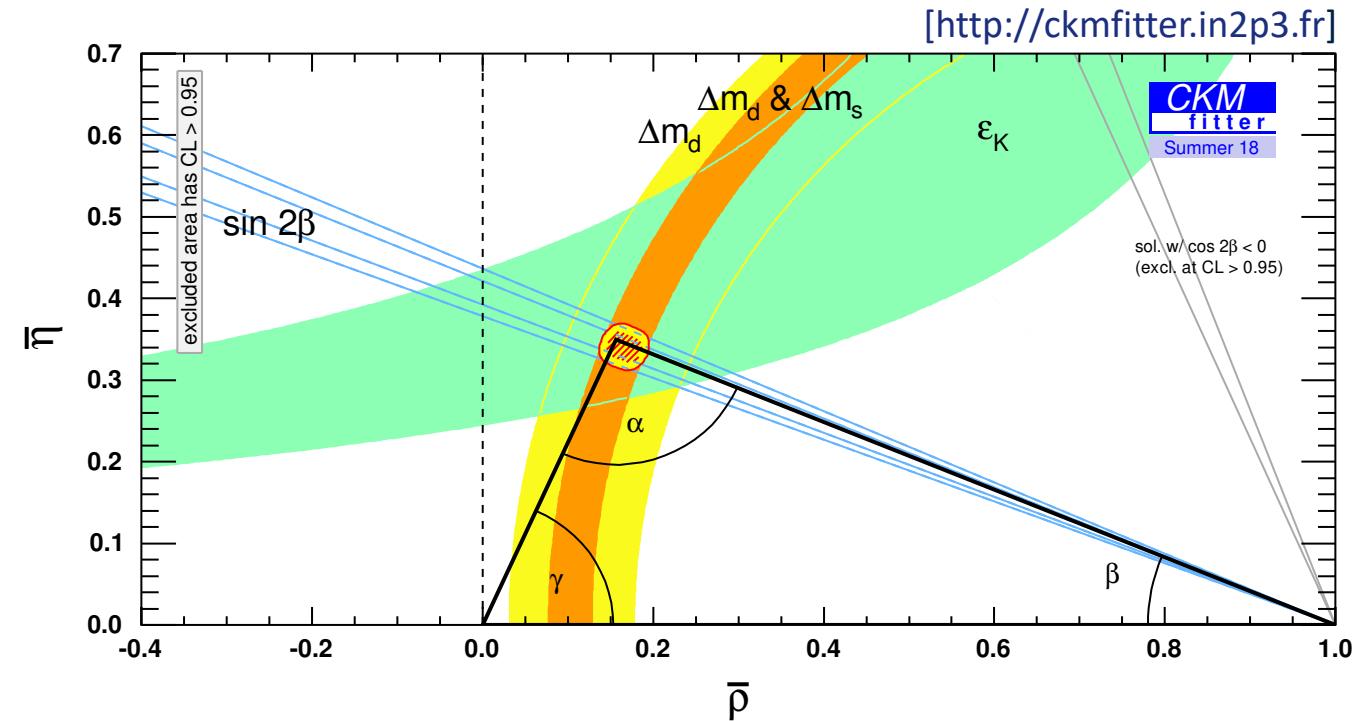
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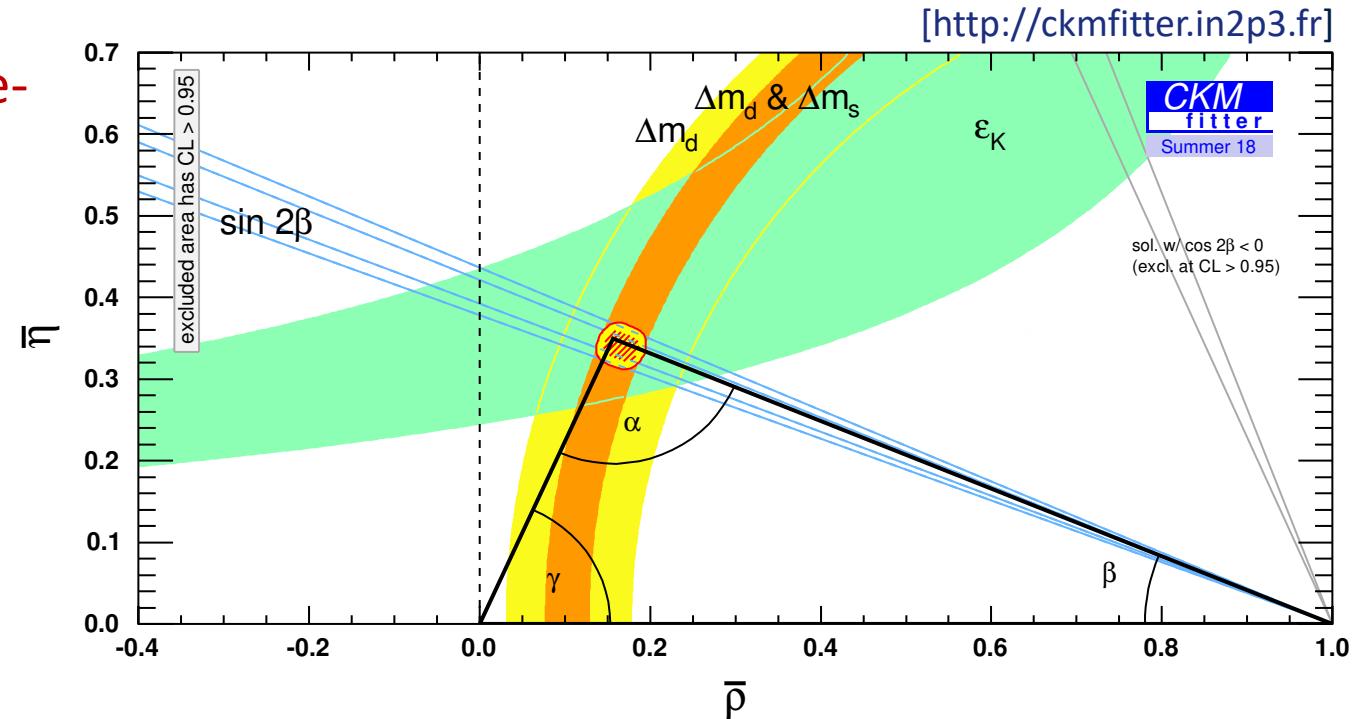
# Measuring $\gamma$ using tree and loop-level decays

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



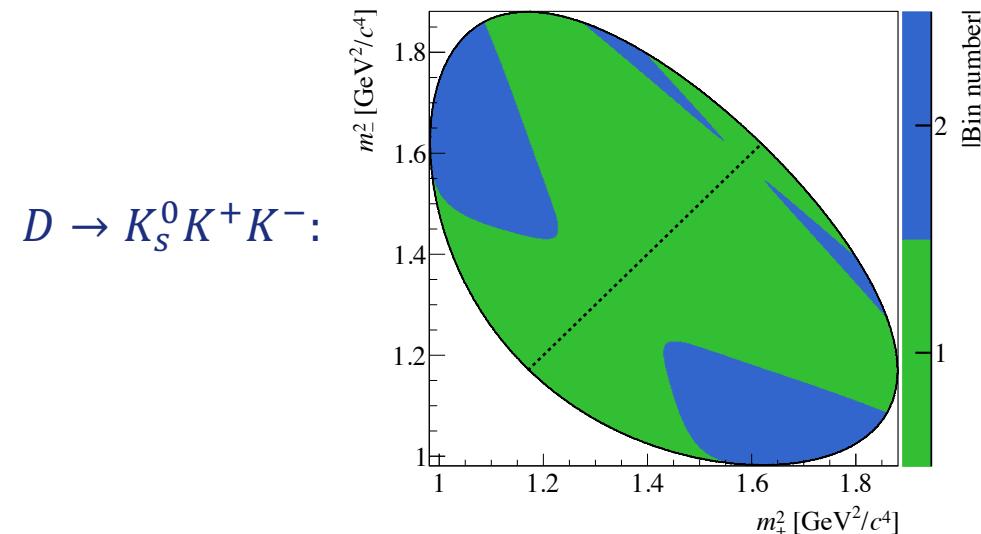
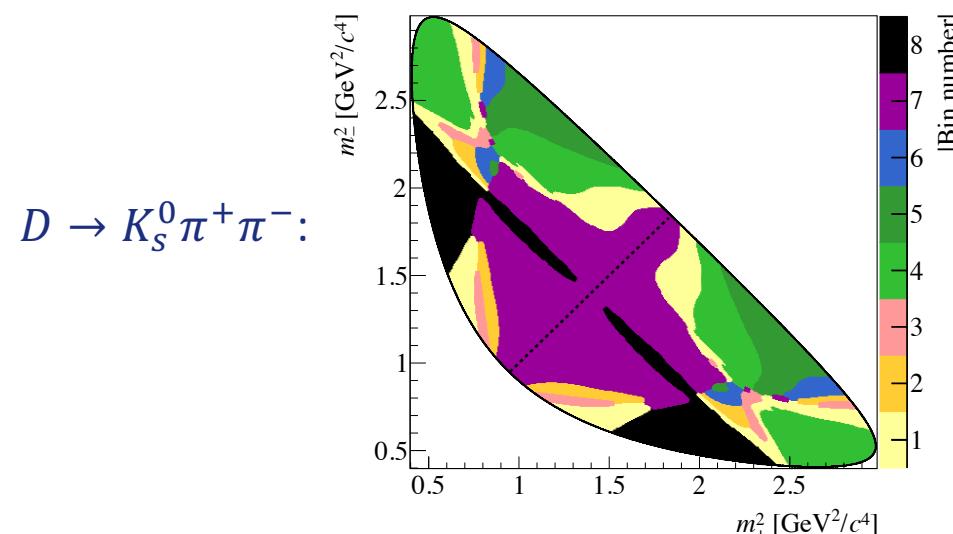
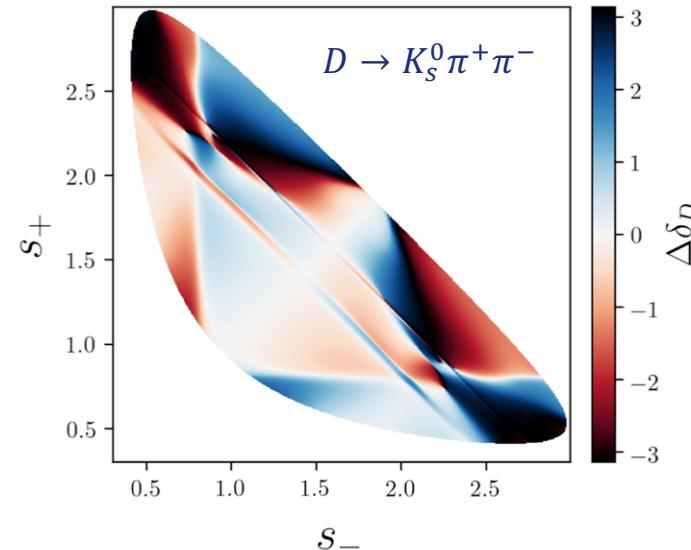
# Measuring $\gamma$ using tree and loop-level decays

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

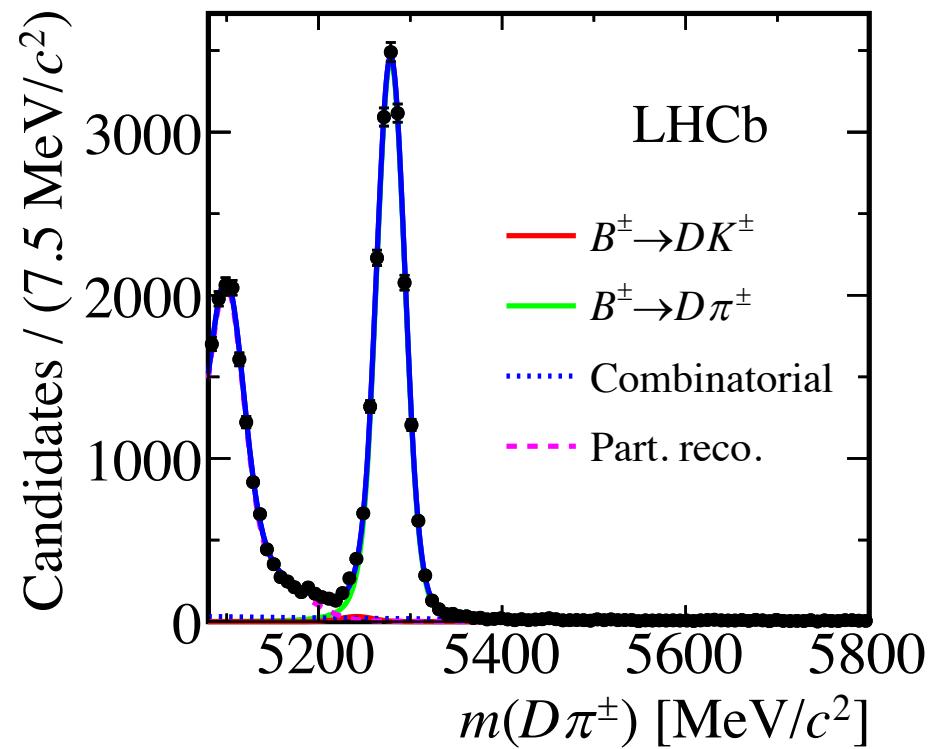
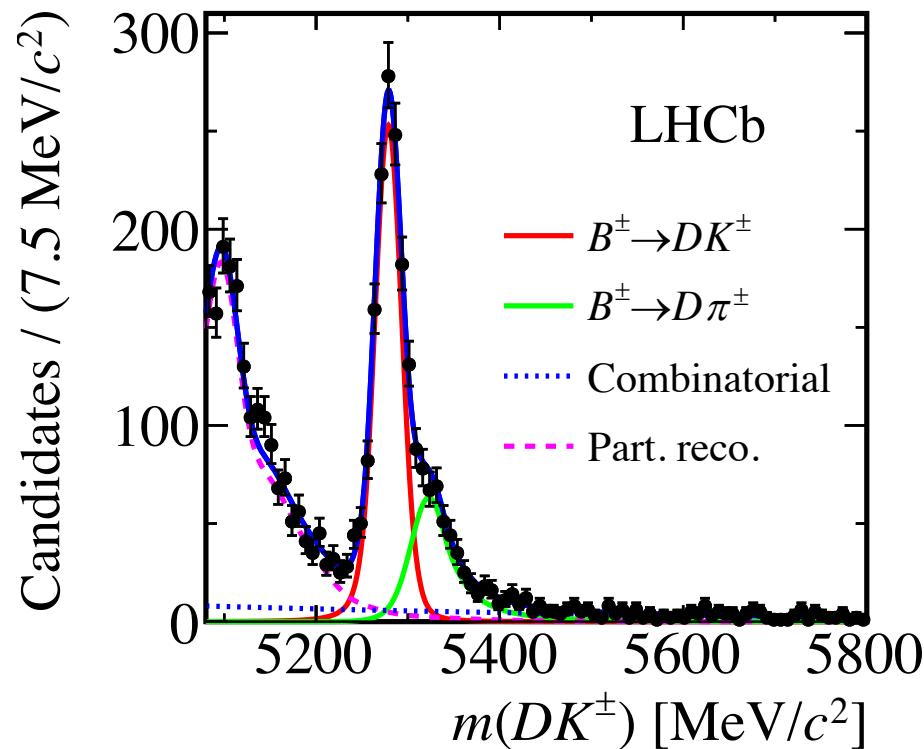


# $B^- \rightarrow [K_s^0 h^+ h^-]_D K^-$ : the GGSZ Method

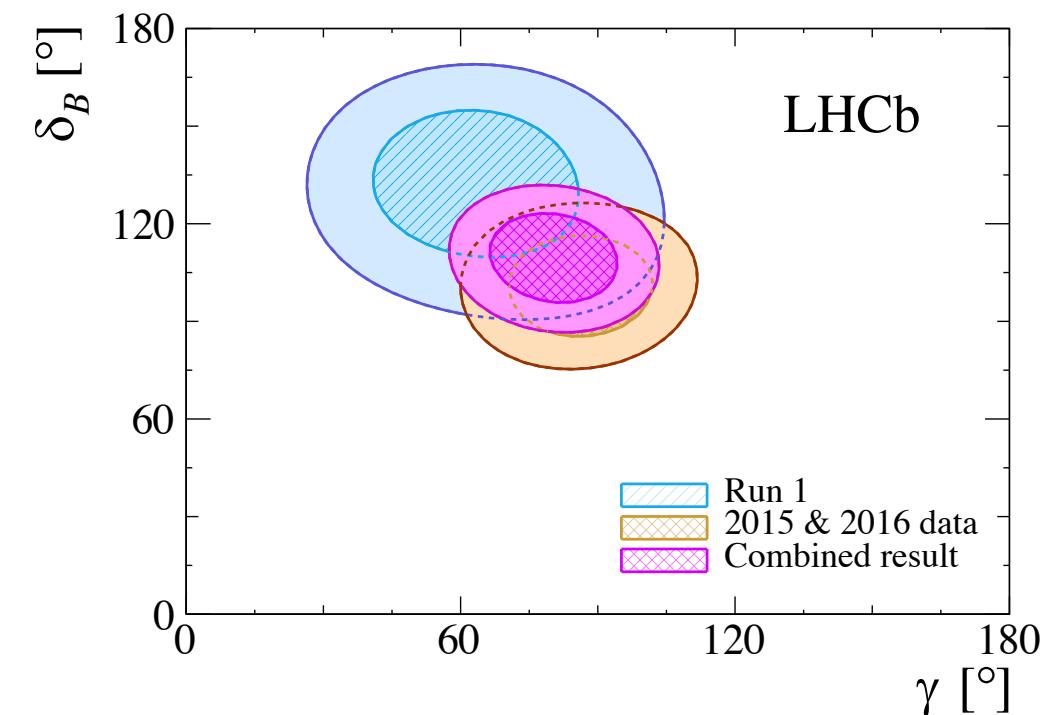
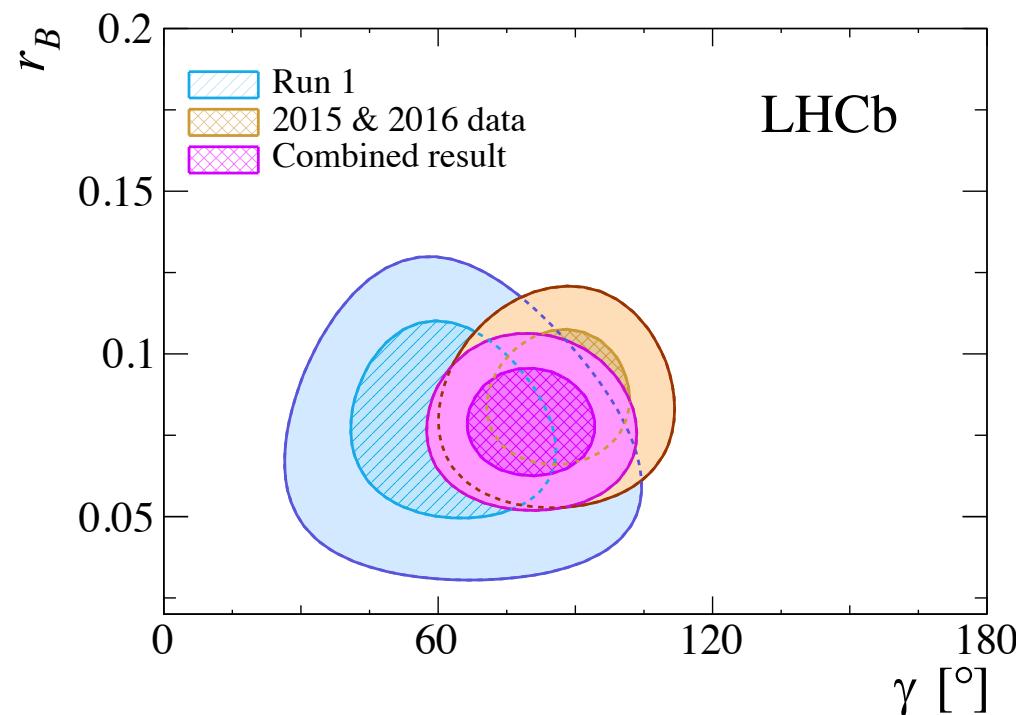
- Strong phase difference,  $\Delta\delta_D = \delta_{\bar{D}} - \delta_D$  varies across the Dalitz plane:
- $s_{\pm} = m_{\pm}^2 = m^2(K_s^0, h^{\pm})$
- Binning schemes chosen to optimize statistical sensitivity to  $\gamma$ :



- An invariant mass fit to the full Dalitz plane ( $K_s^0 h^+ h^-$ ):



- Likelihood contours for combination with Run 1 analysis [JHEP 10 (2014) 97]:



- $B^\pm \rightarrow [K_s^0 h^+ h^-]_D K^-$

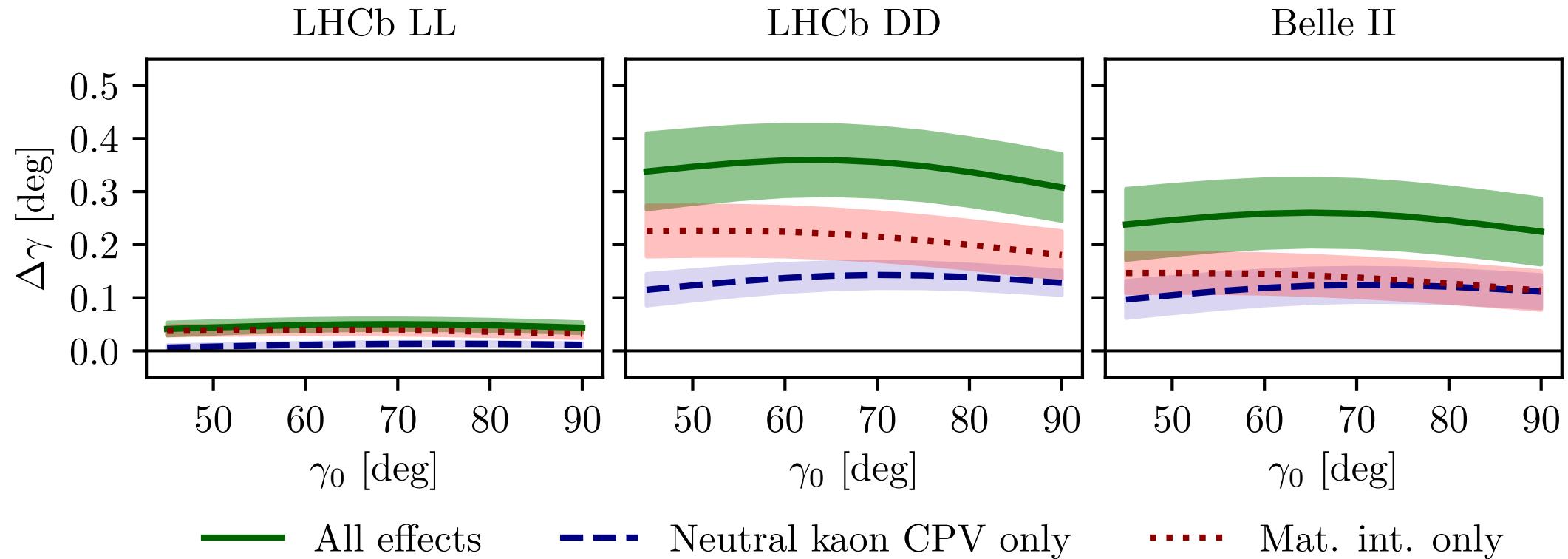


Neutral kaon *CPV* ( $\propto \epsilon \simeq 10^{-3}$ )  $\rightarrow$  source of bias?

- Grossman & Savastio estimated impact on  $\gamma$  measurements in global asymmetry measurements [arXiv:1311.3575]
  - $\frac{\Delta\gamma}{\gamma} = \mathcal{O}\left(\frac{|\epsilon|}{r_B}\right) \simeq 4^\circ$
- Further studies have been performed by Bjørn & Malde
  - For Dalitz-plot-based approach of  $B^\pm \rightarrow [K_s^0 \pi^+ \pi^-]_D K^-$  decays
  - Including kaon material interaction ( $\propto r_\chi = 10^{-3}$ )
  - Bias is estimated for LHCb and Belle II

# Potential biases on $\gamma$ [arXiv:1904.01129]

LHCb  
FCC-~~p~~



# $B^0 \rightarrow DK^{*0}$ 4-body Modes

- $\kappa_D^{K3\pi} = 0.43^{+0.17}_{-0.13}$
- $r_D^{K3\pi} = 0.0549 \pm 0.006$
- $\delta_D^{K3\pi} = (128^{+28}_{-17})^\circ$



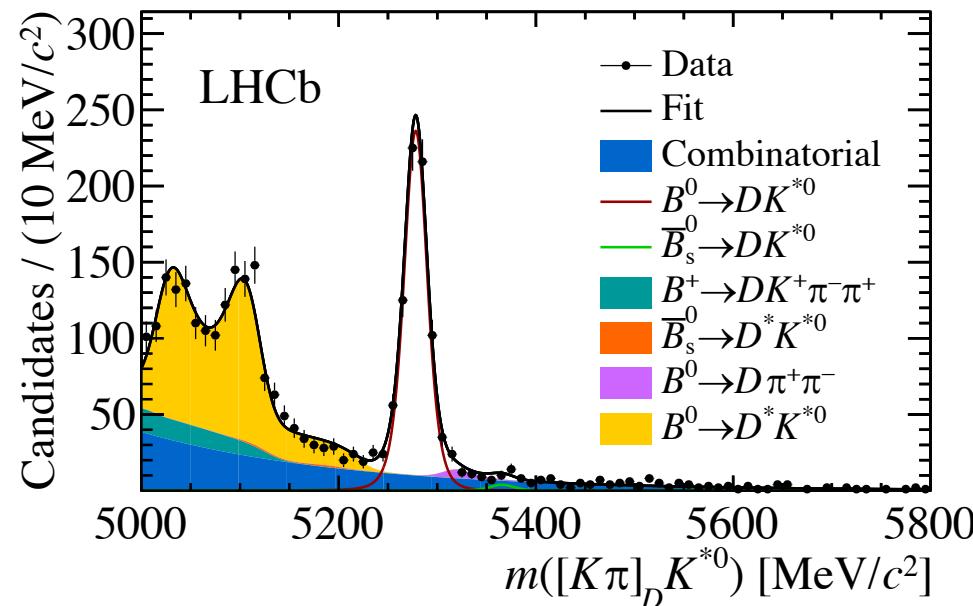
Measured using studies of charm mixing and quantum correlated  $D$ -meson decays [PLB 757 (2016) 520]

- $F_+^{4\pi} = 0.769 \pm 0.023$

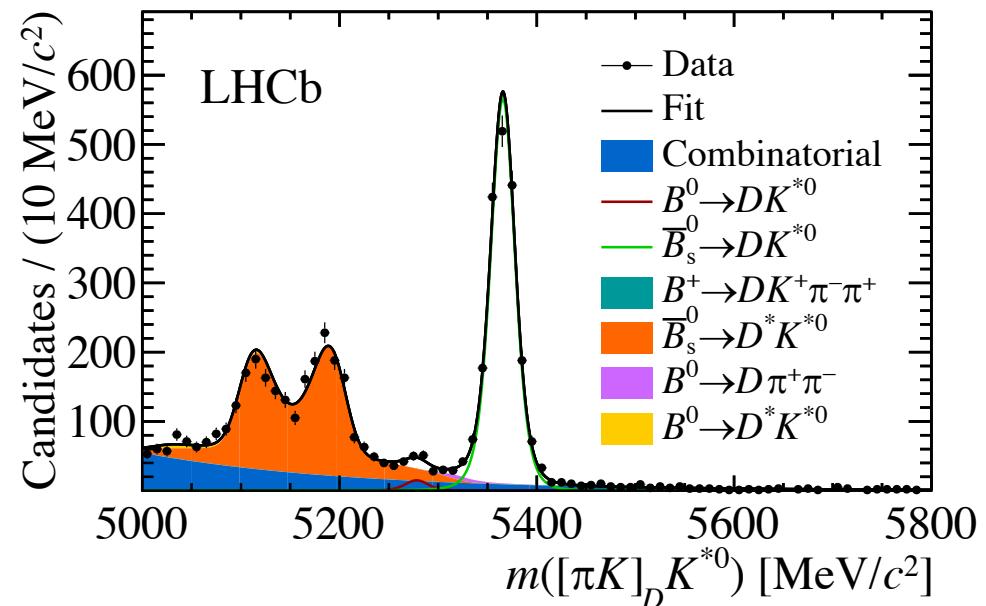


Measured using quantum correlated  $D$ -meson decays  
[JHEP 01 (2018) 144]

Favoured  $B^0 \rightarrow [K^+ \pi^-]_D K^{*0}$



Suppressed  $B^0 \rightarrow [\pi^+ K^-]_D K^{*0}$



Fit components:

1. Signal  $B^0 \rightarrow DK^{*0}$
2.  $\bar{B}_s^0 \rightarrow DK^{*0}$
3. Combinatorial background

4.  $B^0 \rightarrow D^* K^{*0}$  (part reco)
5.  $\bar{B}_s^0 \rightarrow D^* K^{*0}$  (part reco)
6.  $B^+ \rightarrow DK^+ \pi^- \pi^+$  (part reco)
7.  $B^0 \rightarrow D \pi^+ \pi^-$  (mis-ID)

# Observables

- $A_{CP} = \frac{2\kappa r_B^{DK^{*0}} \sin \delta_B^{DK^{*0}} \sin \gamma}{R_{CP}}$
- $R_{CP} = 1 + (r_B^{DK^{*0}})^2 + 2\kappa r_B^{DK^{*0}} \cos \delta_B^{DK^{*0}} \cos \gamma$
- $A_{ADS} \simeq \frac{R_- - R_+}{R_- + R_+} = \frac{2\kappa r_B^{DK^{*0}} r_D^{K\pi} \sin(\delta_B^{DK^{*0}} + \delta_D^{K\pi}) \sin \gamma}{(r_B^{DK^{*0}})^2 + (r_D^{K\pi})^2 + 2\kappa r_B^{DK^{*0}} r_D^{K\pi} \cos(\delta_B^{DK^{*0}} + \delta_D^{K\pi}) \cos \gamma}$
- $R_{ADS} \simeq \frac{R_- + R_+}{2} = \frac{(r_B^{DK^{*0}})^2 + (r_D^{K\pi})^2 + 2\kappa r_B^{DK^{*0}} r_D^{K\pi} \cos(\delta_B^{DK^{*0}} + \delta_D^{K\pi}) \cos \gamma}{1 + (r_B^{DK^{*0}} + r_D^{K\pi})^2 + 2\kappa r_B^{DK^{*0}} r_D^{K\pi} \cos(\delta_B^{DK^{*0}} + \delta_D^{K\pi}) \cos \gamma}$

# Summary of Results [LHCb-PAPER-2019-021]

$$A_{CP}^{\pi\pi} = -0.18 \pm 0.14 \pm 0.01$$

$$R_{CP}^{\pi\pi} = 1.32 \pm 0.19 \pm 0.03$$

$$A_{CP}^{KK} = -0.05 \pm 0.10 \pm 0.01$$

$$R_{CP}^{KK} = 0.92 \pm 0.10 \pm 0.02$$

$$A_{CP}^{4\pi} = -0.03 \pm 0.15 \pm 0.01$$

$$R_{CP}^{4\pi} = 1.01 \pm 0.16 \pm 0.04$$

$$A_{ADS}^{\pi K} = 0.19 \pm 0.19 \pm 0.01$$

$$R_{ADS}^{\pi K} = 0.080 \pm 0.015 \pm 0.002$$

$$A_{ADS}^{\pi K \pi\pi} = -0.01 \pm 0.24 \pm 0.01$$

$$R_{ADS}^{\pi K \pi\pi} = 0.073 \pm 0.018 \pm 0.002$$

The dominant systematics are:

- $A_{CP}$ : Production and detection asymmetry corrections
- $R_{CP}$ : Branching fraction normalisation, selection efficiency correction
- $A_{ADS}$  &  $R_{ADS}$ : Fixed parameters in invariant mass fit