# Precision measurements of the Cabibbo-Kobayashi-Maskawa angle $\gamma$ 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

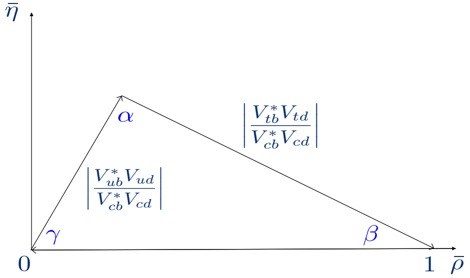
# The CKM matrix and the weak force

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

- Connects $u$- and $d$- type quarks via the weak force
- Each element related to a transition probability, $|V_{ij}|^2$
- $3 \times 3$ 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**



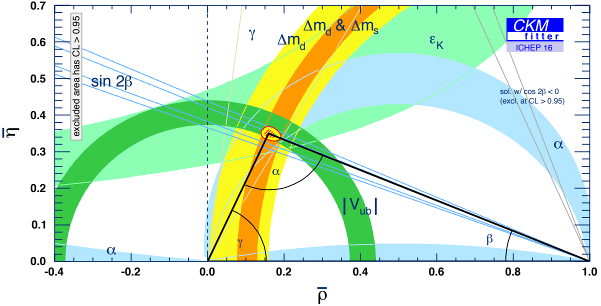
# Is The Unitarity Triangle actually a triangle?

- 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?

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

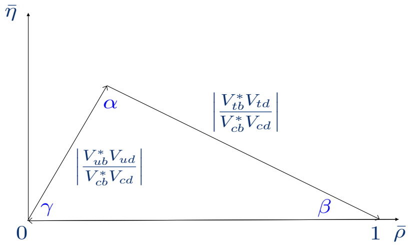
- Global CKM fits performed using information from many measurements
  - Measuring $\beta$ and $\gamma$ is an important part of this process
  - Let's explore $\beta$ first as an example

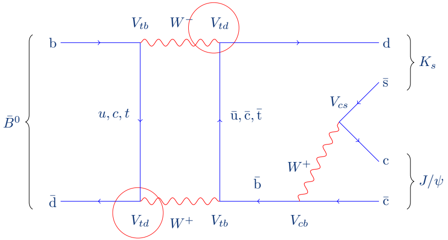


# CKM angle $\beta$

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

- 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 $\beta$, knowing $K^0$ $CP$ violation

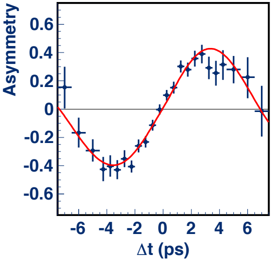


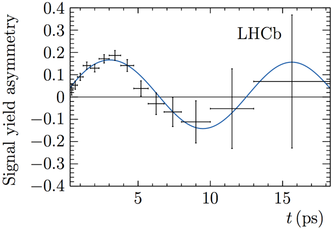



# CKM angle $\beta$

- 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)

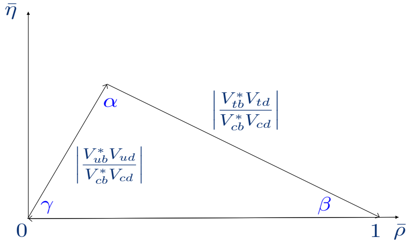
[arXiv:0902.1708, arXiv:1201.4643, LHCb-PAPER-2015-004, LHCb-PAPER-2017-029]



# What about $\gamma$?

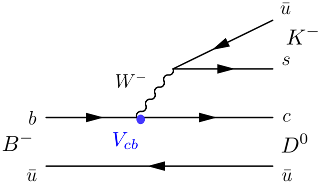
$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$




- No top quark in the definition of $\gamma$
  - 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?

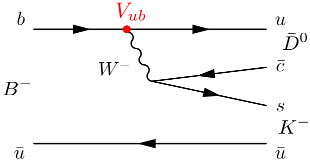
# Measuring $\gamma$ with $B^- \to DK^-$ decays

- 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 $\theta$




**Favoured b → c**

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




**Suppressed b → u**

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

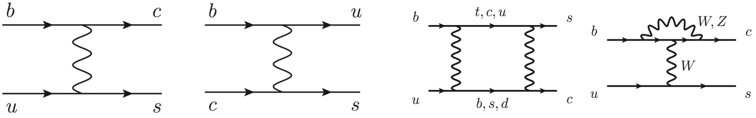
# Measuring $\gamma$ with $B^- \to DK^-$ decays

- $\theta$ contains two parts
  - $\delta_B$ which covers QCD - **strong phase**
  - Other part is the **weak phase** - let's suggestively call it $\gamma$

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

- $B^- \to DK^-$ decays are a theoretically super-clean probe of $\gamma$
  - 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!

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

- $\gamma$ is the $CP$ violating phase $\Rightarrow$ 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 ($\delta_D$)
  - 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

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

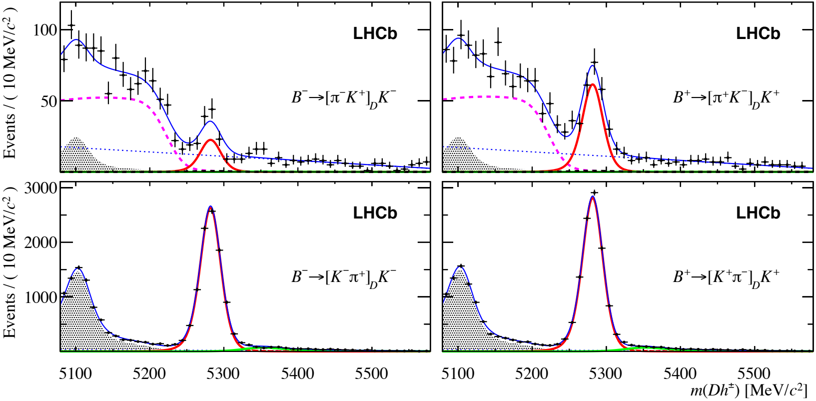
- Also interested in rate of suppressed decays compared to their doubly-favoured counterparts, $B^\pm \to [K^\pm \pi^\mp]_D K^\pm$

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

- Both $A$ and $R$ contain information about $\gamma$

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

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



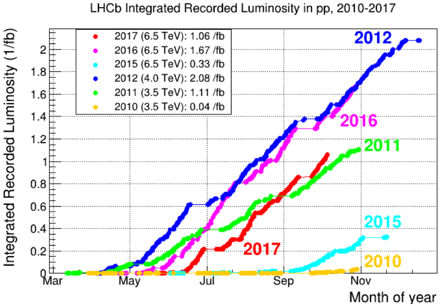
# Constraining $\gamma$ across many final states

- No single method can tell us everything e.g. ADS doesn't give a single $\gamma$ 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 $\text{fb}^{-1}$ in 2015-2016
  - Just crossed 1 $\text{fb}^{-1}$ in 2017
  - Luminosity levelling to achieve desired performance

- Increased statistics not just coming from extra $\text{fb}^{-1}$:
  - Improved software HLT performance
  - Increased $B$ production cross-section at $\sqrt{s} = 13$ TeV

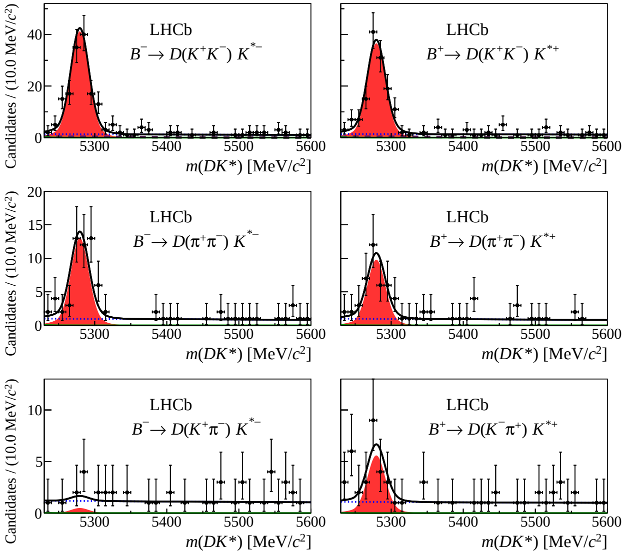


# New modes! $B^{\pm} \to DK^{*\pm}$ (5 fb$^{-1}$) [LHCb-PAPER-2017-030]

- 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

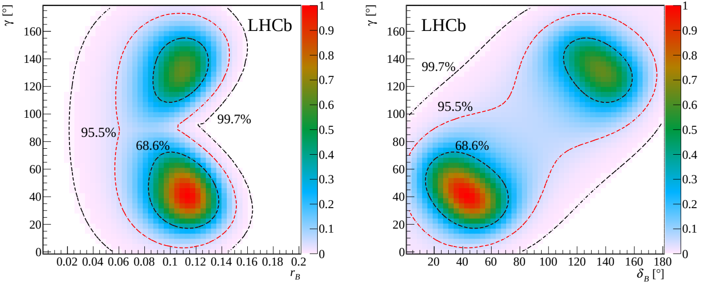
- **Interesting feature** - no background from misidentified $D\pi$-type decays
  - Measure only $B^{\pm} \to DK^{*\pm}$ across various 2- and 4-body $D$ final states
  - Follow the same formalism as $B^{\pm} \to DK^{\pm}$ - **rates and asymmetries**

# $B^{\pm} \to DK^{*\pm}$ (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 $r_B^{DK^*}$, $\delta_B^{DK^*}$, $\gamma$
- This mode will become valuable for constraining $\gamma$ 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 $\gamma$-sensitive sub-decays: $D^{*0} \to D\pi^0$ and $D^{*0} \to D\gamma$
  - $\pi^0$ and $\gamma$ variants have 180° $\delta_D$ difference - opposite $CP$

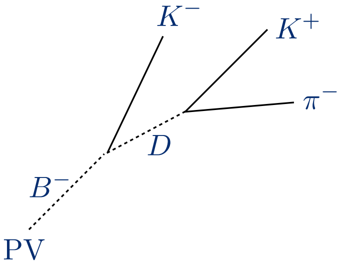
    [Phys. Rev. D 70, 091503(R)]
  - Gives us access to a $CP$-odd mode at LHCb

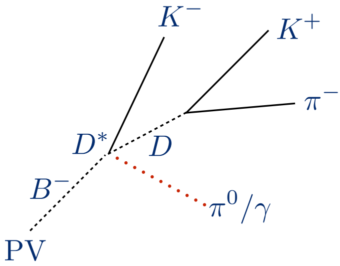
- Measure both $B^{\pm} \to (D^{*0} \to D\pi^0)K^{\pm}$ and $B^{\pm} \to (D^{*0} \to D\gamma)K^{\pm}$ decays to determine $r_B^{D^*K}$, $\delta_B^{D^*K}$, $\gamma$

- Same formalism as $B^{\pm} \to DK^{\pm}$ - measure rates and asymmetries

# Experimental challenge

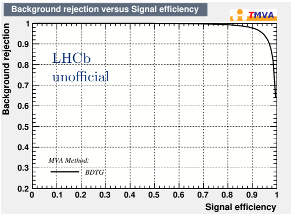
- Soft neutral reconstruction is difficult at LHCb, and has limited efficiency [LHCb-DP-2014-002]
  - $\epsilon(\pi^0) \sim 4\%$
  - $\epsilon(\gamma) \sim 20\%$
- Expect lower statistics than in $B^{\pm} \to DK^{\pm}$ case
  - Is there anything we can do to get around this limitation?

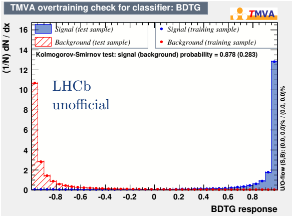


# Partial reconstruction approach

- **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 $m(DK)$

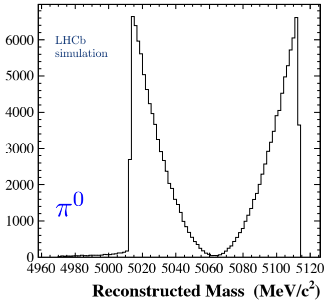


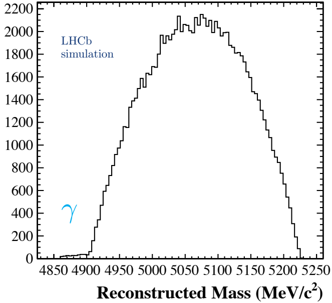



# The $m(DK)$ distribution

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

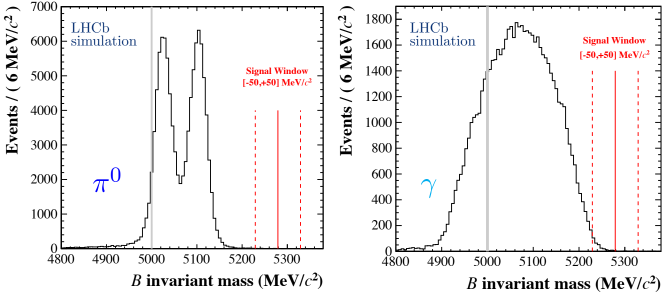
Perfect resolution



# Detector resolution effects

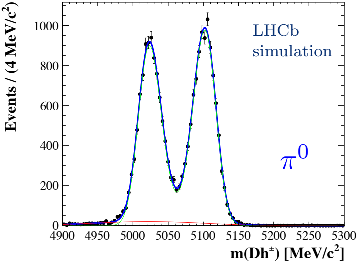
- Detector isn't perfect - convolve parabolas with a double Gaussian resolution function
  - Modelled on the $B^{\pm} \to DK^{\pm}$ peak resolution
- Distinctive distributions for $D^{*0} \to D\pi^0$ and $D^{*0} \to D\gamma$
  - Both sit lower in mass than the $B^{\pm} \to DK^{\pm}$ peak (red region)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

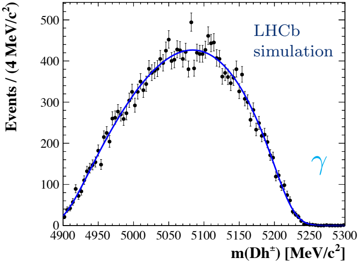


# Fits to $B^\pm \to D^{*0}K^\pm$ simulation

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



# Life is never that simple...

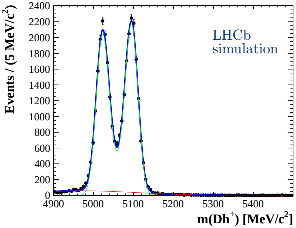
- In reality, there are more $B$ decays than our $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D^{*0}K^{\pm}$ friends!
  - Several other partially reconstructed decays sit in the same invariant mass region as the signals

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

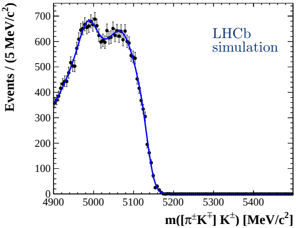
| Fully reco. signal | Partially reco. signal | Partially reco. bkg. |
|---|---|---|
| $B^{\pm} \to DK^{\pm}$ | $B^{\pm} \to (D^{*0} \to D\pi^{0})K^{\pm}$ | $B^{0} \to (D^{*-} \to D\pi^{-})K^{+}$ |
| | $B^{\pm} \to (D^{*0} \to D\gamma)K^{\pm}$ | $B^{\pm} \to DK^{\pm}\pi^{0}$ |
| | | $\bar{B}_s^0 \to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

# Background shapes

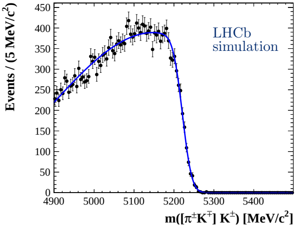
$B^0 \to (D^{*-} \to D\pi^-)K^+$



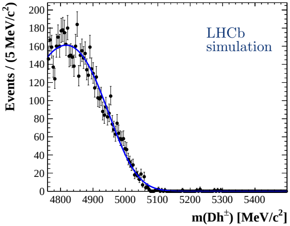

$B^\pm \to DK^\pm\pi^0$




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

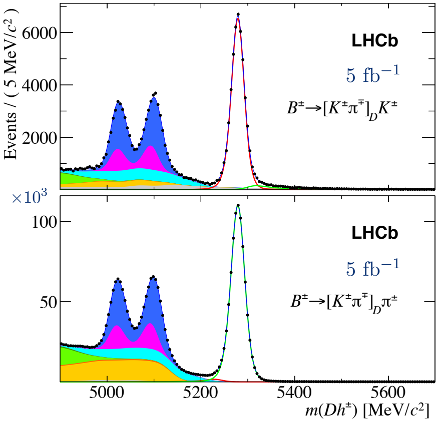



$B \to (D^* \to DX)K^\pm Y$



# $m(Dh^{\pm})$ 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 $(5\ \mathrm{fb}^{-1})$ [LHCb-PAPER-2017-021]

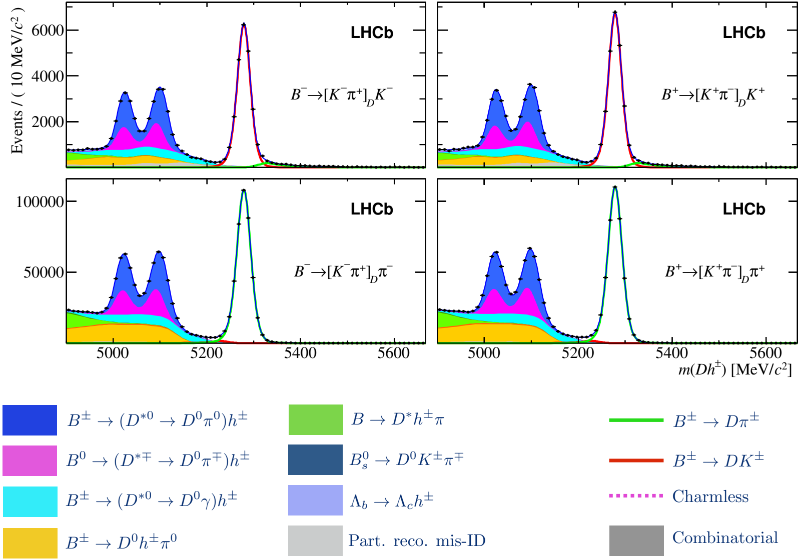
- Fit measures several branching fractions
  - All agree with current world averages ($< 1.3\sigma$)
  - Validation of the partial reconstruction method

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

# Making a $\gamma$-sensitive measurement

- What we really want to measure is $CP$ violation!
  - $\gamma$ 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]

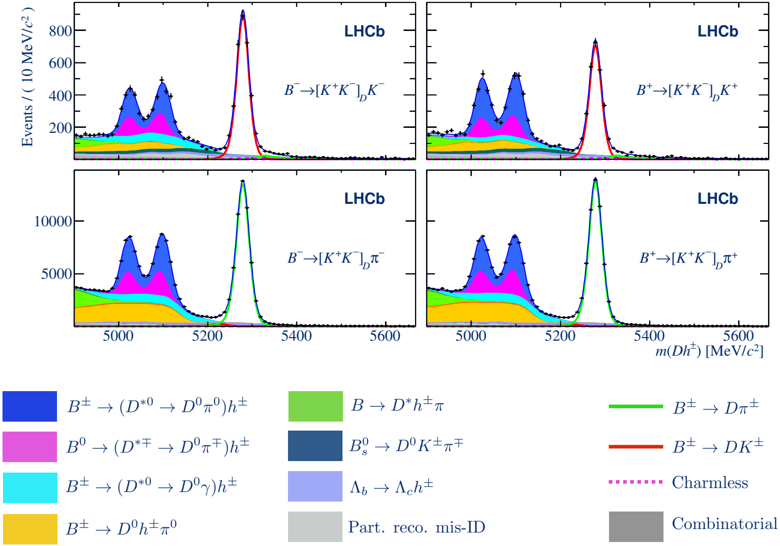


# $CP$ observables $(CP = KK, \pi\pi)$

- Measure $\pi^0$ and $\gamma$ asymmetries in favoured and $CP$ modes
  - 4 observables - $A^{\pi^0}_{K\pi}$, $A^{\gamma}_{K\pi}$, $A^{\pi^0}_{CP}$, $A^{\gamma}_{CP}$
- 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 - $R^{\pi^0}_{CP}$, $R^{\gamma}_{CP}$
- Strong phase difference of 180° between $\pi^0$ and $\gamma$ sub-decays: effectively measuring $R^{\pm}_{CP}$ and $A^{\pm}_{CP}$

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

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



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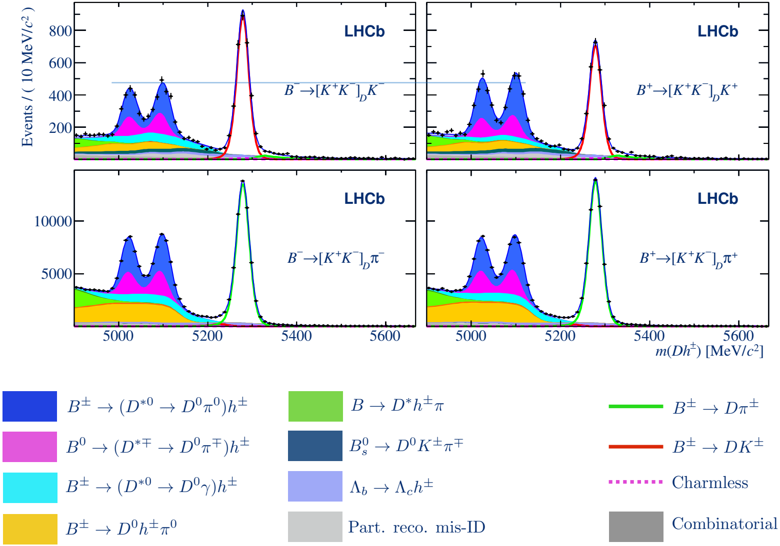

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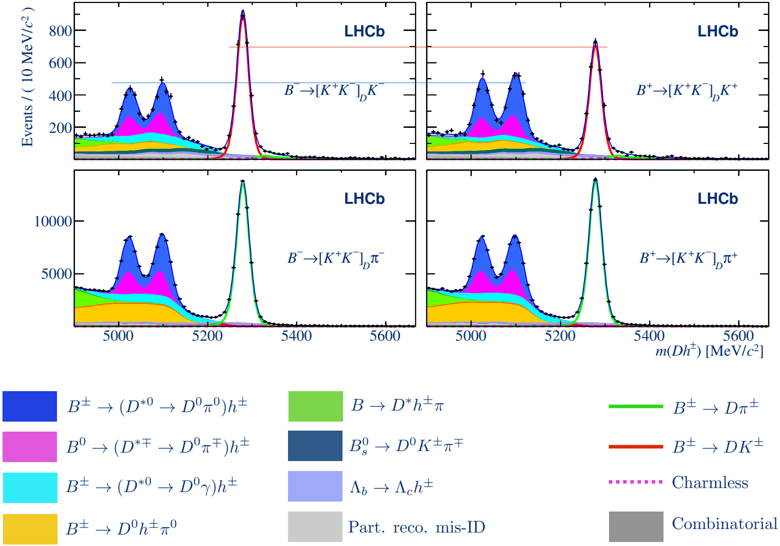
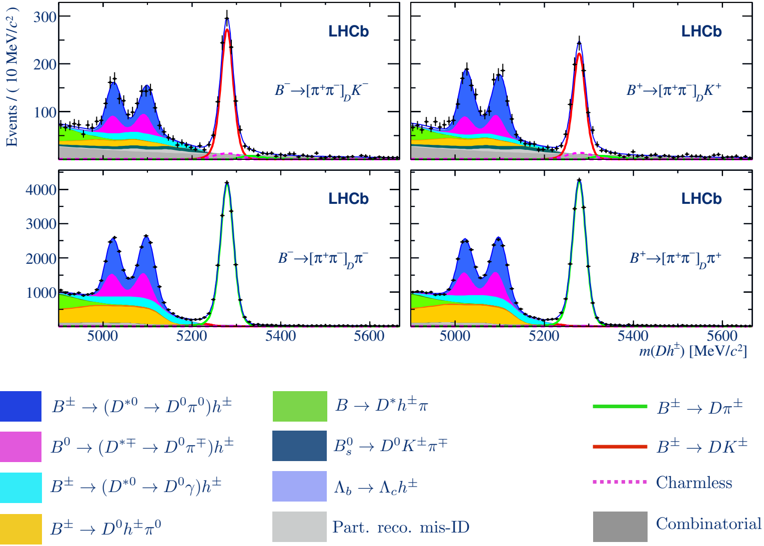


# $m(Dh^{\pm})$ fit, $D \to \pi^+\pi^-$ (5 fb$^{-1}$) [LHCb-PAPER-2017-021]



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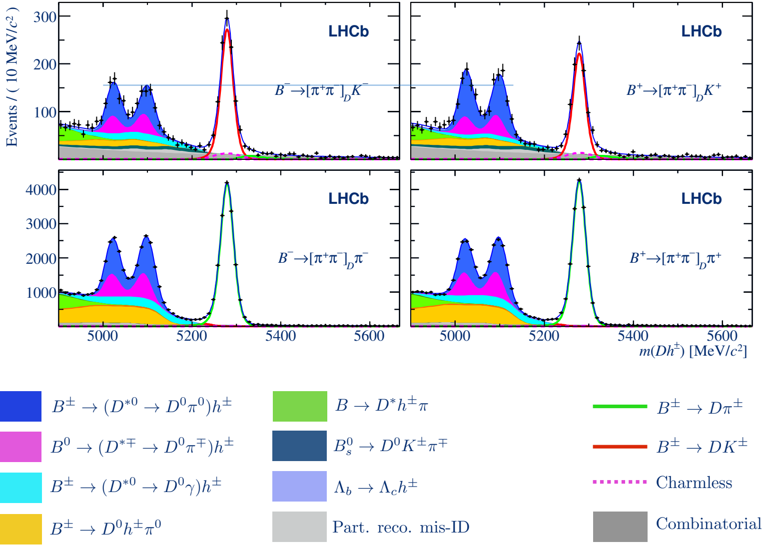

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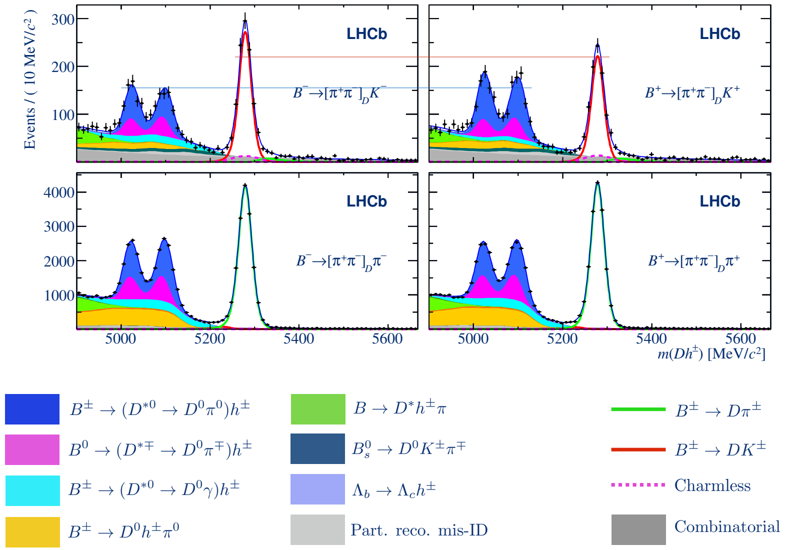


## $CP$ observable results (5 $\text{fb}^{-1}$) [LHCb-PAPER-2017-021]

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

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

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

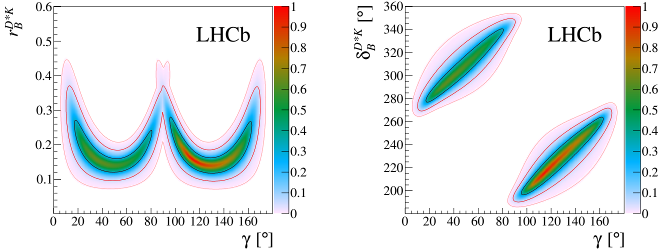
# $B^{\pm} \to DK^{\pm}$ results (5 fb$^{-1}$) [LHCb-PAPER-2017-021]

- 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]**

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

- 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 $\gamma$
- $r_B^{D^*K}$ and $\delta_B^{D^*K}$ align with HFLAV GGSZ averages [arXiv:1612.07233]
- $\gamma$ within $1\sigma$ of 2016 LHCb combination [LHCb-PAPER-2016-032]
  - Will further improve precision with addition of ADS modes



# LHCb $\gamma$ combination [LHCb-CONF-2017-004]

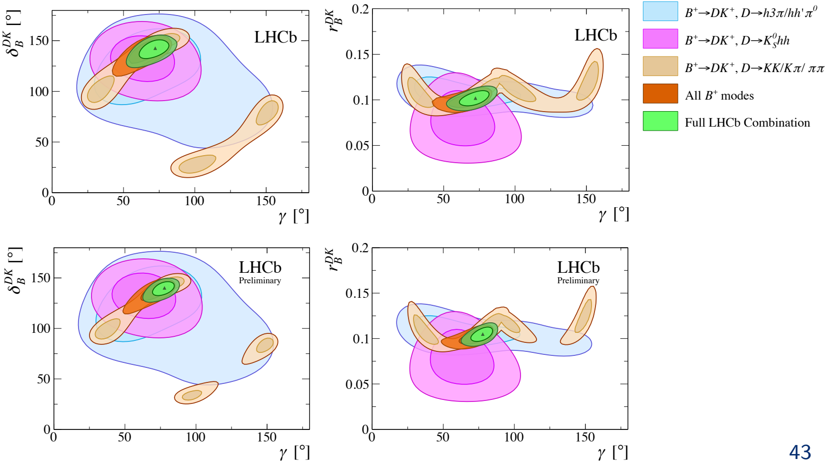
- Perform a statistical combination using observables from several LHCb analyses
  - Many hadronic parameters, but critically $\gamma$ is common to all
- Previous combination based entirely on Run 1 measurements [LHCb-PAPER-2016-032]
- An update has been performed, which includes the following:
  - $B^{\pm} \to DK^{\pm}$ GLW (5 $\text{fb}^{-1}$) 3 $\text{fb}^{-1}$ $\to$ 5 $\text{fb}^{-1}$
  - $B^{\pm} \to D^{*0}K^{\pm}$ GLW (5 $\text{fb}^{-1}$) NEW
  - $B^{\pm} \to DK^{*\pm}$ ADS/GLW (5 $\text{fb}^{-1}$) NEW
  - Time-dependent $B_s^0 \to D_s^- K^+$ (3 $\text{fb}^{-1}$) 1 $\text{fb}^{-1}$ $\to$ 3 $\text{fb}^{-1}$

# 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

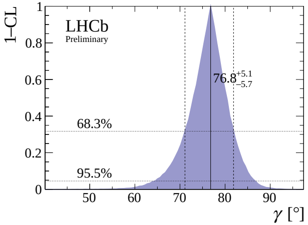
NEW

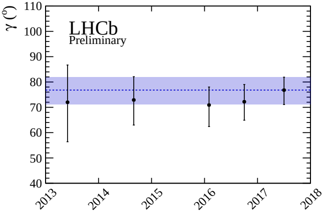


# Measuring $\gamma$ [LHCb-CONF-2017-004]

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

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



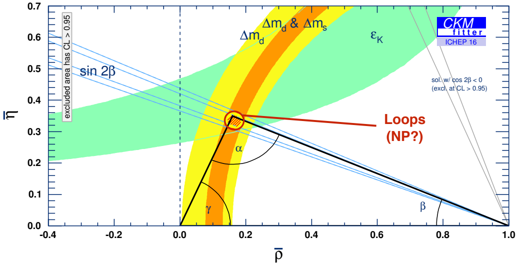

- Current HLFAV average (inc. BaBar and Belle): $\gamma = (76.2^{+4.7}_{-5.0})^\circ$

# Outlook for $\gamma$ at the end of Run 2

- LHCb has more to say on $\gamma$ 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 $\gamma$ precision even further
  - Plenty to stay tuned for in the coming months!

# What does it all mean?

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



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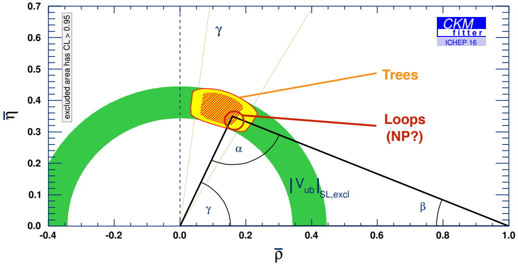

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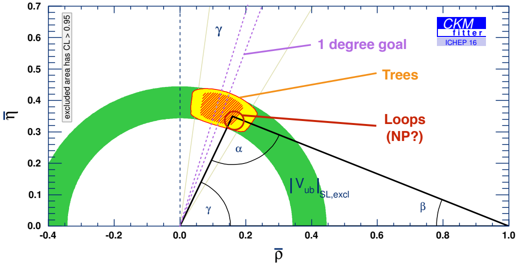


# Comparison with world averages $\gamma$

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

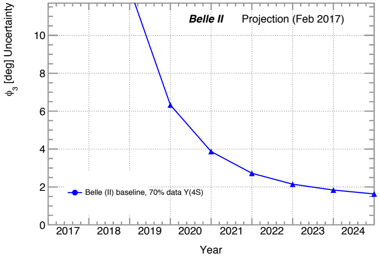
- Can't say anything definitive with current precision, but...
  - LHCb combination is $\sim 2\sigma$ higher than indirect world average
- Strongly motivates the continued pursuit of $\gamma$ with trees
  - LHCb is in a strong position to improve $\gamma$ precision further
  - Will high central value of tree level $\gamma$ 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 $\gamma$ 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 $(\pi^0, \gamma)$: $CP$-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 $\gamma$ sensitivity

- Assuming 10 fb$^{-1}$ BESIII dataset to provide input on GGSZ $c_i$ & $s_i$
    - Belle II expect $3^\circ$ precision from $B^\pm \to DK^\pm$ GGSZ alone
    - Combining with all other $D$ modes gives $1.6^\circ$
- LHCb will work hard to compete well into the upgrade era
    - $1.5^\circ$ by end of Run 3 ($\sim 22$ fb$^{-1}$, 2024) [arXiv:1709.10308]
    - $< 1^\circ$ by end of Run 4 ($\sim 50$ fb$^{-1}$, 2029) [arXiv:1709.10308]
    - $\sim 0.4^\circ$ in Phase II upgrade ($\sim 300$ fb$^{-1}$, 2034) [CERN-LHCC-2017-003]



# Summary

- $\gamma$ 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 $\gamma$ 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

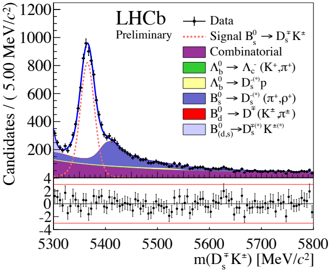
- Many updates to come as we approach the end of Run 2
  - Entering an exciting phase in CKM precision measurements!

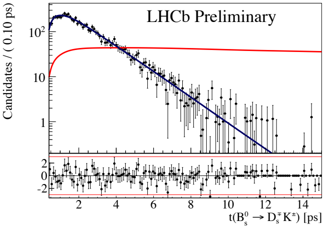
# Backup

# 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
- $\gamma$ sensitive measurement
  - Assume no NP and no penguin pollution
  - Plug in $\phi_s = -0.010 \pm 0.039$ rad [LHCb-PAPER-2014-059]

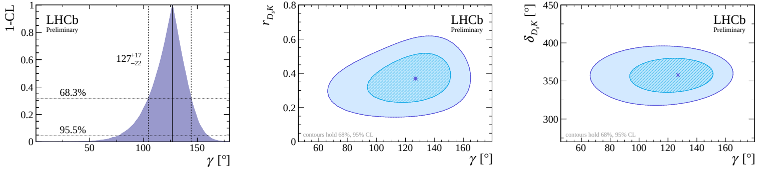
- Flavour-tagged analysis measures $CP$ parameters from fit to decay time distribution



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

$$\gamma = (127^{+17}_{-22})^\circ$$
$$\delta_{D_sK} = (358^{+15}_{-16})^\circ$$
$$r_{D_sK} = 0.37^{+0.10}_{-0.09}$$

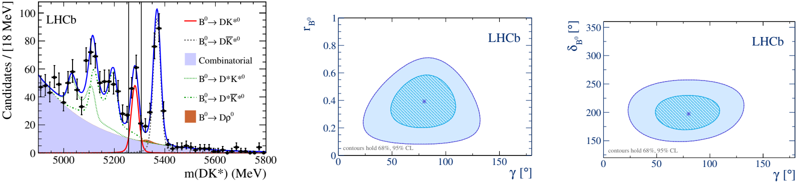



- Input: $\phi_s = -0.010 \pm 0.039$ rad [LHCb-PAPER-2014-059]
- $3.6\sigma$ evidence of $CP$ violation in $B_s^0 \to D_s^\mp K^\pm$
- $2.2\sigma$ compatibility with LHCb time-integrated $\gamma$ combination

# GGSZ modes

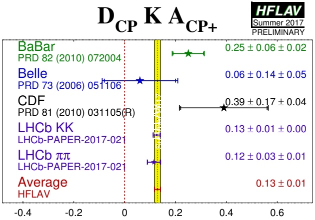
- LHCb has a suite of completed 3 fb$^{-1}$ GGSZ analyses:
    - $B^{\pm} \to D^0 K^{\pm}$ with $D^0 \to K_s^0\pi^+\pi^-, K_s^0 K^+ K^-$ [JHEP 10 (2014) 097]
    - MD $B^0 \to D^0 K^{*0}$ with $D^0 \to K_s^0\pi^+\pi^-$ [JHEP 08 (2016) 137]
    - MI $B^0 \to D^0 K^{*0}$ with $D^0 \to K_s^0\pi^+\pi^-, K_s^0 K^+ K^-$ [JHEP 06 (2016) 131]

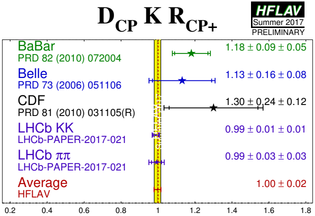
- $B^{\pm} \to D^0 K^{\pm}$ update is active using Run 1 + Run 2 data



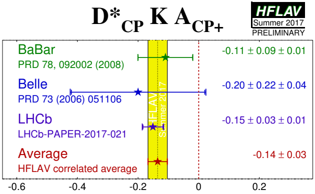

MD $B^0 \to D^0 K^{*0}$ with $D^0 \to K_s^0\pi^+\pi^-$ [JHEP 08 (2016) 137]

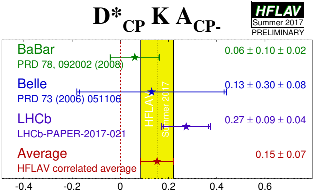
# Summer 2017 HFLAV averages - $B^{\pm} \to D_{CP} K^{\pm}$

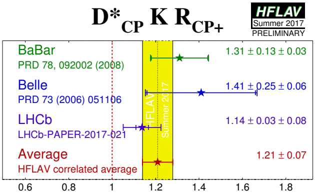


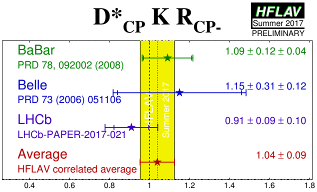



# Summer 2017 HFLAV averages - $B^{\pm} \to D^*_{CP} K^{\pm}$



# 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 $\Rightarrow$ variation in observable results assigned as systematics