Precision measurements of the Cabibbo-Kobayashi-Maskawa angle γ at LHCb

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CERN seminar

10 October 2017

- It's that time of year again - many congratulations to all of those involved on LIGO and VIRGO
- Spare a thought for the C in CKM, who didn't win the Nobel prize in 2008 along with K & M
- Today's talk is dedicated to Cabibbo, and to everyone else who hasn't won a Nobel prize!

"I've already got the prize. The prize is the pleasure of finding the thing out..." - R. P. Feynman

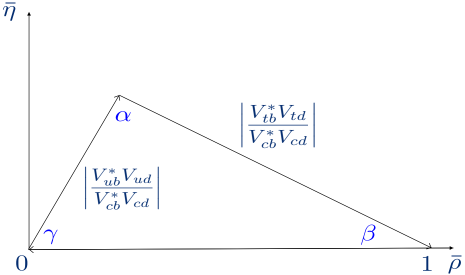
The CKM matrix and the weak force

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

- Connects u- and d- type quarks via the weak force
- Each element related to a transition probability, $|V_{ij}|^2$
- 3×3 unitary matrix is parameterised by three rotation angles and one complex phase
  - Phase changes sign under the CP operator
  - In SM, this phase is the single source of quark sector CP violation

The Unitarity Triangle

- **Unitary matrix:** $\sum_j |V_{ij}|^2 = \sum_i |V_{ij}|^2 = 1$
- Any dot product of two columns is zero
- Take first and third columns:
  - $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
  - Equation of a triangle in the complex plane!
  - **The Unitarity Triangle - 3 angles of similar size**



Is The Unitarity Triangle actually a triangle?

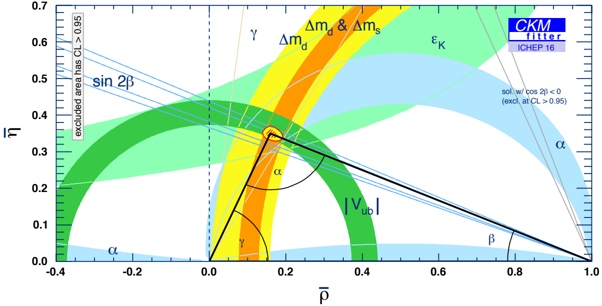
- The Unitarity Triangle is built **assuming unitarity** i.e. no other flavour changing couplings apart from $W^{\pm}$
  - New Physics could violate unitarity

- Need to over-constrain all sides and angles with independent measurements
  - See if the various constraints agree
  - **Is unitarity valid?**

Is The Unitarity Triangle actually a triangle?

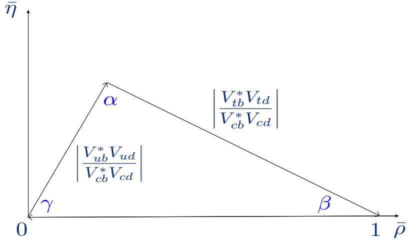
$$\alpha = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \quad \beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \quad \gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

- Global CKM fits performed using information from many measurements
  - Measuring β and γ is an important part of this process
  - Let's explore β first as an example

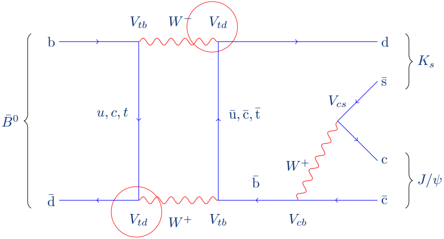


CKM angle β

$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$



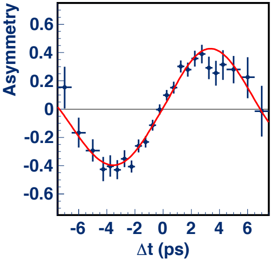
- Contains couplings to the top quark
  - Interested in looking at V_{tb} compared to V_{td}
  - How can we access this?
- Via a handy box diagram!
  - This diagram is responsible for $B^0/\bar{B}^0$ oscillations
  - Can measure β, knowing K^0 CP violation

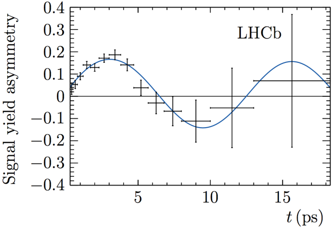


CKM angle β

- If $V_{td} \neq V_{td}^*$:
  - $\Gamma(B^0 \to f_{CP}) \neq \Gamma(\bar{B}^0 \to f_{CP})$
  - Example: $f_{CP} = J/\psi K_s^0$
  - Shows up as CP violation in mixing
- Well studied by the B factories and LHCb - time dependent CP violation
  - Amplitude of oscillation is $\sin(2\beta)$ (diluted by tagging)

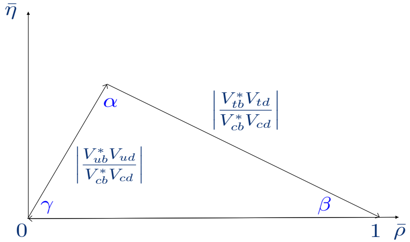
[arXiv:0902.1708, arXiv:1201.4643, LHCb-PAPER-2015-004, LHCb-PAPER-2017-029]





What about γ?

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



- No top quark in the definition of γ
  - This time, we **don't need a box diagram**
  - Can measure purely with **tree level decays**
- Look for direct CP violation by comparing V_{ub} and V_{cb}
  - How do we do that?

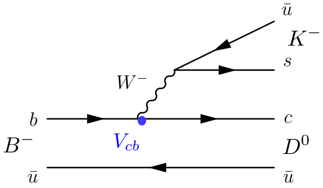
Measuring γ with $B^- \to DK^-$ decays

- Ideal laboratory is $B^- \to DK^-$
    - $D = D^0$ or $\bar{D}^0$ decaying to the same final state

- There are **two competing diagrams**
    - Each of them has an amplitude $\mathcal{A}$

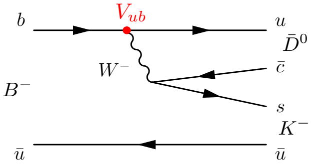
- One diagram is suppressed by a factor r_B

- The diagrams have a relative phase θ



Favoured b → c

$$\mathcal{A} \sim 1$$



Suppressed b → u

$$\mathcal{A} \sim r_B e^{i\theta}$$

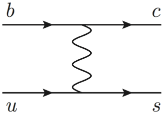
Measuring γ with $B^- \to DK^-$ decays

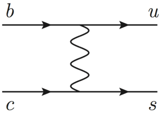
- θ contains two parts
  - δ_B which covers QCD - **strong phase**
  - Other part is the **weak phase** - let's suggestively call it γ

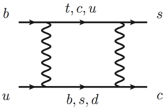
- Weak phase γ in $B^- \to DK^-$ decays is the same as the CKM angle γ within 10^{-4}

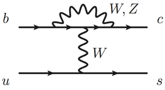
- $B^- \to DK^-$ decays are a theoretically super-clean probe of γ
  - Non-tree SM diagrams contribute $\leq \mathcal{O}(10^{-7})$

[arXiv:1412.1446, arXiv:1308.5663]









From amplitudes to decay rates - the GLW method

- Two possible $B^- \to DK^-$ paths: add 'em up then square!

$$\Gamma \propto |1 + r_B e^{i\theta}|^2 = 1 + r_B^2 + 2 r_B \cos(\theta)$$

- γ is the CP violating phase ⇒ changes sign under charge conjugation
  - **Different decay rates for B^+ and B^-**
  - This is the **GLW method**

$$\Gamma(B^- \to DK^-) \propto 1 \; + \; r_B^2 \; + \; 2\, r_B \; \cos(\delta_B \, -\gamma)$$

$$\Gamma(B^+ \to DK^+) \propto 1 \; + \; r_B^2 \; + \; 2\, r_B \; \cos(\delta_B \, +\gamma)$$

The ADS method

- **ADS method:** choose a D decay with amplitude ratio (r_D) and phase (δ_D)
  - Pick one where $r_D \sim r_B$
  - For $B^- \to DK^-$, $r_B \sim 0.1$
  - Nice choice is $D \to K\pi$, $r_D \sim 0.06$
- **Bigger interference effect $\Rightarrow$ larger B^+/B^- differences**

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

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

The ADS method

- Measure rates of B^+ and B^- decays separately and build asymmetries

$$A = \frac{\Gamma(B^- \to [\pi^- K^+]_D K^-) \; - \; \Gamma(B^+ \to [\pi^+ K^-]_D K^+)}{\Gamma(B^- \to [\pi^- K^+]_D K^-) \; + \; \Gamma(B^+ \to [\pi^+ K^-]_D K^+)}$$

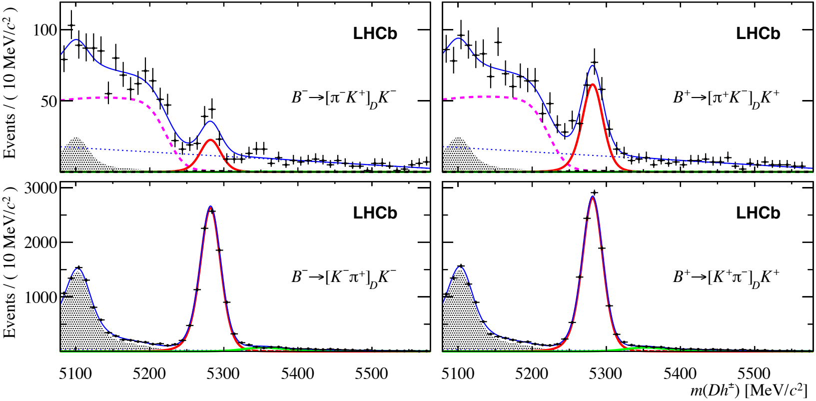
- Also interested in rate of suppressed decays compared to their doubly-favoured counterparts, $B^\pm \to [K^\pm \pi^\mp]_D K^\pm$

$$R = \frac{\Gamma(B^- \to [\pi^- K^+]_D K^-) \; + \; \Gamma(B^+ \to [\pi^+ K^-]_D K^+)}{\Gamma(B^- \to [\pi^+ K^-]_D K^-) \; + \; \Gamma(B^+ \to [\pi^- K^+]_D K^+)}$$

- Both A and R contain information about γ

$B^{\pm} \to [\pi^{\pm}K^{\mp}]_D K^{\pm}$ **(Run 1: 3 fb $^{-1}$)** [LHCb-PAPER-2016-003]

- $B^{\pm} \to DK^{\pm}$ CP violation significance - 8σ
- First observation of CP violation in a single $B^{\pm} \to Dh^{\pm}$ decay $(h = \pi, K)$

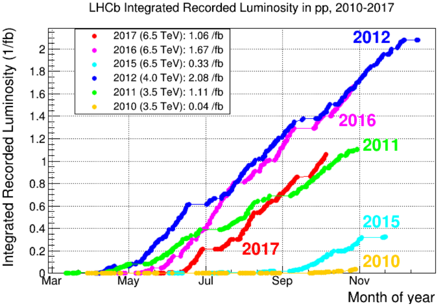


Constraining γ across many final states

- No single method can tell us everything e.g. ADS doesn't give a single γ solution
- Real power comes from **combining lots of D modes**
- LHCb made great strides with $B^{\pm} \to DK^{\pm}$ on several fronts in Run 1:
  - GLW: $D \to KK,\ \pi\pi,\ \pi\pi\pi\pi,\ KK\pi^0,\ \pi\pi\pi^0$
  - ADS: $D \to \pi K,\ \pi K\pi\pi,\ \pi K\pi^0$
  - GGSZ: $D \to K_s^0\pi\pi,\ K_s^0 KK$
  - GLS: $D \to K_s^0 K\pi$
- **Is there anything else out there?**

More data! The Run 2 era is well underway

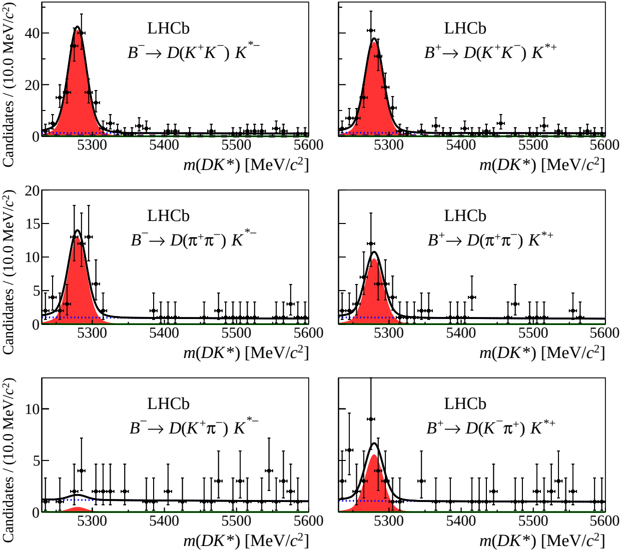
- LHCb collected 2 fb^{-1} in 2015-2016
  - Just crossed 1 fb^{-1} in 2017
  - Luminosity levelling to achieve desired performance
- Increased statistics not just coming from extra fb^{-1}:
  - Improved software HLT performance
  - Increased B production cross-section at $\sqrt{s} = 13$ TeV



New modes! $B^{\pm} \to DK^{*\pm}$ **(5 fb^{-1})** **[LHCb-PAPER-2017-030]**

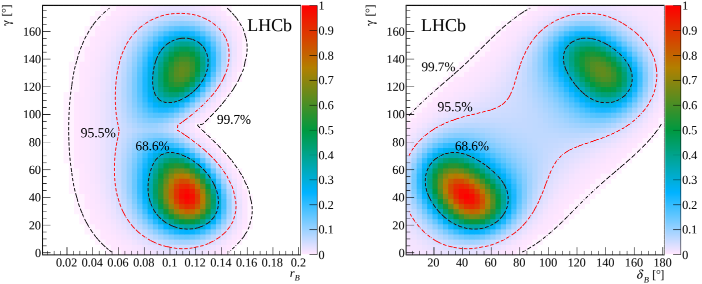
- Add a star to the K - select $K^{*\pm} \to K_s^0 \pi^{\pm}$
- Challenging final state
    - Two extra tracks compared to $B^{\pm} \to DK^{\pm}, D \to hh$
    - $K_s^0 \to \pi\pi$: efficiency $\sim 10\%$
    - Select within $K^*(892)$ window
- **Interesting feature** - no background from misidentified $D\pi$-type decays
    - Measure only $B^{\pm} \to DK^{*\pm}$ across various 2- and 4-body D final states
    - Follow the same formalism as $B^{\pm} \to DK^{\pm}$ - **rates and asymmetries**

$B^{\pm} \to DK^{*\pm}$ (5 fb^{-1}) [LHCb-PAPER-2017-030]



$B^{\pm} \to DK^{*\pm}$ (5 fb^{-1}) [LHCb-PAPER-2017-030]

- 12 CP observables used to determine the fundamental parameters $r_B^{DK^*}$, $\delta_B^{DK^*}$, γ
- This mode will become valuable for constraining γ in future, as more data and D modes are added



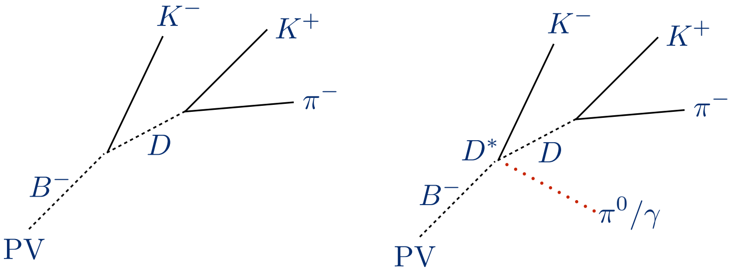
$B^{\pm} \to D^{*0}K^{\pm}$ with $D \to KK, \pi\pi$ (GLW)

- Theoretically similar to $B^{\pm} \to DK^{\pm}$, with interesting extra features
  - Two γ-sensitive sub-decays: $D^{*0} \to D\pi^{0}$ and $D^{*0} \to D\gamma$
  - π^{0} and γ variants have 180° δ_D difference - opposite CP

    [Phys. Rev. D 70, 091503(R)]
  - Gives us access to a CP-odd mode at LHCb
- Measure both $B^{\pm} \to (D^{*0} \to D\pi^{0})K^{\pm}$ and $B^{\pm} \to (D^{*0} \to D\gamma)K^{\pm}$ decays to determine $r_B^{D^*K}$, $\delta_B^{D^*K}$, γ
- Same formalism as $B^{\pm} \to DK^{\pm}$ - measure rates and asymmetries

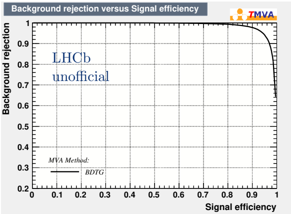
Experimental challenge

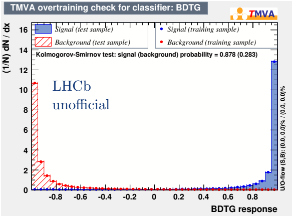
- Soft neutral reconstruction is difficult at LHCb, and has limited efficiency [LHCb-DP-2014-002]
  - $\epsilon(\pi^0) \sim 4\%$
  - $\epsilon(\gamma) \sim 20\%$
- Expect lower statistics than in $B^\pm \to DK^\pm$ case
  - Is there anything we can do to get around this limitation?



Partial reconstruction approach

- **Don't consider the soft neutral at all!**
    - Partially reconstruct and select identically to $B^{\pm} \to DK^{\pm}$
    - No statistics loss due to $\epsilon(\pi^0)$ or $\epsilon(\gamma)$
- BDT trained on combinatorial background in data and $B^{\pm} \to DK^{\pm}$ signal MC
    - Efficiencies very similar for $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D^{*0}K^{\pm}$
- All signal modes end up in the same event sample
    - Differentiate between them based on their $m(DK)$

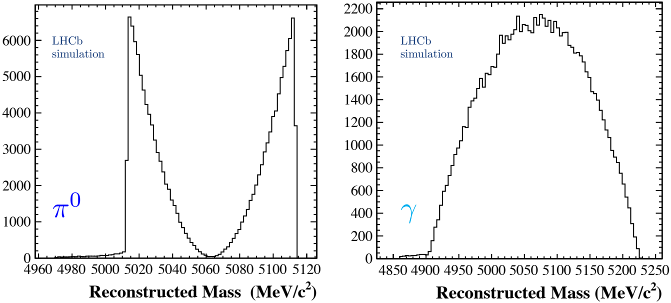




The $m(DK)$ distribution

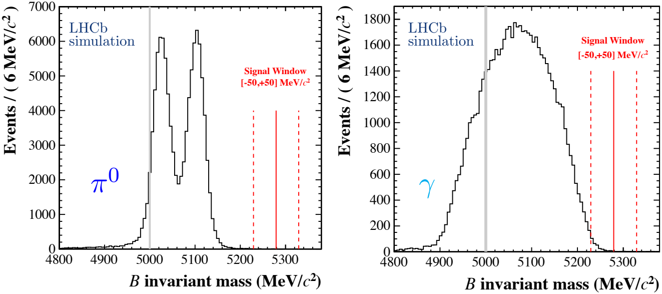
- Fit variable is $m(DK)$ $\Rightarrow$ uniquely related to angular properties of D^{*0} decay daughters
  - Different mass and spin of π^0 and γ - different $m(DK)$
  - Parabolic distributions:
    double peak for $B^{\pm} \to (D^{*0} \to D\pi^0)K^{\pm}$
    single wide peak for $B^{\pm} \to (D^{*0} \to D\gamma)K^{\pm}$

Perfect resolution



Detector resolution effects

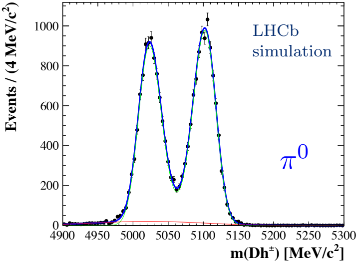
- Detector isn't perfect - convolve parabolas with a double Gaussian resolution function
  - Modelled on the $B^{\pm} \to DK^{\pm}$ peak resolution
- Distinctive distributions for $D^{*0} \to D\pi^0$ and $D^{*0} \to D\gamma$
  - Both sit lower in mass than the $B^{\pm} \to DK^{\pm}$ peak (red region)
  - In previous 3 fb^{-1} $B^{\pm} \to DK^{\pm}$ analysis, these decays were background > 5000 MeV$/c^2$

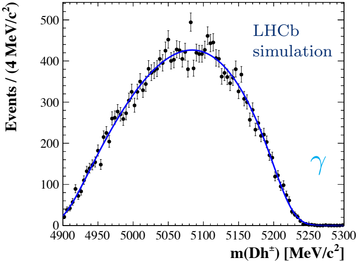


Fits to $B^{\pm} \to D^{*0} K^{\pm}$ simulation

- Custom `RooFit` PDFs authored to model the distributions
  - Parabolic function convolved with a double Gaussian
  - Shape parameters determined from fits to selected signal MC

- **Mission:** measure $B^{\pm} \to D K^{\pm}$, $B^{\pm} \to (D^{*0} \to D\pi^0) K^{\pm}$ and $B^{\pm} \to (D^{*0} \to D\gamma) K^{\pm}$ in a single fit after common $D K^{\pm}$ candidate selection





Life is never that simple...

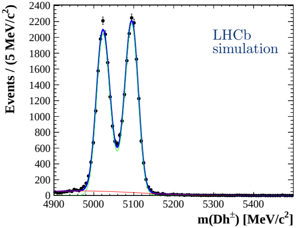
- In reality, there are more B decays than our $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D^{*0}K^{\pm}$ friends!
  - Several other partially reconstructed decays sit in the same invariant mass region as the signals

- Extensive simulation studies performed to understand the $m(DK)$ distributions of each background

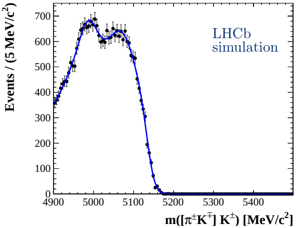
Fully reco. signal	Partially reco. signal	Partially reco. bkg.
$B^{\pm} \to DK^{\pm}$	$B^{\pm} \to (D^{*0} \to D\pi^{0})K^{\pm}$	$B^{0} \to (D^{*-} \to D\pi^{-})K^{+}$
	$B^{\pm} \to (D^{*0} \to D\gamma)K^{\pm}$	$B^{\pm} \to DK^{\pm}\pi^{0}$
		$\bar{B}^{0}_{s} \to DK^{\pm}\pi^{\mp}$
		$B \to (D^{*} \to DX)K^{\pm}Y$

Background shapes

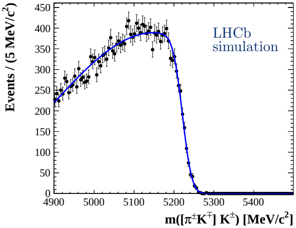
$B^0 \to (D^{*-} \to D\pi^-)K^+$



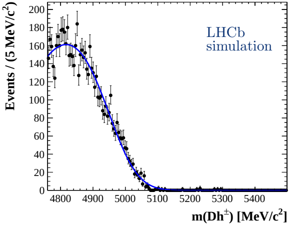
$B^\pm \to DK^\pm\pi^0$



$\bar{B}_s^0 \to DK^\pm\pi^\mp$

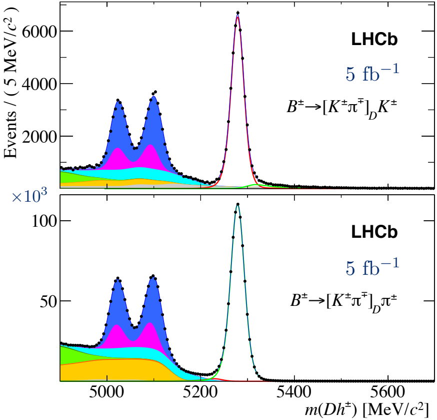


$B \to (D^* \to DX)K^\pm Y$



$m(Dh^{\pm})$ **fit,** $D \to K^{\pm}\pi^{\mp}$ **(5 fb^{-1})** **[LHCb-PAPER-2017-021]**

- Favoured mode data helps us understand the signal and background contributions



— $B^{\pm} \to DK^{\pm}$
— $B^{\pm} \to D\pi^{\pm}$

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

$B^0 \to (D^{*-} \to D\pi^-)h^+$
$B^{\pm} \to Dh^{\pm}\pi^0$
$B \to (D^* \to DX)h^{\pm}Y$
Particle misidentification

Simultaneous fit to $m(DK)$ and $m(D\pi)$ - split based upon particle ID requirement

Crosscheck results (5 fb^{-1}) [LHCb-PAPER-2017-021]

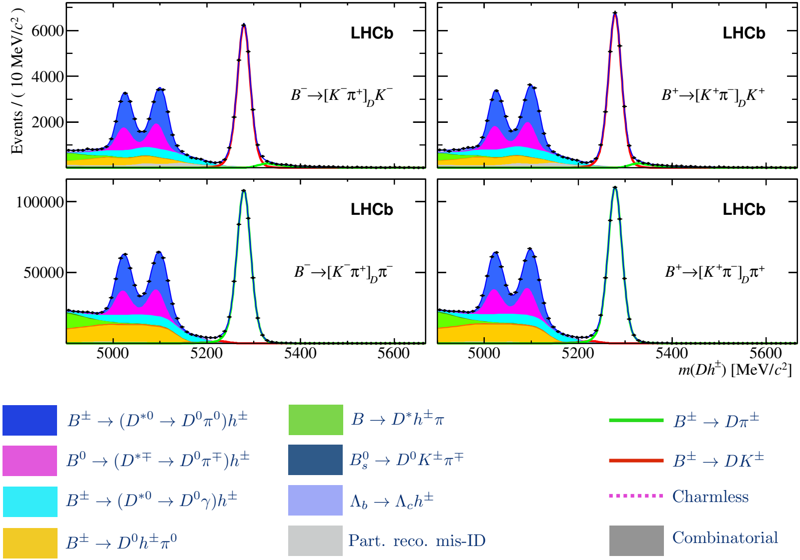
- Fit measures several branching fractions
  - All agree with current world averages ($< 1.3\sigma$)
  - Validation of the partial reconstruction method

Observable	This result	World average
$\frac{\mathcal{B}(B^\pm \to D^{*0} K^\pm)}{\mathcal{B}(B^\pm \to D^{*0} \pi^\pm)}$	$(7.93 \pm 0.57)\%$	$(8.11 \pm 0.77)\%$
$\mathcal{B}(B^\pm \to D^{*0} \pi^\pm)$	$(4.66 \pm 0.27) \times 10^{-3}$	$(5.18 \pm 0.26) \times 10^{-3}$
$\mathcal{B}(D^{*0} \to D^0 \pi^0)$	0.636 ± 0.015	0.647 ± 0.009

Making a γ-sensitive measurement

- What we really want to measure is CP violation!
  - γ causes a difference in B^+ and B^- decay rates
- Split data by B charge and measure **charge asymmetries**
  - Correct all raw asymmetries for $B^\pm$ production asymmetry and additional detection asymmetry effects
- Also interested in **relative rates**
  - Rate of $B^\pm \to D^{*0}K^\pm$ compared to $B^\pm \to D^{*0}\pi^\pm$
  - Rates of CP mode decays $(D \to KK, \pi\pi)$ compared to favoured mode $(D \to K\pi)$

$m(Dh^{\pm})$ **fit,** $D \to K^{\pm}\pi^{\mp}$ **(5 fb^{-1})** [LHCb-PAPER-2017-021]

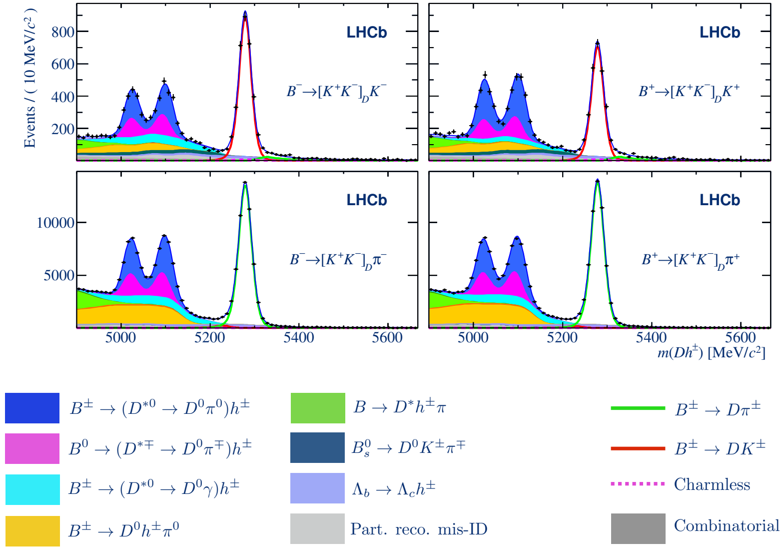


CP **observables** $(CP = KK, \pi\pi)$

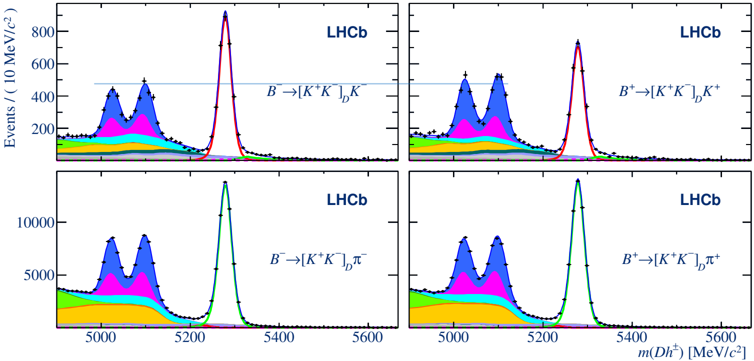
- Measure π^0 and γ asymmetries in favoured and CP modes
  - 4 observables - $A^{\pi^0}_{K\pi}$, $A^{\gamma}_{K\pi}$, $A^{\pi^0}_{CP}$, A^{γ}_{CP}
- Measure rates of $B^\pm \to D^{*0}([CP]_D\pi^0)K^\pm$ and $B^\pm \to D^{*0}([CP]_D\gamma)K^\pm$ compared to favoured mode counterparts
  - 2 observables - $R^{\pi^0}_{CP}$, R^{γ}_{CP}
- Strong phase difference of 180° between π^0 and γ sub-decays: effectively measuring $R^\pm_{CP}$ and $A^\pm_{CP}$

$$
\begin{aligned}
R^{\pi^0}_{CP} &\equiv R^{+}_{CP} = 1 \;+\; r_B^2 + 2\, r_B \cos(\delta_B) \cos(\gamma) \\
R^{\gamma}_{CP} &\equiv R^{-}_{CP} = 1 \;+\; r_B^2 - 2\, r_B \cos(\delta_B) \cos(\gamma) \\
A^{\pi^0}_{CP} &\equiv A^{+}_{CP} = \; + 2\, r_B \sin(\delta_B) \sin(\gamma) / R^{+}_{CP} \\
A^{\gamma}_{CP} &\equiv A^{-}_{CP} = \; - 2\, r_B \sin(\delta_B) \sin(\gamma) / R^{-}_{CP}
\end{aligned}
$$

$m(Dh^{\pm})$ **fit,** $D \to K^+K^-$ **(5 fb^{-1})** **[LHCb-PAPER-2017-021]**

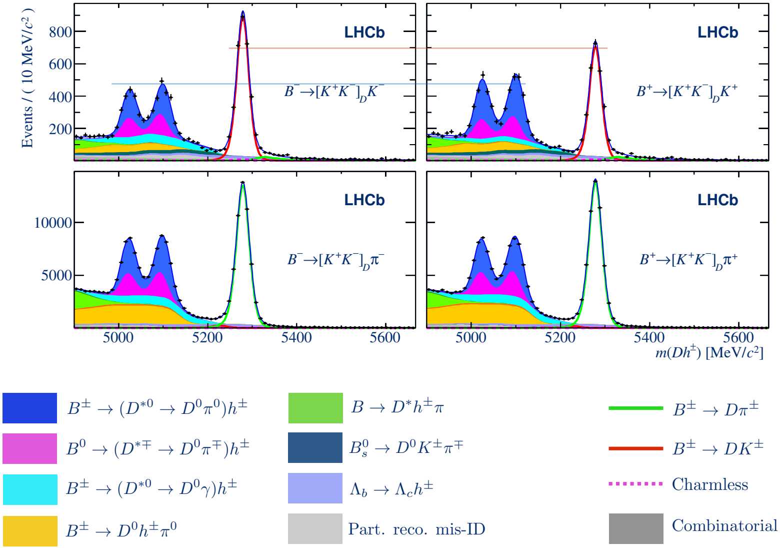


$m(Dh^{\pm})$ fit, $D \to K^+K^-$ (5 fb^{-1}) [LHCb-PAPER-2017-021]

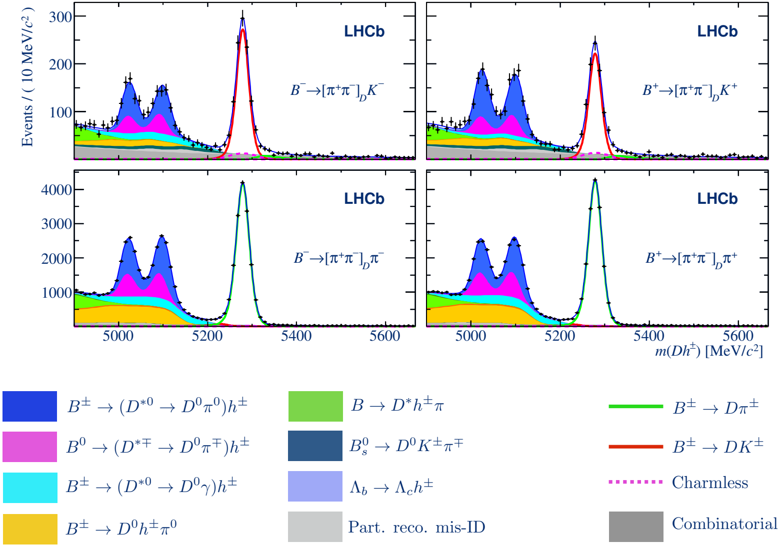


- 🟦 $B^{\pm} \to (D^{*0} \to D^0\pi^0)h^{\pm}$
- 🟪 $B^0 \to (D^{*\mp} \to D^0\pi^{\mp})h^{\pm}$
- 🟦 $B^{\pm} \to (D^{*0} \to D^0\gamma)h^{\pm}$
- 🟨 $B^{\pm} \to D^0h^{\pm}\pi^0$
- 🟩 $B \to D^*h^{\pm}\pi$
- 🟦 $B_s^0 \to D^0K^{\pm}\pi^{\mp}$
- 🟪 $\Lambda_b \to \Lambda_c h^{\pm}$
- ⬜ Part. reco. mis-ID
- — $B^{\pm} \to D\pi^{\pm}$
- — $B^{\pm} \to DK^{\pm}$
- ┈ Charmless
- ⬛ Combinatorial

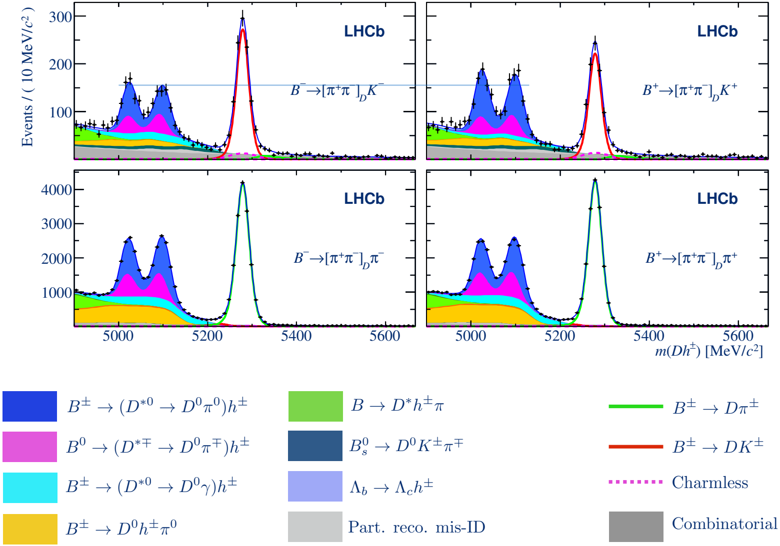
$m(Dh^{\pm})$ fit, $D \to K^+K^-$ (5 fb^{-1}) [LHCb-PAPER-2017-021]



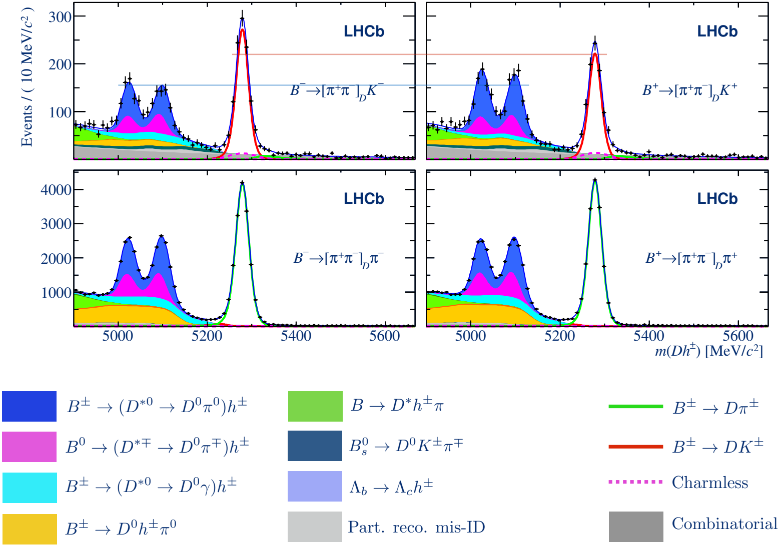
$m(Dh^{\pm})$ **fit,** $D \to \pi^+\pi^-$ **(5 fb^{-1})** **[LHCb-PAPER-2017-021]**



$m(Dh^{\pm})$ **fit,** $D \to \pi^+\pi^-$ **(5 fb^{-1})** [LHCb-PAPER-2017-021]



$m(Dh^{\pm})$ fit, $D \to \pi^+\pi^-$ (5 fb^{-1}) [LHCb-PAPER-2017-021]



CP **observable results (5 fb^{-1})** [LHCb-PAPER-2017-021]

- $B^{\pm} \rightarrow D^{*0} h^{\pm}$ modes measured for the first time at LHCb and using a brand new technique!
    - Currently **GLW** modes are included - **ADS** under investigation
    - Fully reconstructed $B^{\pm} \rightarrow D^{0} h^{\pm}$ results are measured with the same fit

$B^{\pm} \rightarrow D^{*0} K^{\pm}$ results [LHCb-PAPER-2017-021]

$$
\begin{aligned}
A_{K}^{K\pi,\gamma} &= +0.001 \pm 0.021\ (\text{stat}) \pm 0.007\ (\text{syst}) \\
A_{K}^{K\pi,\pi^0} &= +0.006 \pm 0.012\ (\text{stat}) \pm 0.004\ (\text{syst}) \\
A_{K}^{CP,\gamma} &= +0.276 \pm 0.094\ (\text{stat}) \pm 0.047\ (\text{syst}) \\
A_{K}^{CP,\pi^0} &= -0.151 \pm 0.033\ (\text{stat}) \pm 0.011\ (\text{syst}) \\
R^{CP,\gamma} &= 0.902 \pm 0.087\ (\text{stat}) \pm 0.112\ (\text{syst}) \\
R^{CP,\pi^0} &= 1.138 \pm 0.029\ (\text{stat}) \pm 0.016\ (\text{syst})
\end{aligned}
$$

$B^{\pm} \to DK^{\pm}$ results (5 fb^{-1}) [LHCb-PAPER-2017-021]

- Important not to forget the $B^{\pm} \to DK^{\pm}$ GLW updates!
  - World-best measurements supersede those in 3 fb^{-1} analysis
  - Consistent picture between previous results and this update
  - Improved precision as expected from increased statistics
- Statistical precision approaching level of systematics in some observables - future work to drive down systematics

$B^{\pm} \to DK^{\pm}$ results [LHCb-PAPER-2017-021]

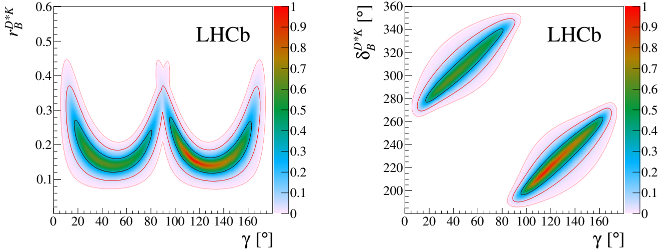
$$\begin{aligned}
A_K^{K\pi} &= -0.019 && \pm\, 0.005 \ \text{(stat)} && \pm\, 0.002 \ \text{(syst)} \\
A_K^{KK} &= +0.126 && \pm\, 0.014 \ \text{(stat)} && \pm\, 0.002 \ \text{(syst)} \\
A_K^{\pi\pi} &= +0.115 && \pm\, 0.025 \ \text{(stat)} && \pm\, 0.007 \ \text{(syst)} \\
R^{KK} &= 0.988 && \pm\, 0.015 \ \text{(stat)} && \pm\, 0.011 \ \text{(syst)} \\
R^{\pi\pi} &= 0.992 && \pm\, 0.027 \ \text{(stat)} && \pm\, 0.015 \ \text{(syst)}
\end{aligned}$$

Determining γ, $r_B^{D^*K}$ and $\delta_B^{D^*K}$ (5 fb^{-1}) [LHCb-PAPER-2017-021]

- 6 partially reconstructed GLW CP observables used to constrain the fundamentals
  - Determine profile likelihood contours for $r_B^{D^*K}$, $\delta_B^{D^*K}$ and γ

- $r_B^{D^*K}$ and $\delta_B^{D^*K}$ align with HFLAV GGSZ averages [arXiv:1612.07233]

- γ within 1σ of 2016 LHCb combination [LHCb-PAPER-2016-032]
  - Will further improve precision with addition of ADS modes



LHCb γ combination [LHCb-CONF-2017-004]

- Perform a statistical combination using observables from several LHCb analyses
    - Many hadronic parameters, but critically γ is common to all

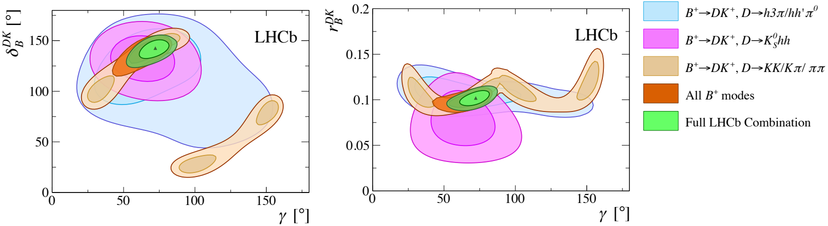
- Previous combination based entirely on Run 1 measurements [LHCb-PAPER-2016-032]

- An update has been performed, which includes the following:
    - $B^{\pm} \to DK^{\pm}$ GLW (5 fb^{-1}) 3 fb^{-1} → 5 fb^{-1}
    - $B^{\pm} \to D^{*0}K^{\pm}$ GLW (5 fb^{-1}) NEW
    - $B^{\pm} \to DK^{*\pm}$ ADS/GLW (5 fb^{-1}) NEW
    - Time-dependent $B_s^0 \to D_s^- K^+$ (3 fb^{-1}) 1 fb^{-1} → 3 fb^{-1}

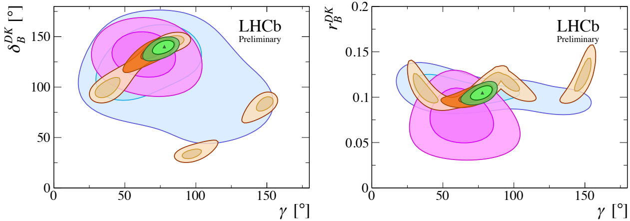
Updated combination results [LHCb-CONF-2017-004]

- Profile likelihood contours have shrunk after updating $B^\pm \to DK^\pm$ GLW and adding new information

OLD



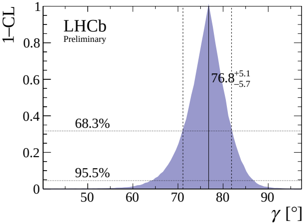
NEW

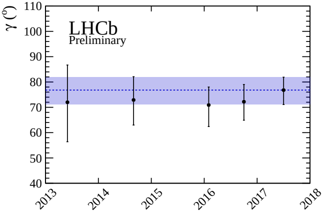


Measuring γ [LHCb-CONF-2017-004]

- New combination supersedes previous - most precise measurement of γ from a single experiment
- Uncertainty reduced by $\sim 1.7^{\circ}$ relative to previous combination

$$\gamma = (76.8^{+5.1}_{-5.7})^{\circ}$$





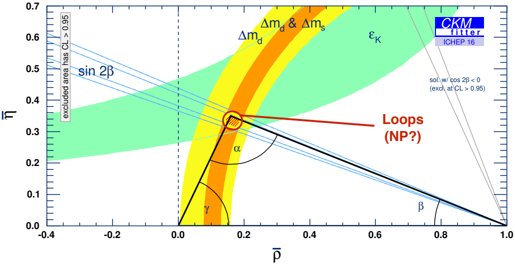
- Current HLFAV average (inc. BaBar and Belle): $\gamma = (76.2^{+4.7}_{-5.0})^{\circ}$

Outlook for γ at the end of Run 2

- LHCb has more to say on γ before Run 2 wraps up
- Several key measurements are underway, to name a few:
  - $B^{\pm} \to DK^{\pm}$ ADS UPDATE
  - $B^{\pm} \to DK^{\pm}$ GGSZ UPDATE
  - $B^{0} \to DK^{*0}$ ADS/GLW UPDATE
  - $B^{\pm} \to DK^{*\pm}$ GGSZ NEW
  - $B^{\pm} \to D^{*0}K^{\pm}$ ADS NEW
- Increased statistical power of Run 1 + Run 2 dataset will improve γ precision even further
  - Plenty to stay tuned for in the coming months!

What does it all mean?

- **Main idea:** compare γ measured in tree level decays with the value inferred from indirect global fits
- Loop processes, which give β, Δm_s & Δm_d, are NP sensitive
- Indirect γ precision $\sim 2^{\circ}$ - limited by QCD theory uncertainty in $B^0/\bar{B}^0$ [MILC]
  - We must strive to push tree level γ below this
  - **Does the Unitarity Triangle close?**



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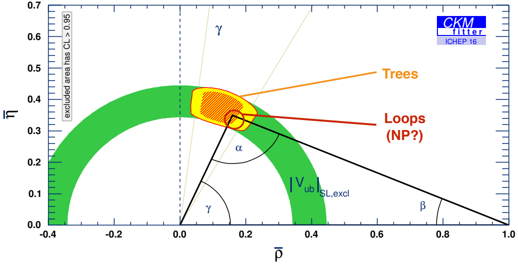

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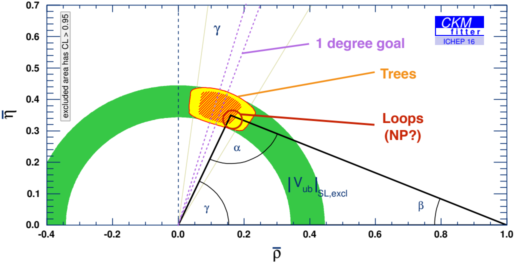


Comparison with world averages γ

Latest LHCb combination (direct) $\gamma = (76.8^{+5.1}_{-5.7})^\circ$

HFLAV 2017 world average (direct) $\gamma = (76.2^{+4.7}_{-5.0})^\circ$

CKMfitter 2016 world average (indirect) $\gamma = (65.3^{+1.0}_{-2.5})^\circ$

- Can't say anything definitive with current precision, but...
  - LHCb combination is $\sim 2\sigma$ higher than indirect world average
- Strongly motivates the continued pursuit of γ with trees
  - LHCb is in a strong position to improve γ precision further
  - Will high central value of tree level γ persist?

Another kid on the block

- Belle II due to start taking data next year
  - Aiming for 50 ab^{-1} by 2025
  - **Expecting $\sim 2^{\circ}$ single experiment precision on γ by the end of running** [I. Komarov, EPS 2017, Venice]

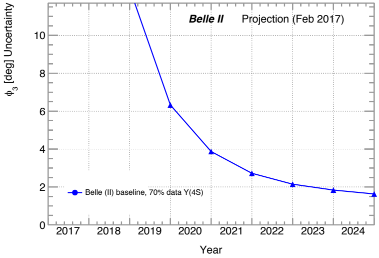
- Belle II has some advantages to help it compete with the power of LHCb statistics:
  - Higher sensitivity to neutrals (π^0, γ): CP-odd $D \to K_s^0 \pi^0$
  - Full event interpretation: semi-leptonic modes $(|V_{ub}|)$

- LHCb will retain the advantage of superior statistics in fully charged modes: $D \to KK, \pi\pi, \pi K$ e.t.c.

Belle II and LHCb upgrade γ sensitivity

- Assuming 10 fb^{-1} BESIII dataset to provide input on GGSZ c_i & s_i
  - Belle II expect 3° precision from $B^\pm \to DK^\pm$ GGSZ alone
  - Combining with all other D modes gives 1.6°

- LHCb will work hard to compete well into the upgrade era
  - 1.5° by end of Run 3 (~ 22 fb^{-1}, 2024) [arXiv:1709.10308]
  - $< 1^\circ$ by end of Run 4 (~ 50 fb^{-1}, 2029) [arXiv:1709.10308]
  - $\sim 0.4^\circ$ in Phase II upgrade (~ 300 fb^{-1}, 2034) [CERN-LHCC-2017-003]



Summary

- γ is a cornerstone of the Standard Model
    - Measured precisely using tree level B decays with negligible theoretical uncertainty

- LHCb keeps making world-best measurements of γ across a range of interesting modes
    - New techniques like $B^{\pm} \to D^{*0}K^{\pm}$ partial reconstruction help squeeze the most out of the data

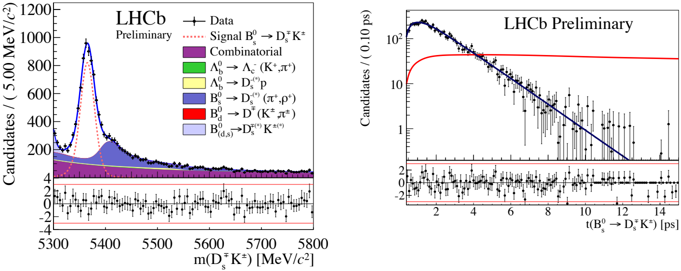
- Many updates to come as we approach the end of Run 2
    - Entering an exciting phase in CKM precision measurements!

Backup

Time-dependent $B_s^0 \to D_s^- K^+$ (3 fb^{-1}) [LHCb-CONF-2016-015]

- Time-dependent CP asymmetries - measure interference between mixing and decay
- γ sensitive measurement
    - Assume no NP and no penguin pollution
    - Plug in $\phi_s = -0.010 \pm 0.039$ rad [LHCb-PAPER-2014-059]

- Flavour-tagged analysis measures CP parameters from fit to decay time distribution

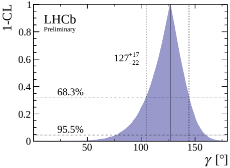


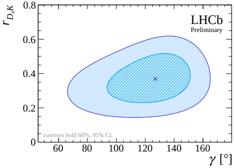
Time-dependent $B_s^0 \to D_s^- K^+$ (3 fb^{-1}) [LHCb-CONF-2016-015]

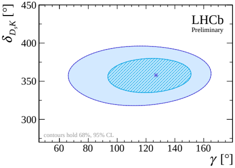
$$\gamma = (127^{+17}_{-22})^\circ$$

$$\delta_{D_s K} = (358^{+15}_{-16})^\circ$$

$$r_{D_s K} = 0.37^{+0.10}_{-0.09}$$







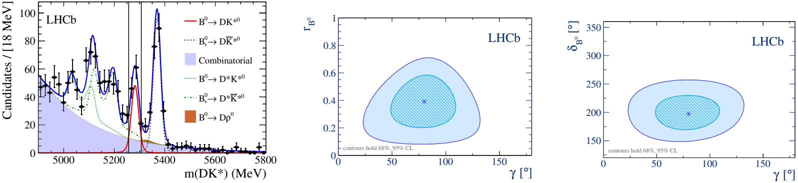
- Input: $\phi_s = -0.010 \pm 0.039$ rad [LHCb-PAPER-2014-059]
- 3.6σ evidence of CP violation in $B_s^0 \to D_s^\mp K^\pm$
- 2.2σ compatibility with LHCb time-integrated γ combination

GGSZ modes

- LHCb has a suite of completed 3 fb^{-1} GGSZ analyses:
  - $B^{\pm} \to D^0 K^{\pm}$ with $D^0 \to K_s^0 \pi^+ \pi^-, K_s^0 K^+ K^-$ [JHEP 10 (2014) 097]
  - MD $B^0 \to D^0 K^{*0}$ with $D^0 \to K_s^0 \pi^+ \pi^-$ [JHEP 08 (2016) 137]
  - MI $B^0 \to D^0 K^{*0}$ with $D^0 \to K_s^0 \pi^+ \pi^-, K_s^0 K^+ K^-$

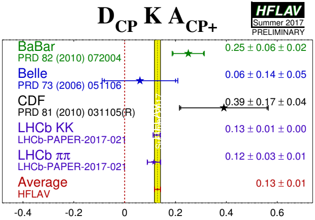
    [JHEP 06 (2016) 131]

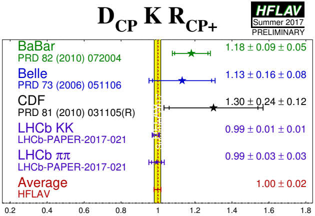
- $B^{\pm} \to D^0 K^{\pm}$ update is active using Run 1 + Run 2 data



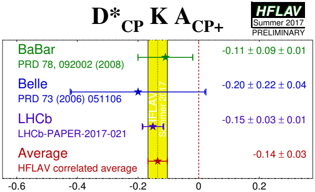
MD $B^0 \to D^0 K^{*0}$ with $D^0 \to K_s^0 \pi^+ \pi^-$ [JHEP 08 (2016) 137]

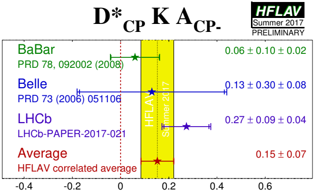
Summer 2017 HFLAV averages - $B^{\pm} \to D_{CP} K^{\pm}$

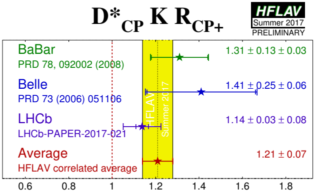


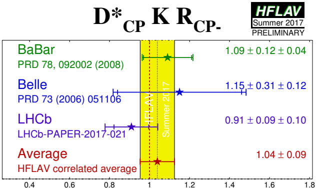


Summer 2017 HFLAV averages - $B^{\pm} \to D^{*}_{CP} K^{\pm}$


D^{*}_{CP} K A_{CP+}


D^{*}_{CP} K A_{CP-}


D^{*}_{CP} K R_{CP+}


D^{*}_{CP} K R_{CP-}

Systematic uncertainties

- Analysis measures **ratios of very similar final states** - large degree of systematic uncertainty cancellation

- Some residual effects remain:
  - Fixed shape parameters from MC fits
  - Use of MC to determine efficiencies
  - Fixed background yields using PDG branching fractions
  - Data-driven method to measure particle ID efficiencies

- All systematics relate to use of **fixed parameters** in the fit
  - Run the fit many times and vary their values ⇒ variation in observable results assigned as systematics