CKM measurements and the scope for New Physics therein

Matthew Kenzie

Warwick EPP Seminar

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Who's this bloke then?

Started at Warwick on Tuesday

From Cambridge

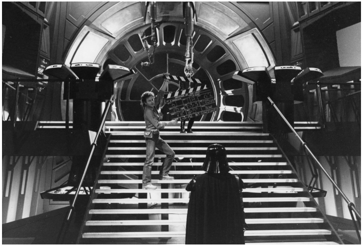
- Grew up in the house that was built by my great-grandfather
- He founded "Kenzie's Coaches"
- My father was a cinematographer

Education

- Undergraduate at Durham (BSc Physics)
- Masters at Imperial (MSc Theoretical Physics)
- PhD at Imperial / CERN (CMS $H \to \gamma\gamma$)

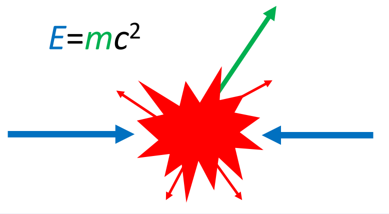
Research Career

- CERN Fellow (LHCb)
- Junior Research Fellow (Cambridge, LHCb)
- STFC Ernest Rutherford Fellow (Cambridge, LHCb)
- Now at Warwick



High energy frontier

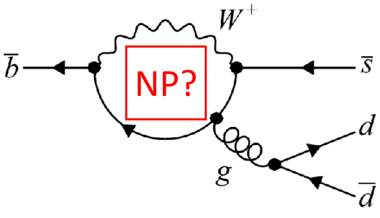
Direct observation



Require $E > mc^2$ for direct production

Precision frontier

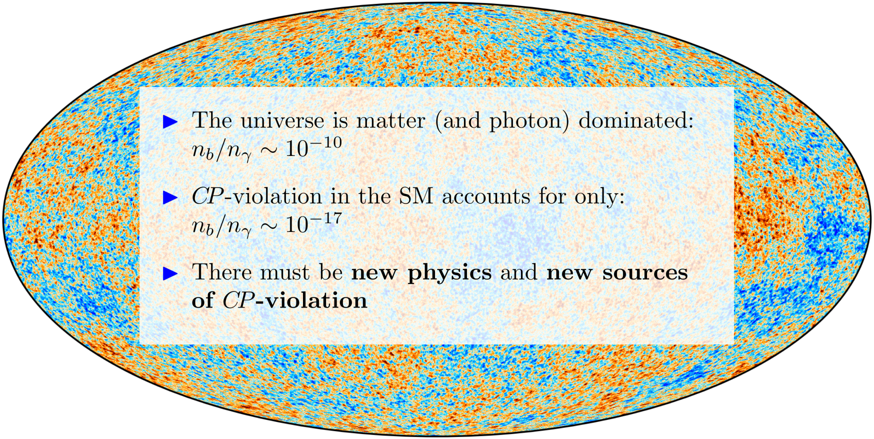
Indirect effects



New particles effect loop processes

- Most HEP direct discoveries have been preceeded by **indirect evidence first!**
  - Think charm, bottom and top quarks, even the Higgs
- If we don't see New Physics directly at the LHC, indirect evidence can guide us where to look (or what to build) next

Why is the universe matter dominated?



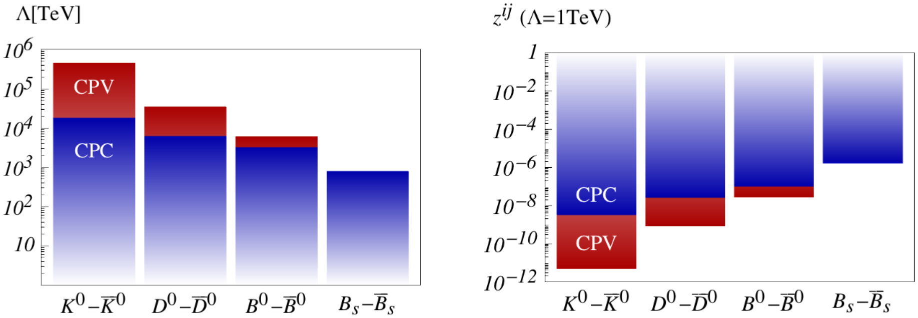
- The universe is matter (and photon) dominated: $n_b/n_\gamma \sim 10^{-10}$
- CP-violation in the SM accounts for only: $n_b/n_\gamma \sim 10^{-17}$
- There must be **new physics** and **new sources of CP-violation**

- *CP*-violation in the SM is generated by **quark flavour transitions**
- These contain the **only** source of *CP*-violation in the SM ($\theta_{\mathrm{QCD}} = m_\nu = 0$)

New Physics from Flavour sector

- Direct NP discovery by ATLAS/CMS is still possible
- **The flavour sector provides another window of opportunity**
  - High Energy scales, Λ
  - Low coupling scales, z

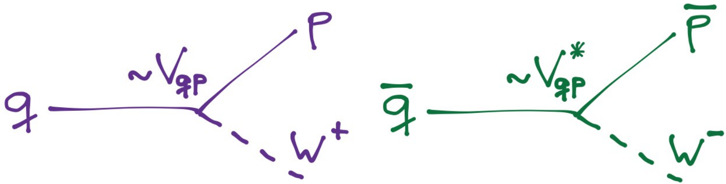
$$\mathcal{Q}_{AB}^{(6)} \sim z_{ij}[\bar{q}_i \Gamma^A q_j] \otimes [\bar{q}_i \Gamma^B q_j]$$



Isidori, Nir and Perez, [*Ann. Rev. Nucl. Part. Sci* (2010) 60:355]

The CKM quark mixing matrix

- In the SM quarks can change flavour by emission of a $W^{\pm}$ boson
  - So must also change charge (i.e. from up-type to down-type or vice-versa)



- The probability for such a transition is governed by the elements of the 3×3 **unitary** CKM matrix

CKM matrix

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

flavour eigenstates — mass eigenstates

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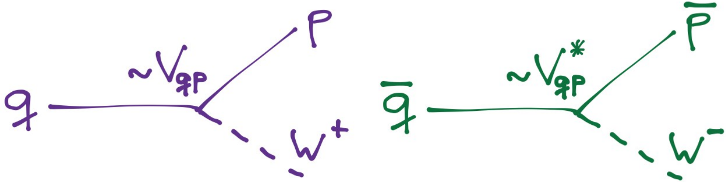

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  - It exhibits a **clear hierarchy** (which sets strong constraints on NP)

CKM hierarchy

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

experimentally determined values

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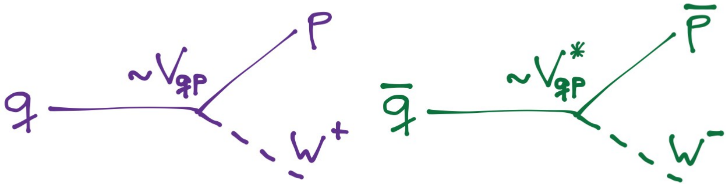

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Wolfenstein parametrisation

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

4 $\mathcal{O}(1)$ real parameters (A, λ, ρ, η)

The B^0 unitarity triangle

- Unitarity imposes several conditions ($V^\dagger V = \mathbb{1}$)
  - Gives rise to "unitarity" triangles
  - Internal area dictates the **total amount of CPV** in the quark sector

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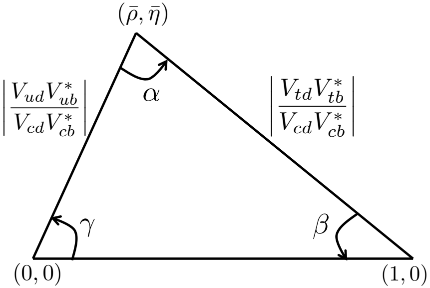
"The B^0 unitarity triangle"

$$\underbrace{V_{ud}V_{ub}^*}_{\sim\lambda^3} + \underbrace{V_{cd}V_{cb}^*}_{\sim\lambda^3} + \underbrace{V_{td}V_{tb}^*}_{\sim\lambda^3} = 0$$



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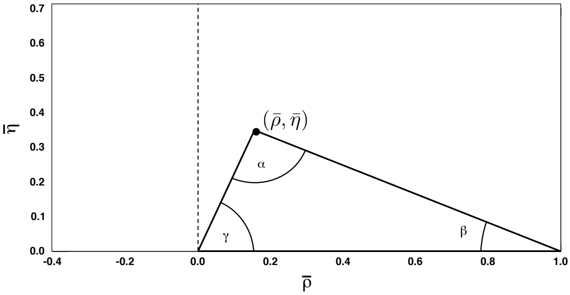

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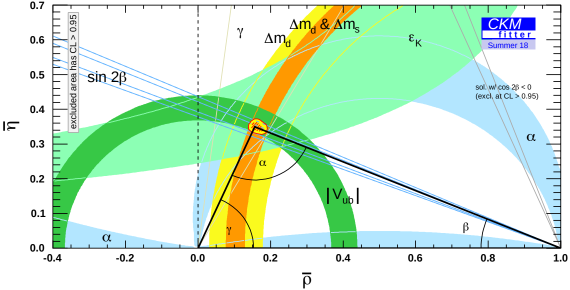


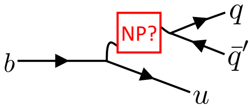
New Physics effects in the flavour sector

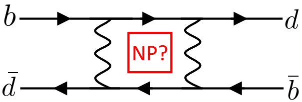
- Discrepancy between "tree" and "loop" constraints $\Rightarrow$ clear sign of New Physics
- Sensitive to NP effects at extremely high energy scales $\sim \mathcal{O}(10^2 - 10^3)$ TeV

Direct: $\gamma = (72.1^{+5.4}_{-5.7})^\circ$

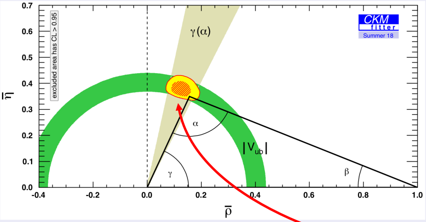
Indirect: $\gamma = (65.6^{+1.0}_{-3.4})^\circ$

Currently a $\sim 2\sigma$ tension

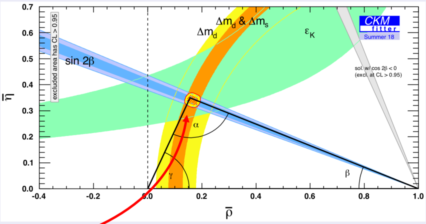




Tree-level constraints



Loop-level constraints



NP?

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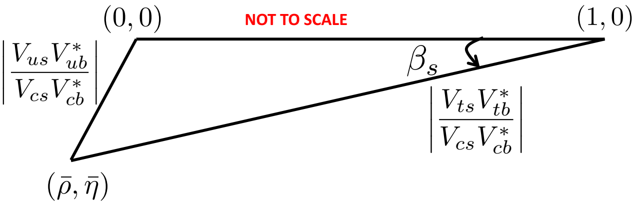

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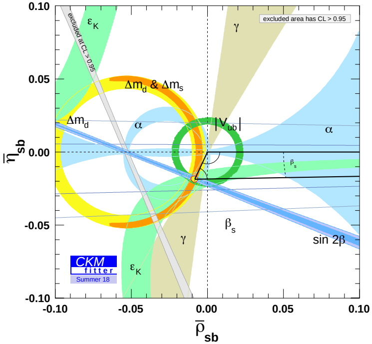
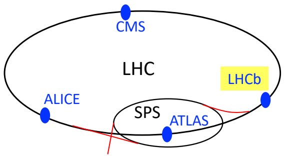


Why LHCb?

- Copius production of B^+, B^0, B_s^0, Λ_b^0 (100K $b\overline{b}$/ s)
- **LHCb detector** is specifically designed to study them



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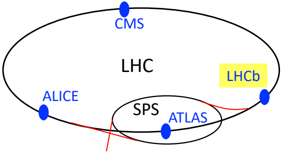

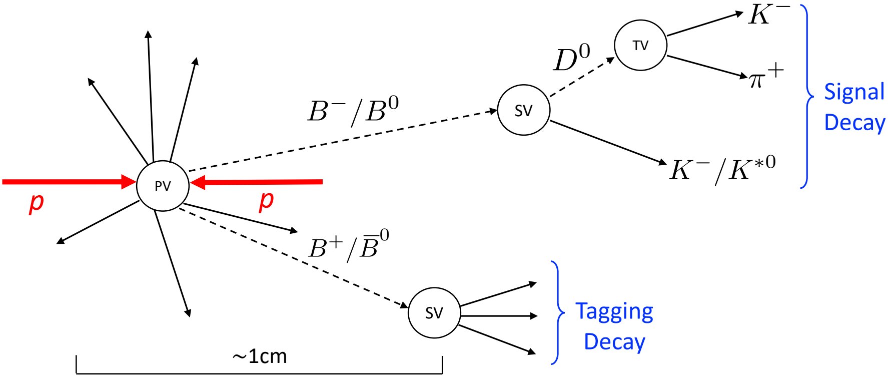

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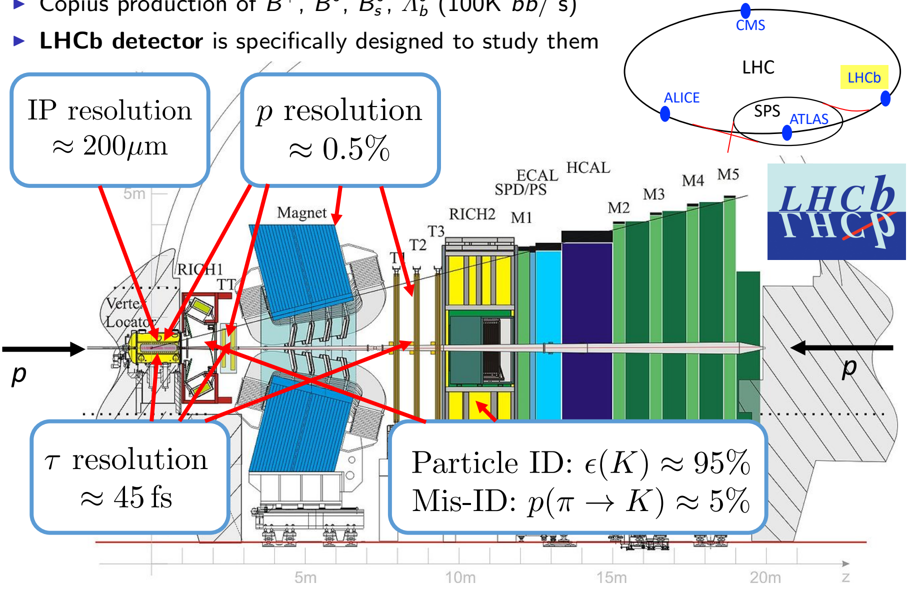
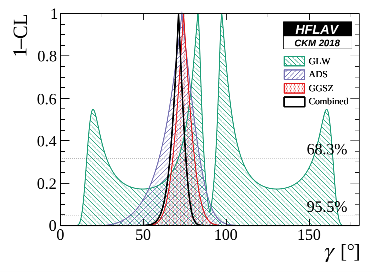


1. Measurements of γ

CKM angle γ

- Theoretically clean, $\sigma_\gamma/\gamma \sim \mathcal{O}(10^{-7})$
- Historically poorly known
- Experimentally challenging, $BR \sim \mathcal{O}(10^{-7})$
- In 10 years will become *the* precision benchmark for SM CKM measurements

World average for γ

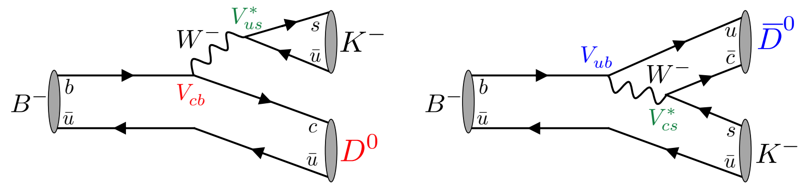


- Total of 136 input observables
- From 40 different measurements
- Across 6 different experiments

Measuring γ

- γ is the phase between $V_{ub}^* V_{ud}$ and $V_{cb}^* V_{cd}$
  - Require interference between $b \to cW$ and $b \to uW$ to access it
  - No dependence on CKM elements involving the top
  - **Can be measured using tree level B decays**
- The "textbook" case is $B^{\pm} \to \overset{(-)}{D}{}^0 K^{\pm}$:
  - Transitions themselves have different final states (D^0 and $\bar{D}^0$)
  - Interference occurs when D^0 and $\bar{D}^0$ decay to the same final state f

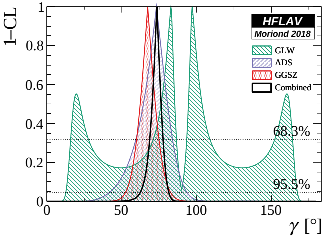
Reconstruct the $D^0/\bar{D}^0$ in a final state accessible to both to acheive interference



- **The crucial feature of these (and similar) decays is that the D^0 can be reconstructed in several different final states** [all have same weak phase γ]

Categorise decays sensitive to γ depending on the $\overset{(-)}{D}{}^0 \to f$ final state

Optimal sensitivity is only acheived when combining them all together

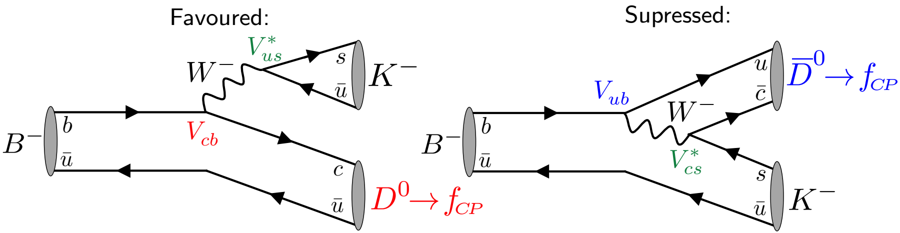


- GLW
  - CP eigenstates e.g. $D \to KK$, $D \to \pi\pi$
  - [Phys. Lett. B253 (1991) 483]
  - [Phys. Lett. B265 (1991) 172]
- ADS
  - CF or DCS decays e.g. $D \to K\pi$
  - [Phys. Rev. D63 (2001) 036005]
  - [Phys. Rev. Lett. 78 (1997) 3257]
- GGSZ
  - 3-body final states e.g. $D \to K^0_S\pi\pi$
  - [Phys. Rev. D68 (2003) 054018]
- TD (Time-dependent)
  - Interference between mixing and decay e.g. $B^0_s \to D^-_s K^+$ [phase is $(\gamma - 2\beta_s)$]
  - Penguin free measurement of ϕ_s?
- Dalitz
  - Look at 3-body B decays with D^0 or $\overline{D}^0$ in the final state, e.g. $B^0 \to \overline{D}^0 K^+\pi^-$
  - [Phys. Rev. D79 (2009) 051301]

1.1 The GLW Method

γ with CP eigenstates (GLW)

- Use the $B^{\pm} \to \overset{(-)}{D}{}^0 K^{\pm}$ case as an example:
  - **Consider only D decays to CP eigenstates, f_{CP}**
  - Favoured: $b \to c$ with strong phase δ_F and weak phase ϕ_F
  - Supressed: $b \to u$ with strong phase δ_S and weak phase ϕ_S



Subsequent amplitude to final state f_{CP} is:

$$B^- : A_f = |F|e^{i(\delta_F - \phi_F)} + |S|e^{i(\delta_S - \phi_S)} \quad (1)$$

$$B^+ : \bar{A}_f = |F|e^{i(\delta_F + \phi_F)} + |S|e^{i(\delta_S + \phi_S)} \quad (2)$$

because strong phases (δ) don't change sign under CP while weak phases (ϕ) do

γ with *CP* eigenstates (GLW)

- Can define the sum and difference of rates with B^+ and B^-

Rate difference and sum

$$|\bar{A}_{\bar{f}}|^2 - |A_f|^2 = 2|F||S|\sin(\delta_F - \delta_S)\sin(\phi_F - \phi_S) \quad (3)$$

$$|\bar{A}_{\bar{f}}|^2 + |A_f|^2 = |F|^2 + |S|^2 + 2|F||S|\cos(\delta_F - \delta_S)\cos(\phi_F - \phi_S) \quad (4)$$

- Choose $r_B = \frac{|S|}{|F|}$ (so that $r < 1$) and use strong phase difference $\delta_B = \delta_F - \delta_S$
- γ is the weak phase difference $\phi_F - \phi_S$
- Subsequently have two **experimental observables** which are

GLW *CP* asymmetry

$$\mathcal{A}_{CP} = \frac{\pm 2 r_B \sin(\delta_B)\sin(\gamma)}{1 + r_B^2 \pm 2 r_B \cos(\delta_B)\cos(\gamma)}$$

GLW total rate

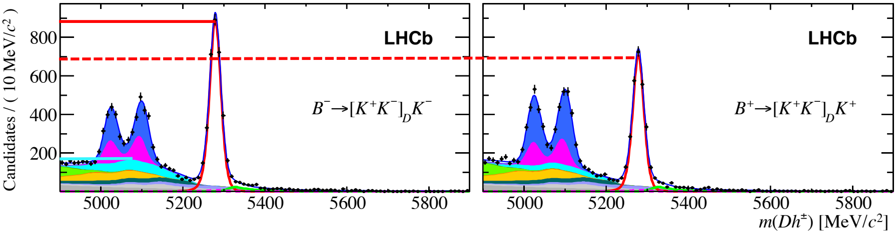
$$\mathcal{R}_{CP} = 1 + r_B^2 \pm 2 r_B \cos(\delta_B)\cos(\gamma)$$

- The $+(-)$ sign corresponds to *CP*-even (-odd) final states
- Note that r_B and δ_B (ratio and strong phase difference of favoured and supressed modes) are different for each B decay
- **The value of γ is shared by all such decays**

GLW observables

$$A_{CP} = \frac{\Gamma(B^- \to D^0_{CP} K^-) - \Gamma(B^+ \to D^0_{CP} K^+)}{\Gamma(B^- \to D^0_{CP} K^-) + \Gamma(B^+ \to D^0_{CP} K^+)} = \frac{\pm 2 r_B \sin(\delta_B)\sin(\gamma)}{1 + r_B^2 \pm 2 r_B \cos(\delta_B)\cos(\gamma)} \quad (1)$$

$$R_{CP} = \frac{\Gamma(B^- \to D^0_{CP} K^-) + \Gamma(B^+ \to D^0_{CP} K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to D^0 K^+)} = 1 + r_B^2 \pm 2 r_B \cos(\delta_B)\cos(\gamma) \quad (2)$$



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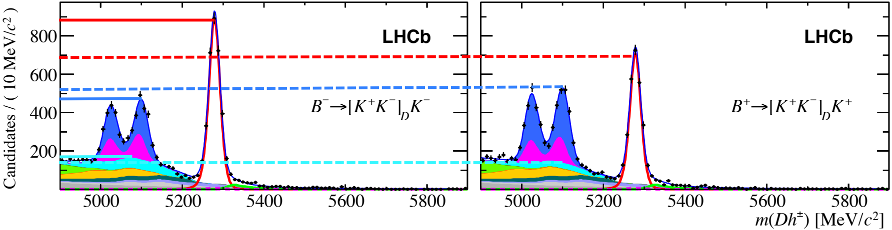

- **LHCb has recently extracted GLW observables from partially reconstructed $B^- \to D^{*0} K^-$ in the same fit** - [arXiv:1708.06370]

GLW observables

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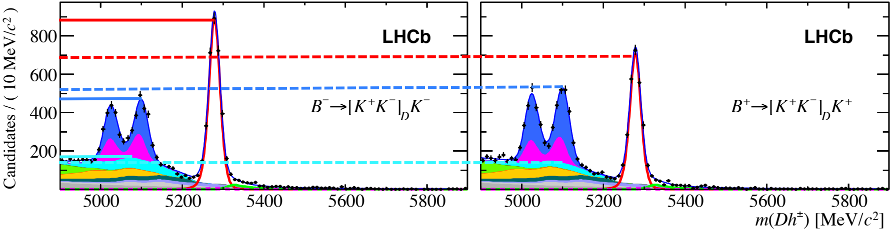

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- Can extend to quasi-CP-eigenstates ($D^0 \to KK\pi^0$) if fraction of CP content, F^+, is known

GLW Method

GLW observables

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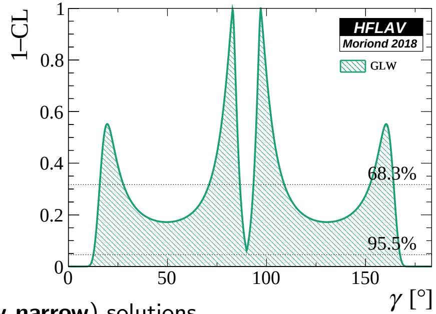


- Multiple (**but very narrow**) solutions
- Require knowledge of F^+ from charm friends

1.2 The ADS Method

γ with CF and DCS decays (ADS)

- A 2-body D decay to final state f accesible to both D^0 and $\bar{D}^0$ can be
  - Cabibbo-favoured (CF) - $D^0 \to \pi^- K^+$
  - Doubly-Cabibbo-supressed (DCS) - $\bar{D}^0 \to \pi^- K^+$
- Introduces 2 new hadronic parameters:
  - r_D - ratio of magnitudes for D^0 and $\bar{D}^0$ decay to f
  - δ_D - relative phase for D^0 and $\bar{D}^0$ decay to f
- Gives a modified asymmetry and rate defintion

ADS asymmetry

$$\mathcal{A}_{ADS} = \frac{2 r_D r_B \sin(\delta_B + \delta_D) \sin(\gamma)}{r_D^2 + r_B^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos(\gamma)}$$

ADS ratio

$$\mathcal{R}_{ADS} = \frac{|\bar{A}_{\bar{f}}|^2 + |A_f|^2}{|\bar{A}_f|^2 + |A_{\bar{f}}|^2} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos(\gamma)$$

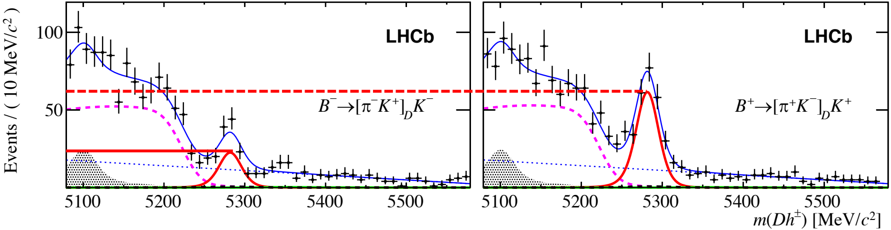
- Hadronic parameters r_D and δ_D can be de independently determined (using CLEO data and HFAG averages)

ADS Method

ADS observables

$$A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)} = \frac{2r_B r_D \sin(\delta_B + \delta_D)\sin(\gamma)}{r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma)}$$

$$R_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma)$$



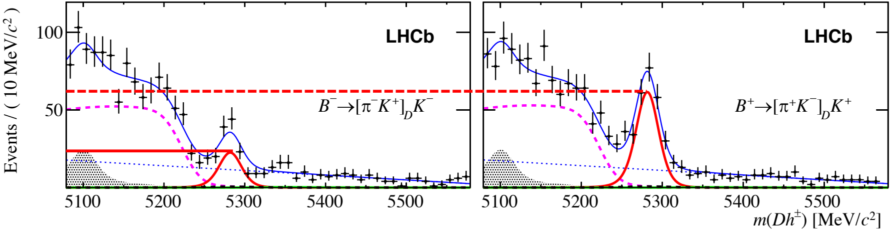
- **Much harder to extract partially reconstructed observables because of $B_s^0 \to D^{(*)0} K^+\pi^-$ backgrounds.**

ADS Method

ADS observables

$$A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)} = \frac{2 r_B r_D \kappa_D \sin(\delta_B + \delta_D) \sin(\gamma)}{r_B^2 + r_D^2 + 2 r_B r_D \kappa_D \cos(\delta_B + \delta_D) \cos(\gamma)}$$

$$R_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)} = r_B^2 + r_D^2 + 2 r_B r_D \kappa_D \cos(\delta_B + \delta_D) \cos(\gamma)$$



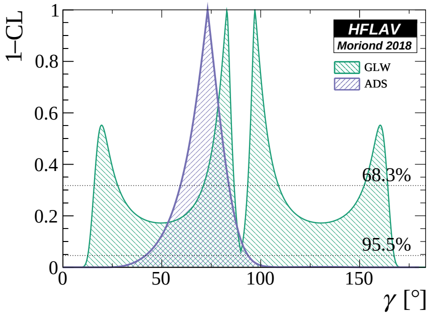
- **Much harder to extract partially reconstructed observables because of $B_s^0 \to D^{(*)0} K^+ \pi^-$ backgrounds.**
- Can extend to multibody-DCS-decays ($D^0 \to K\pi\pi^0$) if dilution from interference, κ_D, is known

ADS Method

ADS observables

$$A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)} = \frac{2 r_B r_D \kappa_D \sin(\delta_B + \delta_D)\sin(\gamma)}{r_B^2 + r_D^2 + 2 r_B r_D \kappa_D \cos(\delta_B + \delta_D)\cos(\gamma)}$$

$$R_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)} = r_B^2 + r_D^2 + 2 r_B r_D \kappa_D \cos(\delta_B + \delta_D)\cos(\gamma)$$



- A single (**yet broader**) solution
- Require knowledge of r_D, δ_D, κ_D from charm friends

1.3 The GGSZ Method

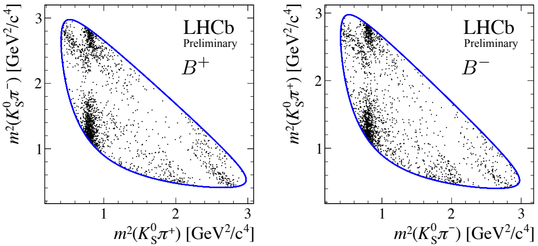
γ with 3-body self-conjugate states (GGSZ)

- Now get additional sensitivity over the 3-body phase space
- Idea is to perform a GLW/ADS type analysis across the D decay phase space
- For example $D^0 \to K^0_S\pi^+\pi^-$ has contributions from
  - Singly-Cabibbo-suppressed decay $D^0 \to K^0_S\rho^0$
  - Doubly-Cabibbo-suppressed decay $D^0 \to K^{*+}\pi^-$
  - Interference between them enhances sensitivity and resolves ambiguities in γ

GGSZ observables (partial rate as function of Dalitz position)

$$d\Gamma_{B\pm}(\mathbf{x}) = A^2_{(\pm,\mp)} + r_B^2 A^2_{(\mp,\pm)} + 2A_{(\pm,\mp)}A_{(\mp,\pm)}\left[r_B\cos(\delta_B \pm \gamma)\cos(\delta_{D(\pm,\mp)}) + r_B\sin(\delta_B \pm \gamma)\sin(\delta_{D(\pm,\mp)})\right] \quad (3)$$

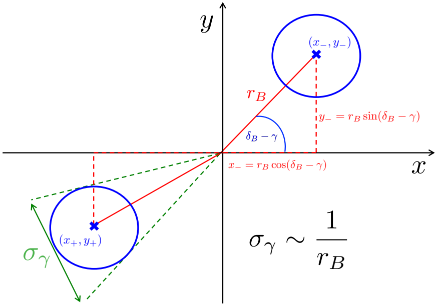
From [LHCb-PAPER-2018-017]



GGSZ Method

GGSZ observables (partial rate as function of Dalitz position)

$$d\Gamma_{B^\pm}(\mathbf{x}) = A^2_{(\pm,\mp)} + r_B^2 A^2_{(\mp,\pm)} + 2A_{(\pm,\mp)}A_{(\mp,\pm)}\Big[\underbrace{r_B\cos(\delta_B \pm \gamma)}_{x_\pm}\,\underbrace{\cos(\delta_{D(\pm,\mp)})}_{c_i} + \underbrace{r_B\sin(\delta_B \pm \gamma)}_{y_\pm}\,\underbrace{\sin(\delta_{D(\pm,\mp)})}_{s_i}\Big] \quad (4)$$

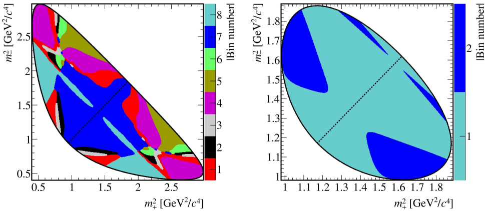


- $x_\pm + iy_\pm = r_B e^{i(\delta_B \pm \gamma)}$
- **Uncertainty on γ is inversely proportional to central value of hadronic unknown!!**
- Fluctuation in nuisance parameter = fluctuation in error on parameter of interest!

Model-independent GGSZ Analysis

[LHCb-PAPER-2018-017]

- Consider both $D \to K_S^0 \pi\pi$ and $D \to K_S^0 KK$ decays
- Divide up the Dalitz space into $2N$ symmetric bins chosen to optimise sensitivity to γ



Decay amplitude is a superposition of supressed and favoured contributions

$$A_B(m_-^2, m_+^2) \propto A_D(m_-^2, m_+^2) + r_B e^{i(\delta_B - \gamma)} A_{\overline{D}}(m_-^2, m_+^2)$$

Expected number of B^+ (B^-) events in bin i

$$N_{\pm i}^{+} = h_{B^+} \left[F_{\mp i} + (x_+^2 + y_+^2) F_{\pm i} + 2\sqrt{F_i F_{-i}} (x_+ c_{\pm i} - y_+ s_{\pm i}) \right]$$

$$N_{\pm i}^{-} = h_{B^-} \left[F_{\pm i} + (x_-^2 + y_-^2) F_{\mp i} + 2\sqrt{F_i F_{-i}} (x_- c_{\pm i} - y_- s_{\pm i}) \right]$$

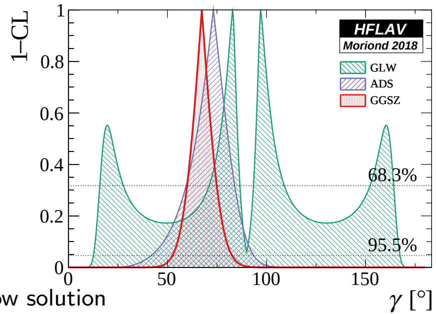
- $N_{\pm i}^{\pm}$ - events in each bin
- $F_{\pm i}$ - from $B \to D^{*\pm} \mu^{\mp} \nu_\mu X$
- c_i, s_i - from CLEO-c (QC $D^0 \overline{D}^0$) measurements
- $h_{B^\pm}$ - overall normalisation

GGSZ Method

Expected number of B^+ (B^-) events in bin i

$$N^+_{\pm i} = h_{B^+}\left[F_{\mp i} + (x_+^2 + y_+^2)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})\right]$$

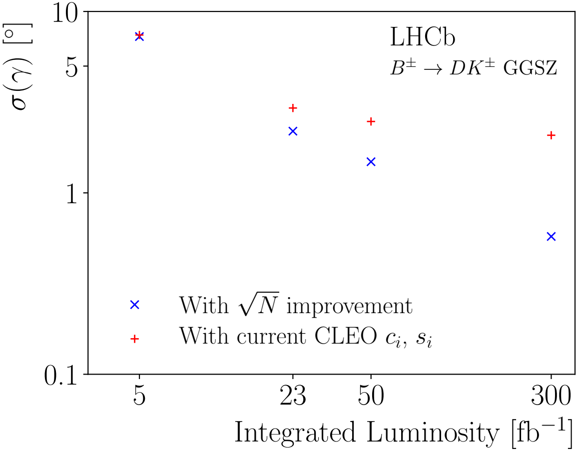
$$N^-_{\pm i} = h_{B^-}\left[F_{\pm i} + (x_-^2 + y_-^2)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} - y_- s_{\pm i})\right]$$



- A single and narrow solution
- Require knowledge of $c_{\pm i}$ and $s_{\pm i}$ from charm friends

A comment on GGSZ systematics

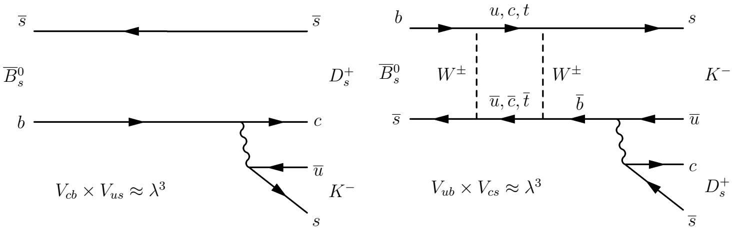
- Sensitivty to γ starts to degrade due to dependence on input from charm sector
- Measurements from BES-III (Beijing) will be vital to achieve ultimate precision on γ



1.4 The TD Method

The time-dependent method with $B_s^0 \to D_s^{\mp} K^{\pm}$

- B_s^0 and $\overline{B}_s^0$ can both decay to same final state $D_s^{\mp} K^{\pm}$ (one via $b \to cW$, the other via $b \to uW$)
- Intereference acheived by neutral B_s^0 mixing (requires knowledge of $-2\beta_s \equiv \phi_s$)
  - Weak phase difference is $(\gamma - 2\beta_s)$



- Requires tagging the initial B_s^0 flavour
- Requires a time-dependent analysis to observe the meson oscillations
- Fit the decay-time-dependent decay rates
- Also requires knowledge of Γ_s, $\Delta\Gamma_s$, Δm_s

The time-dependent method with $B_s^0 \to D_s^{\mp} K^{\pm}$

Time-dependent decay rate for initial B_s^0 or $\bar{B}_s^0$ at $t = 0$

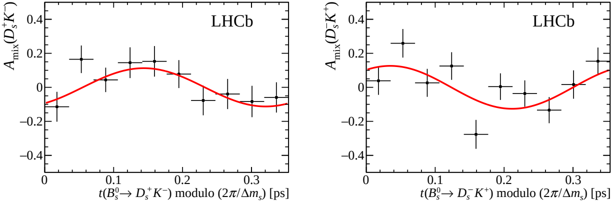
$$\frac{d\Gamma_{B_s^0 \to f}(t)}{dt} \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma_s}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f\cos(\Delta m_s t) - S_f\sin(\Delta m_s t)\right]$$

$$\frac{d\Gamma_{\bar{B}_s^0 \to f}(t)}{dt} \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma_s}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f\cos(\Delta m_s t) + S_f\sin(\Delta m_s t)\right]$$

Time-dependent rate asymmetry

$$\mathcal{A}_{CP}(t) = \frac{\Gamma_{\bar{B}_s^0 \to f}(t) - \Gamma_{B_s^0 \to f}(t)}{\Gamma_{\bar{B}_s^0 \to f}(t) + \Gamma_{B_s^0 \to f}(t)} = \frac{S_f\sin(\Delta m_s t) - C_f\cos(\Delta m_s t)}{\cosh(\frac{\Delta\Gamma_s t}{2}) + A_f^{\Delta\Gamma_s}\sinh(\frac{\Delta\Gamma_s t}{2})}$$

- Fit for decay-time-dependent asymmetry

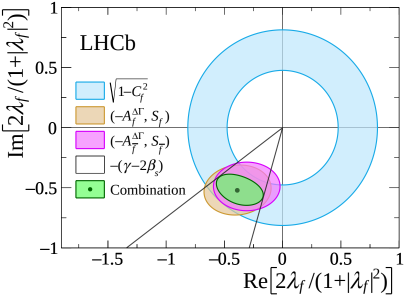


Variable definitions

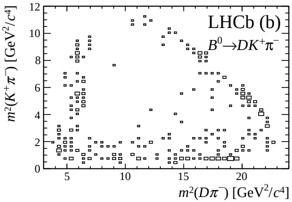
$$C_f = -C_{\bar{f}} = \frac{1 - r_B^2}{1 + r_B^2}$$

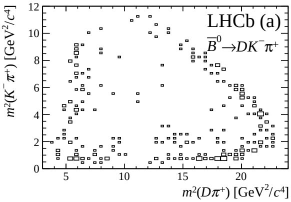
$$A^{\Delta\Gamma_s}_{f(\bar{f})} = \frac{-2 r_B \cos(\gamma - 2\beta_s \mp \delta_B)}{1 + r_B^2}$$

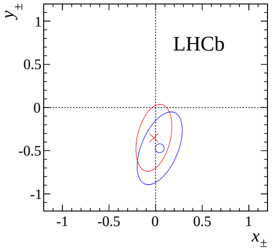
$$S_{f(\bar{f})} = \frac{\pm 2 r_B \sin(\gamma - 2\beta_s \mp \delta_B)}{1 + r_B^2}$$



- Study Dalitz structure of 3-body *B* **decays** with $B^0 \to DK^+\pi^-$
  - In principle has excellent sensitivity to γ
  - "GW method"? (Gershon-Williams - [arXiv:0909.1495])
- Get multiple interfering resonances which increase sensitivity to γ
  - $D^*{}_0(2400)^-$, $D^*{}_2(2460)^-$, $K^*(892)^0$, $K^*(1410)^0$, $K^*{}_2(1430)^0$
- Fit *B* decay Dalitz Plot for cartesian parameters (similar to GGSZ except for the *B* not the *D*)
  - $D \to K^+K^-$, $D \to \pi^+\pi^-$ - GLW-Dalitz (done by LHCb - [arXiv:1602.03455])
  - $D \to K^\pm\pi^\mp$ - ADS-Dalitz (problematic backgrounds from $B_s^0 \to DK^\pm\pi^\mp$)
  - $D \to K_S^0\pi^+\pi^-$ - GGSZ-Dalitz (double Dalitz!)



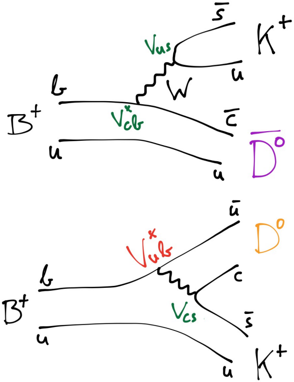




Building up sensitivity

Different *B* decays

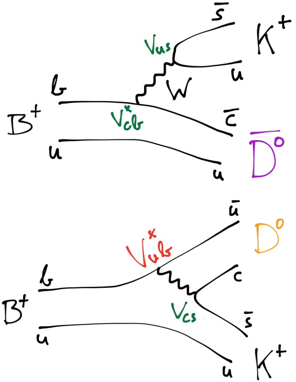
$B^\pm \to DK^\pm$	$B^\pm \to D^*K^\pm$	$B^\pm \to DK^{*\pm}$	$B^0 \to DK^{*0}$
$r_B^{DK},\ \delta_B^{DK}$	$r_B^{D^*K},\ \delta_B^{D^*K}$	$r_B^{DK^*},\ \delta_B^{DK^*}$	$r_B^{DK^{*0}},\ \delta_B^{DK^{*0}}$



Building up sensitivity

Different B decays →

$B^{\pm} \to DK^{\pm}$	$B^{\pm} \to D^{*}K^{\pm}$	$B^{\pm} \to DK^{*\pm}$	$B^{0} \to DK^{*0}$
$r_B^{DK},\ \delta_B^{DK}$	$r_B^{D^*K},\ \delta_B^{D^*K}$	$r_B^{DK^*},\ \delta_B^{DK^*}$	$r_B^{DK^{*0}},\ \delta_B^{DK^{*0}}$



Different D decays ↓

$D \to hh$	
$D \to hh\pi^0$	F^+
$D \to hhhh$	F^+
$D \to hh'$	$r_D,\ \delta_D$
$D \to hh'\pi^0$	$r_D,\ \delta_D,\ \kappa_D$
$D \to hh'hh$	$r_D,\ \delta_D,\ \kappa_D$
$D \to K_S hh$	$c_i,\ s_i$

MANY NUISANCE PARAMETERS

LHCb Input Status

			Highest Statistics	Poorer sensitivity			High potential (Dalitz structure of B)		Low stats (multibody B)
Method		B Decay / D Decay	$B^- \to D^0K^-$	$B^- \to D^0K^{*-}$ $[K^{*-} \to K^0_S\pi^-]$	$B^- \to D^{*0}K^-$ $[D^{*0} \to D^0\pi^0],[D^{*0} \to D^0\gamma]$ part-rec	full-rec	$B^0 \to D^0K^+\pi^-$ K^{*0} res	Dalitz	$B^- \to D^0K^-\pi^+\pi^-$
GLW	(+)	$D^0 \to K^+K^-$	$5\,\mathrm{fb}^{-1}$	$5\,\mathrm{fb}^{-1}$	$5\,\mathrm{fb}^{-1}$	●	$3\,\mathrm{fb}^{-1}$(●)	$3\,\mathrm{fb}^{-1}$	$3\,\mathrm{fb}^{-1}$
		$D^0 \to \pi^+\pi^-$	$5\,\mathrm{fb}^{-1}$	$5\,\mathrm{fb}^{-1}$	$5\,\mathrm{fb}^{-1}$	●	$3\,\mathrm{fb}^{-1}$(●)	$3\,\mathrm{fb}^{-1}$	$3\,\mathrm{fb}^{-1}$
		$D^0 \to K^+K^-\pi^0$	$3\,\mathrm{fb}^{-1}$(●)	-	-	-	-	-	-
		$D^0 \to \pi^+\pi^-\pi^0$	$3\,\mathrm{fb}^{-1}$	-	-	-	-	-	-
		$D^0 \to K^+K^-\pi^+\pi^-$	●	-	-	-	-	-	-
		$D^0 \to \pi^+\pi^-\pi^+\pi^-$	$3\,\mathrm{fb}^{-1}$(●)	$5\,\mathrm{fb}^{-1}$	●	●	●	-	-
	(−)	$D^0 \to K^0_S\pi^0$	●	-	-	-	-	-	-
ADS		$D^0 \to K^+\pi^-$	$3\,\mathrm{fb}^{-1}$(●)	$5\,\mathrm{fb}^{-1}$	●	●	$3\,\mathrm{fb}^{-1}$(●)	●	$3\,\mathrm{fb}^{-1}$
		$D^0 \to K^+\pi^-\pi^0$	$3\,\mathrm{fb}^{-1}$	-	-	-	-	-	-
		$D^0 \to K^+\pi^-\pi^+\pi^-$	$3\,\mathrm{fb}^{-1}$(●)	$5\,\mathrm{fb}^{-1}$	●	●	●	-	-
GGSZ		$D^0 \to K^0_S\pi^+\pi^-$	$5\,\mathrm{fb}^{-1}$	●	-	●	$3\,\mathrm{fb}^{-1}$(●)	●	●
		$D^0 \to K^0_S K^+K^-$	$5\,\mathrm{fb}^{-1}$	●	-	●	$3\,\mathrm{fb}^{-1}$(●)	●	●
		$D^0 \to K^0_S\pi^+\pi^-\pi^0$	●	-	-	-	-	-	-
		$D^0 \to K^0_S K^+K^-\pi^0$	●	-	-	-	-	-	-

KEY: ●: (update) in progress

●: requires input from Charm sector (r_D,δ_D, κ_D)

NOTE: TD result with $B^0_s \to D^-_s K^+$ $3\,\mathrm{fb}^{-1}$(●)

TD result with $B^0 \to D^-\pi^+$ $3\,\mathrm{fb}^{-1}$

GLS result from $B^- \to D^0K^-$ with $D^0 \to K^0_S K^\pm\pi^\mp$ $3\,\mathrm{fb}^{-1}$(●)

Working on $B^- \to D^0K^{*-}$ with $K^{*-} \to K^-\pi^0$ ●

LHCb Input Status

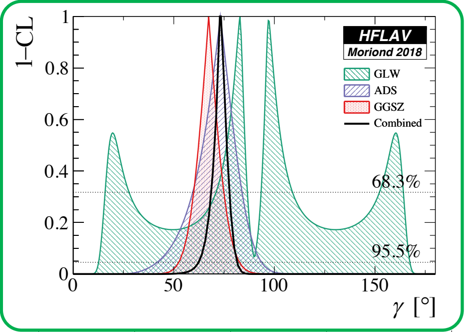
	Highest Statistics	Poorer sensitivity		High potential (Dalitz structure of B)	Low stats (multibody B)
Method / **D Decay** \ **B Decay**	$B^- \to D^0 K^-$ (GLW)	$B^- \to D^0 K^{*-}$ $[K^{*-} \to K^0_S \pi^-]$	$B^- \to D^{*0} K^-$ $[D^{*0} \to D^0\pi^0],[D^{*0} \to D^0\gamma]$	$B^0 \to D^0 K^+ \pi^-$	$B^- \to D^0 K^- \pi^+ \pi^-$
GLW (+) $D^0 \to K^+K^-$	$5\,\text{fb}^{-1}$				
GLW (+) $D^0 \to \pi^+\pi^-$	$5\,\text{fb}^{-1}$				
GLW (+) $D^0 \to K^+K^-\pi^0$	$3\,\text{fb}^{-1}$(•)				
GLW (+) $D^0 \to \pi^+\pi^-\pi^0$	$3\,\text{fb}^{-1}$	-	-		
GLW (+) $D^0 \to K^+K^-\pi^+\pi^-$	•	-	-		
GLW (+) $D^0 \to \pi^+\pi^-\pi^+\pi^-$	$3\,\text{fb}^{-1}$(•)	$5\,\text{fb}^{-1}$	•		
GLW (−) $D^0 \to K^0_S\pi^0$	•	-	-		
ADS $D^0 \to K^+\pi^-$	$3\,\text{fb}^{-1}$(•)	$5\,\text{fb}^{-1}$	•		
ADS $D^0 \to K^+\pi^-\pi^0$		-	-		
ADS $D^0 \to K^+\pi^-\pi^+\pi^-$	[illegible](•)				
GGSZ $D^0 \to K^0_S\pi^+\pi^-$	$5\,\text{fb}^{-1}$				
GGSZ $D^0 \to K^0_S K^+K^-$	$5\,\text{fb}^{-1}$				
GGSZ $D^0 \to K^0_S\pi^+\pi^-\pi^0$	•				
GGSZ $D^0 \to K^0_S K^+K^-\pi^0$	•	-	-		

GLW

These guys drive the sensitivity

GGSZ

These guys resolve the ambiguities



KEY: •: (update) in progress

•: requires input from Charm sector (r_D,δ_D, κ_D)

NOTE: TD result with $B^0_s \to D_s^- K^+$ $3\,\text{fb}^{-1}$(•)

TD result with $B^0 \to D^-\pi^+$ $3\,\text{fb}^{-1}$

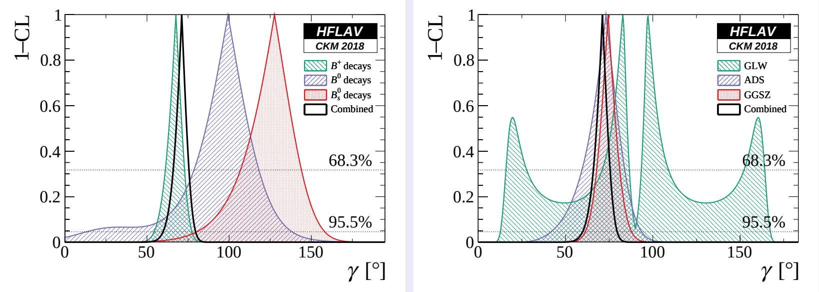
GLS result from $B^- \to D^0 K^-$ with $D^0 \to K^0_S K^\pm \pi^\mp$ $3\,\text{fb}^{-1}$(•)

Working on $B^- \to D^0 K^{*-}$ with $K^{*-} \to K^-\pi^0$ •

Combined constraints on γ

World Average (HFLAV) - [Spring update]

$$\gamma = (71.1^{+4.6}_{-5.3})^\circ$$



Indirect constraints are: $\gamma = (65.3^{+1.0}_{-2.5})^\circ$ $(\sim 2\sigma)$

Comparison between B_s^0 and B^+ initial states $\sim 2\sigma$

$(B_s^0 \to D_s^\mp K^\pm$ is hugely important for resolving this)

Sensitivity to tree-level Wilson coefficients

- We always say CKM angle γ is a SM benchmark with negligible theoretical uncertainty - $\mathcal{O}(10^{-7})^\circ$
- This is only true **if we assume no NP at tree-level**
- Brod, Lenz et. al [Phys. Rev. D92 (2015) 033002] show how much "wiggle" room is in this assumption

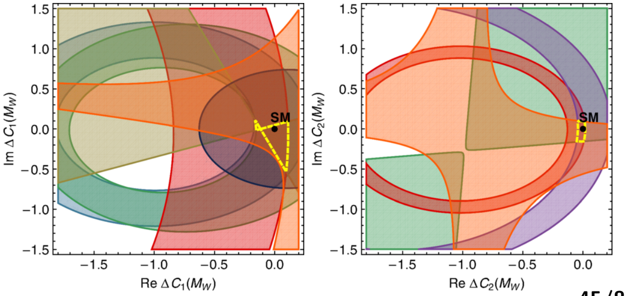
Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{ub} V_{cs}^* [\mathcal{C}_1 O_1 + \mathcal{C}_2 O_2]$$

Interference terms require modification

$$\frac{\overline{\mathcal{A}}_f}{\mathcal{A}_f} \sim e^{-i\gamma} \to e^{-i\gamma}\left[1 + \mathcal{O}\left(\frac{\Delta\mathcal{C}_1}{\mathcal{C}_2}\right)\right]$$

$$\mathcal{C}_1 = \mathcal{C}_1^{SM} + \Delta\mathcal{C}_1^{NP}$$
$$\mathcal{C}_2 = \mathcal{C}_2^{SM} + \Delta\mathcal{C}_2^{NP}$$



Sensitivity to tree-level Wilson coefficients

- A NP contribution to C_1 or C_2 gives a modification to our amplitude ratio:

Modification of amplitude ratio

$$r_B e^{i(\delta_B \pm \gamma)} \to r_B e^{i(\delta_B \pm \gamma)} \left[1 + (r_{A'} - r_A)\frac{\Delta\mathcal{C}_1^{NP}}{\mathcal{C}_2}\right]$$

In particular note that:

$$\gamma \to \gamma \left[1 + (r_A - r_{A'})\frac{\mathrm{Im}(\Delta\mathcal{C}_1^{NP})}{\mathcal{C}_2}\right]$$

where r_A ($r_{A'}$) are hadronic unknowns representing the favoured (suppressed) colour singlet / rearranged amplitude ratio

- Can redefine all GLW/ADS/GGSZ relations shifting by a single complex NP contribution $A = (r_{A'} - r_A)\Delta\mathcal{C}_1^{NP}/\mathcal{C}_2$

Modification of decay rate

$$\Gamma(B^\pm \to DK^\pm) \to \left| r_D e^{-i\delta_D} + r_B e^{i(\delta_B \pm \gamma)}(1 + A)\right|^2$$

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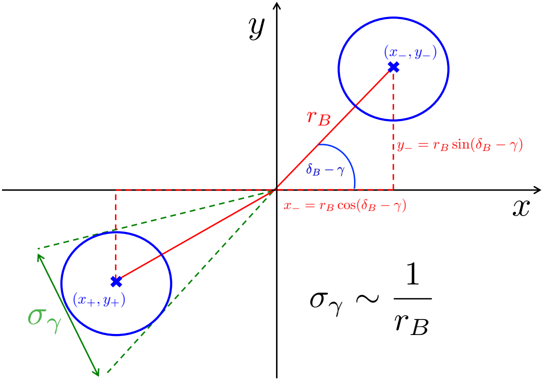

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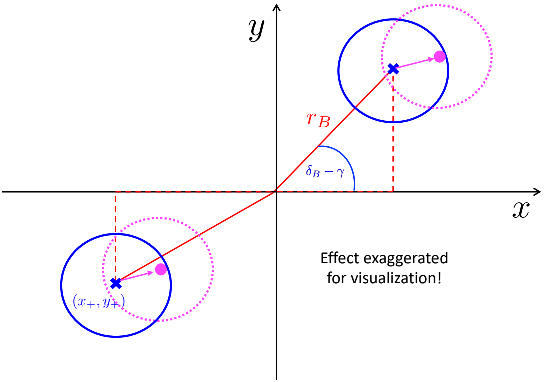
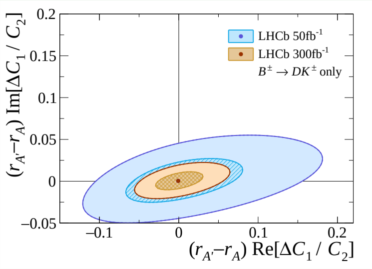


Sensitivity to tree-level Wilson coefficients

Sensitivity to generic NP contribution in complex number A

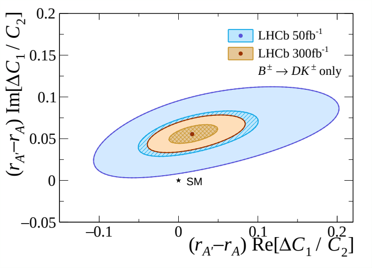
$$A = (r_{A'} - r_A)\frac{\Delta\mathcal{C}_1^{NP}}{\mathcal{C}_2}$$

Future exclusion profile for A



- What values of A can be excluded in the future

Using "still allowed" NP contribution



- Estimate $\Delta r = r_{A'} - rA \approx 0.6$ and allow $\mathrm{Im}(\Delta\mathcal{C}_1^{NP}(m_b)) \sim \mathcal{O}(10\%)$

This includes only GLW, ADS and GGSZ modes for $B^\pm \to D^0 K^\pm$

Can do even more by including rates from other $b \to c/u$ processes:

$B \to D\pi$, $B \to D^{*0}h^0$, $B \to X_{d(s)}\gamma$, $a_{sl}^{d(s)}$, $B \to \pi\pi$

Sensitivity to tree-level Wilson coefficients

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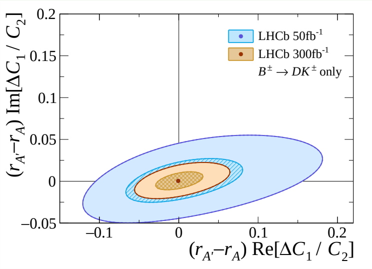

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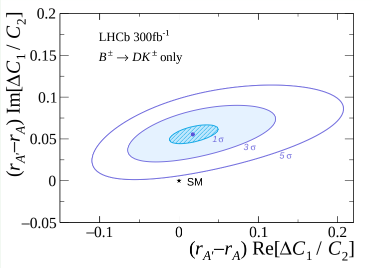

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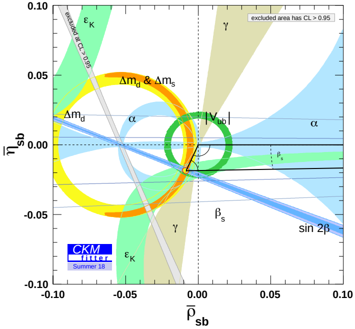
2. Measurements of ϕ_s

Measurements of ϕ_s

"The B_s^0 unitarity triangle"

$$\underbrace{V_{us}V_{ub}^*}_{\sim\lambda^4} + \underbrace{V_{cs}V_{cb}^*}_{\sim\lambda^2} + \underbrace{V_{ts}V_{tb}^*}_{\sim\lambda^2} = 0$$



- CKM fits give a precise prediction for the **small** but **non-zero** value of β_s in the SM

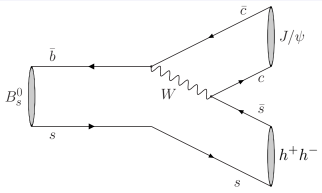
$$-2\beta_s = (-0.0370 \pm 0.0006)\,\mathrm{rad}$$

Sensitivity to ϕ_s

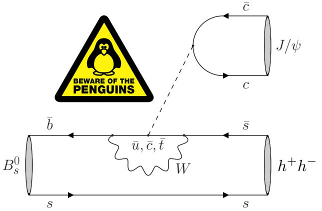
- The weak phase ϕ_s arises in the interference between decay and mixing of *e.g.* $B_s^0 \to f$ and $B_s^0 \to \overline{B}_s^0 \to f$

Golden mode: $B_s^0 \to J/\psi\, K^+ K^-$ - [Phys. Rev. Lett. 114 (2015) 041801]

$$\phi_s = \underbrace{\phi_{\rm SM}}_{-2\beta_s} + \Delta\phi_{\rm peng} + \Delta\phi_{\rm NP}$$



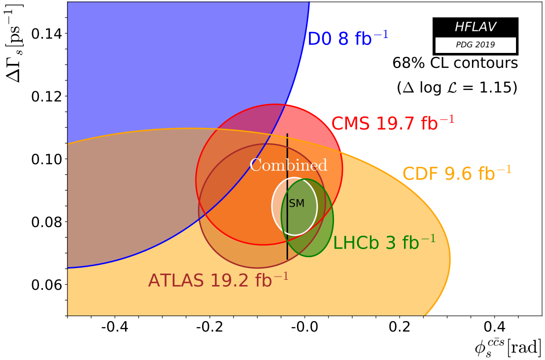
$+$



- Only for $b \to c\bar{c}s$ transitions ($\phi_s^{c\bar{c}}$)
- Estimate $\Delta\phi_{\rm peng} \approx 0.003$ [JHEP 11 (2015) 082] ($B^0 \to J/\psi\, \rho$, $B_s^0 \to J/\psi\, K^{*0}$)

- World average for these modes currently dominated by LHCb
- Consistent with both the SM and zero - [arXiv:1909.12524]

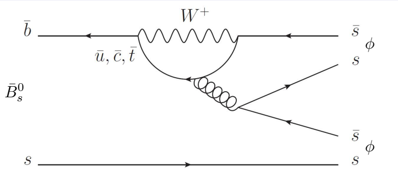
$$\phi_s^{c\bar{c}}(\mathrm{SM}) = (-0.0370 \pm 0.0006)\,\mathrm{rad}$$
$$\phi_s^{c\bar{c}}(\mathrm{WA}) = (-0.021 \pm 0.031)\,\mathrm{rad}$$



$B_s^0 \to \phi\phi$ decays

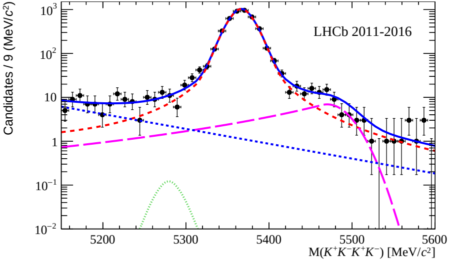
- **Pure penguin decay** - $b \to s s \bar{s}$ transition
- New Physics can be significantly enhanced
- Purely hadronic final state
- The ϕ resonance is very narrow

$B_s^0 \to \phi\phi$



$$\phi_s^{s\bar{s}} = (-0.073 \pm 0.115 \pm 0.027)\,\text{rad}$$

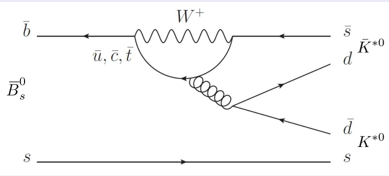
[arXiv:1907.10003]



$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ decays

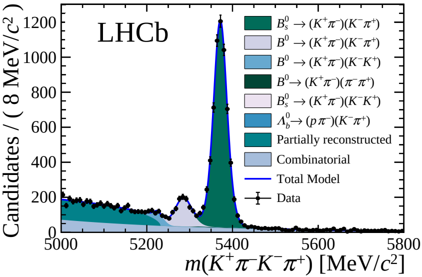
- **Pure penguin decay** - $b \to sd\bar{d}$ transition
- New Physics can be significantly enhanced and entirely different from $B_s^0 \to J/\psi\,\phi$ and $B_s^0 \to \phi\phi$
- Expect similar statistical precision to $B_s^0 \to \phi\phi$
- CPV in decay is also possible

$B_s^0 \to K^{*0}\overline{K}^{*0}$



$$\phi_s^{d\bar{d}} = (-0.10 \pm 0.13 \pm 0.14)\,\mathrm{rad}$$

[JHEP 03 (2018) 140]



$$\phi_s^{c\bar{c}} \neq \phi_s^{s\bar{s}} \neq \phi_s^{d\bar{d}}$$

Measurement of ϕ_s in $B^0_{(s)} \to (K^+\pi^-)(K^-\pi^+)$ decays

- **A combined B^0 and $B^0_s \to (K^+\pi^-)(K^-\pi^+)$ analysis** would be very powerful
- The SU(3) partner B^0 mode is a $\Delta S = 0$ transition and expected to have a much smaller NP contribution
- Allows for much easier theory interpretation as B^0 mode sets a SM benchmark for comparison with B^0_s mode
- Simplified time-dependent rate asymmetry for each polarization amplitude

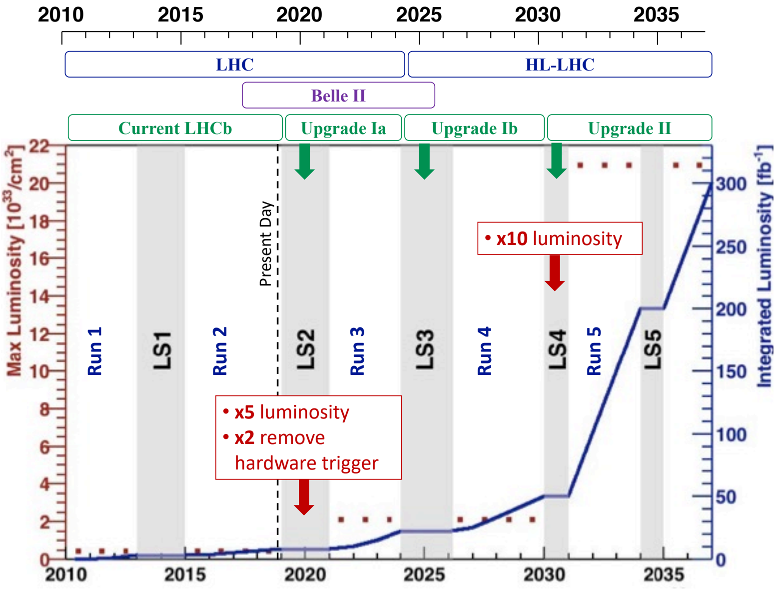
$$A_{CP}(t) \approx (1-2w)e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2} \eta_f \sin(\phi_s) \sin(\Delta m_s t)$$

Experimentally challenging and requires use of LHCb's full armoury

- Need to tag initial B flavour
- Decay-time dependence (1 time dimension)
- Seperate various wide K^* contributions (2 mass dimensions)
- Seperate different spin components (3 angular dimensions)
- Purely hadronic final state

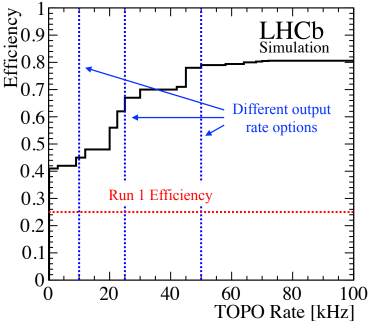
Summary and Outlook

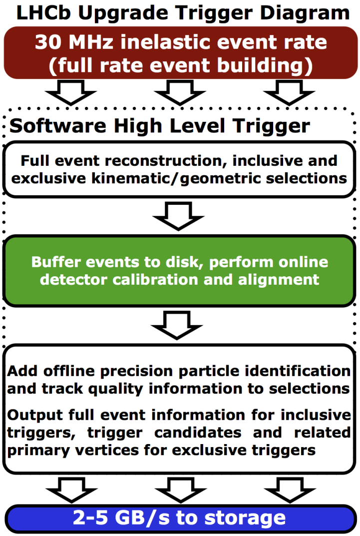
Future prospects



Future prospects

- LHCb Upgrade will be installed in LS2
- Ready for operation in Run 3
- Completely redesigned tracking systems
- Redesigned readout for all subsystems





Summary

- Finding new sources of CP violation can lead us to New Physics
- Measurements of CKM elements are becoming increasingly precise

Measurements of γ

- Will evenutally reach $\mathcal{O}(0.4^\circ)$ precision
- Will have $< 1^\circ$ precision independently in B^+, B^0 and B_s^0 modes
- Will allow for penguin free measurement of ϕ_s with $\sim 0.02\,\mathrm{rad}$ precision
- Can eventually set limits on / directly probe generic new physics contributions at tree-level
- Have the potential to be even more sophisticated than this when including additional inputs

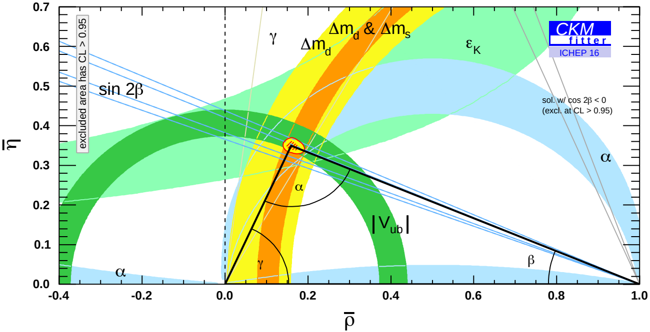
Measurements of ϕ_s

- Will eventually reach $\mathcal{O}(0.003\,\mathrm{rad})$ precision for $b \to c\bar{c}s$
- Will eventually reach $\mathcal{O}(0.01\,\mathrm{rad})$ precision for penguin modes $b \to s s\bar{s}$ and $b \to s d\bar{d}$

The SM is beautiful, now let's **BREAK IT!**

BACK UP

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



How does CP-violation manifest itself?

- Must have **two** interfering amplitudes with **different** strong (δ) and weak (ϕ) phases
- For a B_s^0 decay to a CP-eigenstate, f, CP-violation effects depend on $\lambda = \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}$

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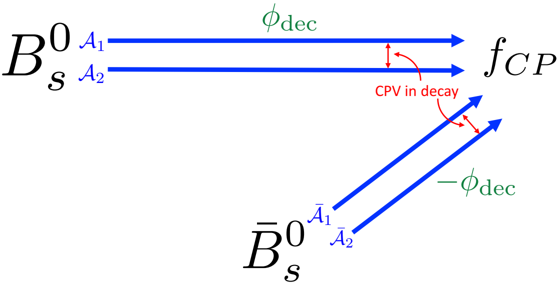
CPV in decay:

- $P(B_s^0 \to f) \neq P(\bar{B}_s^0 \to f)$
- $|\bar{\mathcal{A}}_f / \mathcal{A}_f| \neq 1$



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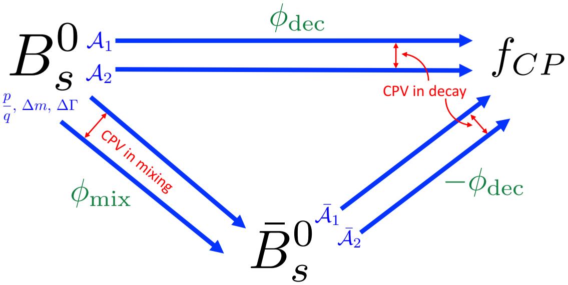
CPV in mixing:

- $P(B_s^0 \to \bar{B}_s^0) \neq P(\bar{B}_s^0 \to B_s^0)$
- $|q/p| \neq 1$



How does *CP*-violation manifest itself?

- Must have **two** interfering amplitudes with **different** strong (δ) and weak (ϕ) phases
- For a B_s^0 decay to a *CP*-eigenstate, f, *CP*-violation effects depend on $\lambda = \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}$

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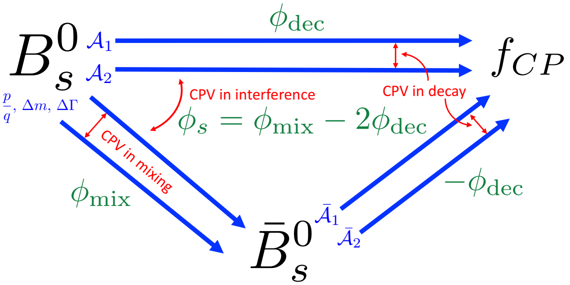


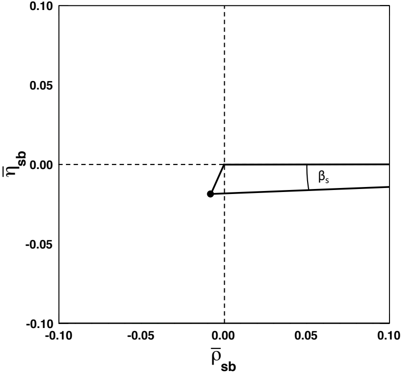
CPV in the interference between decay and mixing:

- $P(B_s^0 \to f) \neq P(B_s^0 \to \bar{B}_s^0 \to f)$
- $\arg(\lambda) \neq 0$

- Unitarity imposes several conditions ($V^\dagger V = \mathbb{1}$)
  - Gives rise to "unitarity" triangles
  - The triangles' area dictates the **total amount of CPV** in the quark sector

Wolfenstein parametrisation

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



- β_s is incredibly small and precisely known in the SM
- Potential NP effects are large

New Physics effects in the flavour sector

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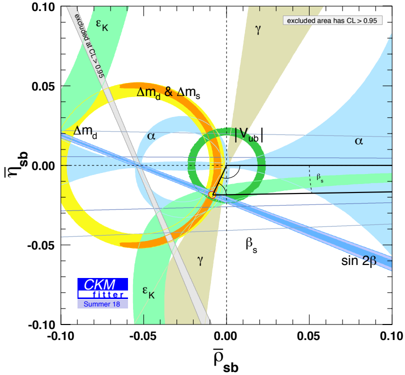


- β_s is incredibly small and precisely known in the SM
- Potential NP effects are large

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

- γ is known very well
- Can be determined entirely from tree decays
  - Unique property among all *CP* violation parameters
  - Hadronic parameters can be determined from data
- Neglible theoretical uncertainty (Zupan and Brod 2013)

Theory uncertainty on γ

$\delta\gamma/\gamma \approx \mathcal{O}(10^{-7})$ - [arXiv:1308.5663]

- γ can probe for new physics at extrememly high energy scales (Zupan)
  - (N)MFV new physics scenarios: $\sim \mathcal{O}(10^2)$ TeV
  - gen. FV new physics scenarios: $\sim \mathcal{O}(10^3)$ TeV
- NP contributions to $C_{1,2}$ can cause sizeable shifts ($\mathcal{O}(4^\circ)$) in γ (Brod, Lenz et. al 2014) - [arXiv:1412.1446]

γ from experiment

- γ is NOT known very well
- It is quite challenging to measure
- The decay rates are small

Branching ratio for suppressed γ mode

$$BR(B^- \to DK^-, D \to \pi K) \approx 2 \times 10^{-7}$$

- Small interference effect typically $\sim 10\%$
- Fully hadronic decays - hard to trigger on
- Many channels have a K_S^0 or π^0 in the final state - low efficiency at LHCb
- Many different decay channels, many observables and many hadronic unknowns make it statistically challenging
- Inputs for charm parameters are needed

Measuring γ

Categorise decays sensitive to γ depending on the $\overset{(-)}{D}{}^0 \to f$ final state

- GLW (Gronau, London, Wyler) [1991]
  - CP eigenstates e.g. $D \to KK$, $D \to \pi\pi$
- ADS (Atwood, Dunietz, Soni) [1997,2001]
  - CF or DCS decays e.g. $D \to K\pi$
- GGSZ (Giri, Grossman, Soffer, Zupan) [2003]
  - 3-body final states e.g. $D \to K^0_S\pi\pi$
- TD (Time-dependent)
  - Interference between mixing and decay e.g. $B^0_s \to D^-_s K^+$ [phase is $(\gamma - 2\beta_s)$]
  - Penguin free measurement of ϕ_s?
- Dalitz
  - Look at 3-body B decays with D^0 or $\overline{D}^0$ in the final state, e.g. $B^0 \to D^0 K^+\pi^-$

GLW Method

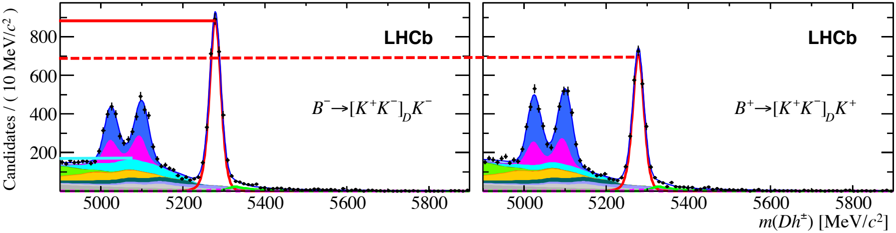
- CP eigenstates e.g. $D \to KK$, $D \to K^0_S \pi^0$
- Gronau, London, Wyler (1991)

- [Phys. Lett. B253 (1991) 483]
- [Phys. Lett. B265 (1991) 172]

GLW observables

$$A_{CP} = \frac{\Gamma(B^- \to D^0_{CP} K^-) - \Gamma(B^+ \to D^0_{CP} K^+)}{\Gamma(B^- \to D^0_{CP} K^-) + \Gamma(B^+ \to D^0_{CP} K^+)} = \frac{\pm 2 r_B \sin(\delta_B)\sin(\gamma)}{1 + r_B^2 \pm 2 r_B \cos(\delta_B)\cos(\gamma)} \quad (1)$$

$$R_{CP} = \frac{\Gamma(B^- \to D^0_{CP} K^-) + \Gamma(B^+ \to D^0_{CP} K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to D^0 K^+)} = 1 + r_B^2 \pm 2 r_B \cos(\delta_B)\cos(\gamma) \quad (2)$$



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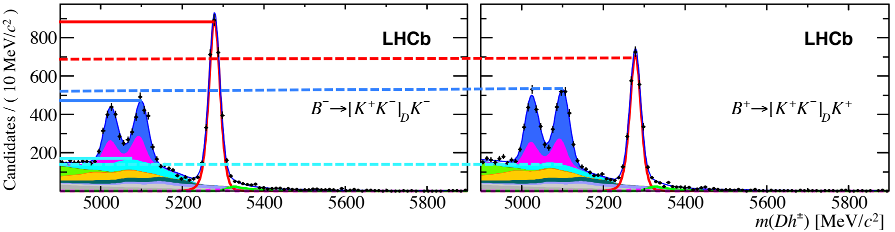

- **LHCb has recently extracted GLW observables from partially reconstructed $B^- \to D^{*0} K^-$ in the same fit** - [Phys. Lett. B777 (2018) 16]

GLW Method

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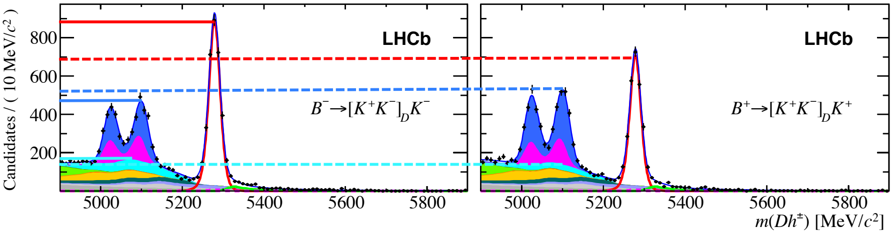


- **LHCb has recently extracted GLW observables from partially reconstructed $B^- \to D^{*0}K^-$ in the same fit** - [Phys. Lett. B777 (2018) 16]
- Can extend to quasi-CP-eigenstates ($D^0 \to KK\pi^0$) if fraction of CP content, F^+, is known

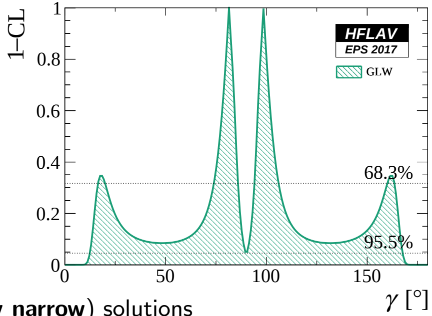
GLW Method

- CP eigenstates e.g. $D \to KK$, $D \to K^0_S \pi^0$
- Gronau, London, Wyler (1991)
- [Phys. Lett. B253 (1991) 483]
- [Phys. Lett. B265 (1991) 172]

GLW observables

$$A_{CP} = \frac{\Gamma(B^- \to D^0_{CP} K^-) - \Gamma(B^+ \to D^0_{CP} K^+)}{\Gamma(B^- \to D^0_{CP} K^-) + \Gamma(B^+ \to D^0_{CP} K^+)} = \frac{\pm 2 r_B (2F^+ + 1) \sin(\delta_B) \sin(\gamma)}{1 + r_B^2 \pm 2 r_B (2F^+ + 1) \cos(\delta_B) \cos(\gamma)} \quad (1)$$

$$R_{CP} = \frac{\Gamma(B^- \to D^0_{CP} K^-) + \Gamma(B^+ \to D^0_{CP} K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to D^0 K^+)} = 1 + r_B^2 \pm 2 r_B (2F^+ + 1) \cos(\delta_B) \cos(\gamma) \quad (2)$$



- Multiple (**but very narrow**) solutions
- Require knowledge of F^+ from charm friends

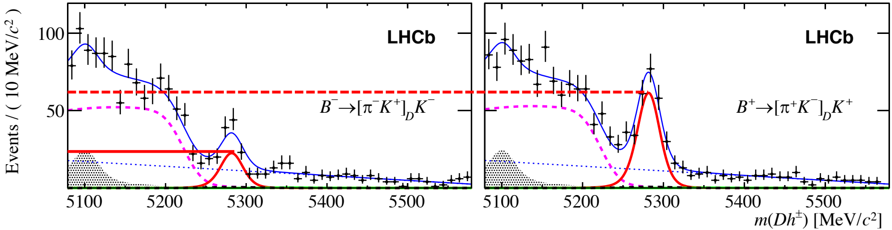
- CF or DCS decays e.g. $D \to K\pi$
- Atwood, Dunietz, Soni (1997,2001)

- [Phys. Rev. D63 (2001) 036005]
- [Phys. Rev. Lett. 78 (1997) 3257]

ADS observables

$$A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)} = \frac{2 r_B r_D \sin(\delta_B + \delta_D)\sin(\gamma)}{r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma)} \quad (3)$$

$$R_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma) \quad (4)$$



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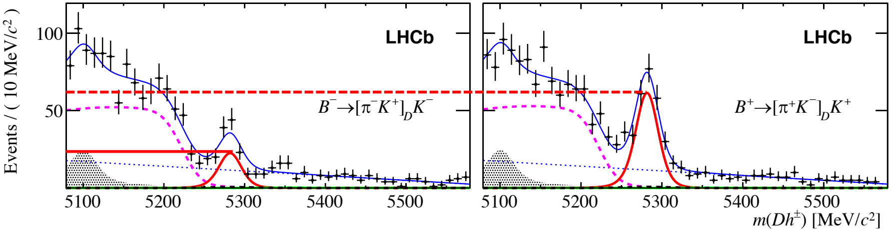

- **Much harder to extract partially reconstructed observables because of $B_s^0 \to D^{(*)0} K^+ \pi^-$ backgrounds.**

ADS Method

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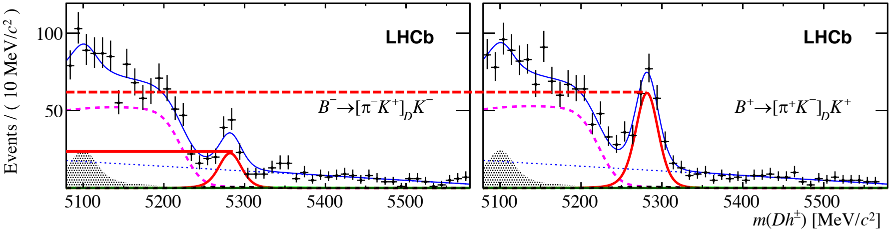

- **Much harder to extract partially reconstructed observables because of $B_s^0 \to D^{(*)0} K^+ \pi^-$ backgrounds.**
- Can extend to multibody-DCS-decays ($D^0 \to K\pi\pi^0$) if dilution from interference, κ_D, is known

ADS Method

- CF or DCS decays e.g. $D \to K\pi$
- Atwood, Dunietz, Soni (1997,2001)
- [Phys. Rev. D63 (2001) 036005]
- [Phys. Rev. Lett. 78 (1997) 3257]

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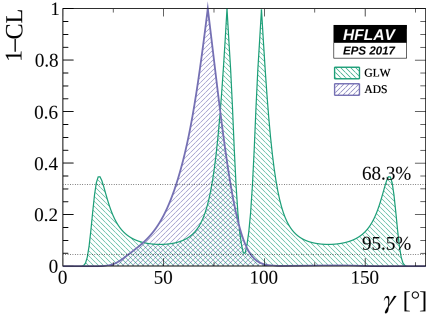


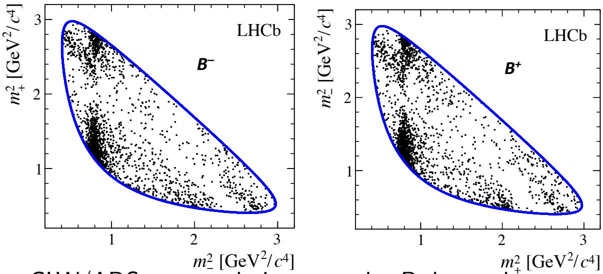
- A single (**yet broader**) solution
- Require knowledge of r_D, δ_D, κ_D from charm friends

GGSZ Method

- 3-body final states e.g. $D \to K_S^0 \pi\pi$
- Giri, Grossman, Soffer, Zupan (2003)
- [Phys. Rev. D68 (2003) 054018]

GGSZ observables (partial rate as function of Dalitz position)

$$d\Gamma_{B^\pm}(\mathbf{x}) = A^2_{(\pm,\mp)} + r_B^2 A^2_{(\mp,\pm)} + 2A_{(\pm,\mp)}A_{(\mp,\pm)}\Big[\underbrace{r_B\cos(\delta_B \pm \gamma)}_{x_\pm}\underbrace{\cos(\delta_{D(\pm,\mp)})}_{c_i} + \underbrace{r_B\sin(\delta_B \pm \gamma)}_{y_\pm}\underbrace{\sin(\delta_{D(\pm,\mp)})}_{s_i}\Big] \quad (5)$$



- Essentially a GLW/ADS type analysis across the D decay phase space
- Excellent sensitivity from interference between various contributions

GGSZ Method

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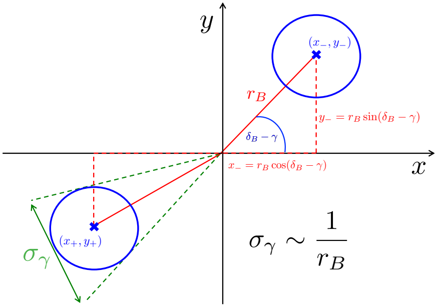
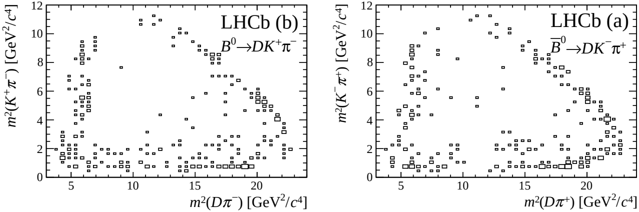
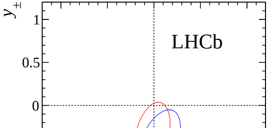


- $x_\pm + iy_\pm = r_B e^{i(\delta_B \pm \gamma)}$
- **Uncertainty on γ is inversely proportional to central value of hadronic unknown!!**
- Fluctuation in nuisance parameter = fluctuation in error on parameter of interest!

Dalitz (GW) Method

- Use Dalitz structure of **B** decays
- $B^0 \to D^0 K^+ \pi^-$
- Gershon, Williams (2009)
- [Phys. Rev. D80 (2009) 092002]
- Get multiple interfering resonances which increase sensitivity to γ
  - $D_0^*(2400)^-$, $D_2^*(2460)^-$, $K^*(892)^0$, $K^*(1410)^0$, $K_2^*(1430)^0$
- Fit B decay Dalitz Plot for cartesian parameters (similar to GGSZ except for the B not the D)
  - $D \to K^+K^-$, $D \to \pi^+\pi^-$ - GLW-Dalitz (done by LHCb - [arXiv:1602.03455])
  - $D \to K^\pm \pi^\mp$ - ADS-Dalitz (difficult due to backgrounds from $B_s^0 \to D^{(*)0} K^+ \pi^-$)
  - $D \to K_S^0 \pi^+ \pi^-$ - GGSZ-Dalitz (double Dalitz!)



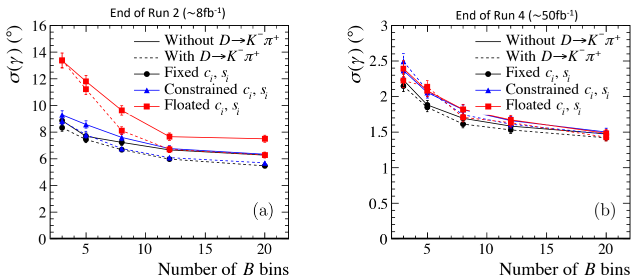


Dalitz (GW) Method

- Some studies of future prospects of the B Dalitz method with GGSZ modes in [arXiv:1712.07853]
- Can include GLW, ADS and GGSZ modes in single framework to improve constraints on B Dalitz bins, $\varkappa_j$ and σ_j
- The double Dalitz method has sufficient information (large number of bins) to extract c_i and s_i

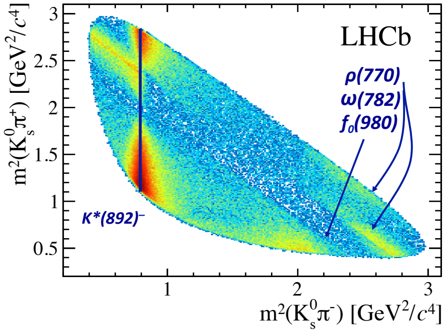
Double Dalitz observables (partial rate as function of both Dalitz positions)

$$|A|^2 = |A_B|^2|A_D|^2 + |\bar{A}_B|^2|\bar{A}_D|^2 + 2|A_B||A_D||\bar{A}_B||\bar{A}_D|[(\varkappa c - \sigma s)\cos(\gamma) - (\varkappa s + \sigma c)\sin(\gamma)]$$

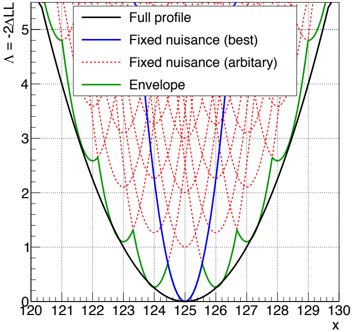


Amplitude measurements of γ

- Most sensitive method to measure γ is a full kinematic analysis
- Take advantage of the rich structure in the kinematic plane
- Make use of "discrete profiling method" I developed at Imperial College
- Build upon expertise in amplitude models at Cambridge



Dauncey, Kenzie, Wardle, *JINST* **10** (2015) 04, P04015



- Exploit several decay modes
  - $B^- \to D^0 K^-$, $B^- \to D^0 K^{*-}$, $B^- \to D^{*0} K^-$, $B^0 \to D^0 K^{*0}$

Status of γ at LHCb

Method		D Decay \ B Decay	Highest Statistics: $B^- \to D^0 K^-$	Poorer sensitivity: $B^- \to D^0 K^{*-}$ $[K^{*-} \to K^0_S \pi^-]$	Poorer sensitivity: $B^- \to D^{*0} K^-$ $[D^{*0} \to D^0\pi^0]$,$[D^{*0} \to D^0\gamma]$		High potential (Dalitz structure of B): $B^0 \to D^0 K^+ \pi^-$		Low stats (multibody B): $B^- \to D^0 K^- \pi^+ \pi^-$
					part-rec	full-rec	K^{*0} res	Dalitz	
GLW	(+)	$D^0 \to K^+ K^-$	$5\,\text{fb}^{-1}$	$5\,\text{fb}^{-1}$	$5\,\text{fb}^{-1}$	•	$3\,\text{fb}^{-1}$(•)	$3\,\text{fb}^{-1}$	$3\,\text{fb}^{-1}$
		$D^0 \to \pi^+ \pi^-$	$5\,\text{fb}^{-1}$	$5\,\text{fb}^{-1}$	$5\,\text{fb}^{-1}$	•	$3\,\text{fb}^{-1}$(•)	$3\,\text{fb}^{-1}$	$3\,\text{fb}^{-1}$
		$D^0 \to K^+ K^- \pi^0$	$3\,\text{fb}^{-1}$(•)	-	-	-	-	-	-
		$D^0 \to \pi^+ \pi^- \pi^0$	$3\,\text{fb}^{-1}$	-	-	-	-	-	-
		$D^0 \to K^+ K^- \pi^+ \pi^-$	•	-	-	-	-	-	-
		$D^0 \to \pi^+ \pi^- \pi^+ \pi^-$	$3\,\text{fb}^{-1}$(•)	$5\,\text{fb}^{-1}$	•	•	•	-	-
	(−)	$D^0 \to K^0_S \pi^0$	•	-	-	-	-	-	-
ADS		$D^0 \to K^+ \pi^-$	$3\,\text{fb}^{-1}$(•)	$5\,\text{fb}^{-1}$	•	•	$3\,\text{fb}^{-1}$(•)	•	$3\,\text{fb}^{-1}$
		$D^0 \to K^+ \pi^- \pi^0$	$3\,\text{fb}^{-1}$	-	-	-	-	-	-
		$D^0 \to K^+ \pi^- \pi^+ \pi^-$	$3\,\text{fb}^{-1}$(•)	$5\,\text{fb}^{-1}$	•	•	•	-	-
GGSZ		$D^0 \to K^0_S \pi^+ \pi^-$	$5\,\text{fb}^{-1}$	•	-	•	$3\,\text{fb}^{-1}$(•)	•	•
		$D^0 \to K^0_S K^+ K^-$	$5\,\text{fb}^{-1}$	•	-	•	$3\,\text{fb}^{-1}$(•)	•	•
		$D^0 \to K^0_S \pi^+ \pi^- \pi^0$	•	-	-	-	-	-	-
		$D^0 \to K^0_S K^+ K^- \pi^0$	•	-	-	-	-	-	-

KEY: •: (update) in progress

•: requires input from Charm sector (r_D,δ_D, κ_D)

NOTE: TD result with $B^0_s \to D^-_s K^+$ $3\,\text{fb}^{-1}$(•)

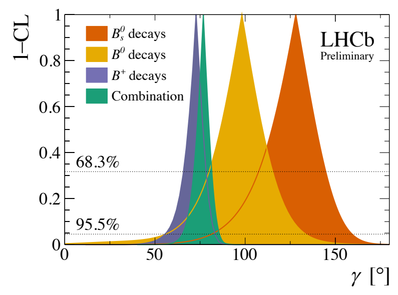
TD result with $B^0 \to D^- \pi^+$ $3\,\text{fb}^{-1}$

GLS result from $B^- \to D^0 K^-$ with $D^0 \to K^0_S K^\pm \pi^\mp$ $3\,\text{fb}^{-1}$(•)

Working on $B^- \to D^0 K^{*-}$ with $K^{*-} \to K^- \pi^0$ •

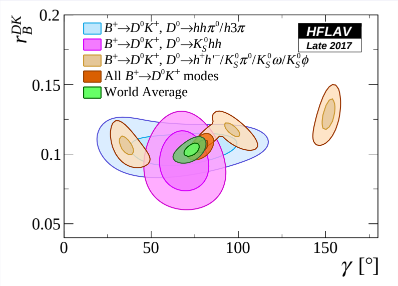
LHCb Average

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



World Average (HFLAV)

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



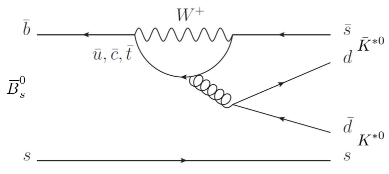
Indirect constraints are: $\gamma = (65.3^{+1/0}_{-2.5})^\circ$ $(\sim 2\sigma)$

Comparison between B_s^0 and B^+ initial states $\sim 2\sigma$

$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ decays

- **Pure penguin decay** - $b \to s d\bar{d}$ transition
- New Physics can be significantly enhanced and entirely different from $B_s^0 \to J/\psi\,\phi$ and $B_s^0 \to \phi\phi$
- Expect similar statistical precision to $B_s^0 \to \phi\phi$
- CPV in decay is also possible

$B_s^0 \to K^{*0}\overline{K}^{*0}$



$\phi_s^{d\bar{d}} = ?$

LHCb-PAPER-2017-048

Experimentally challenging:

- Low branching fraction (100 times smaller than $B_s^0 \to J/\psi\,\phi$)
- Purely hadronic final state
- K^* is fairly wide (several resonant and non-resonant components)
- Several peaking backgrounds

$$\phi_s^{c\bar{c}} \neq \phi_s^{s\bar{s}} \neq \phi_s^{d\bar{d}}$$

Ingredients required for a ϕ_s analysis

- In the simplest case, and **only** if there is no CP-violation in decay, the time-dependent CP-asymmetry

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0_s \to f) - \Gamma(B^0_s \to f)}{\Gamma(\overline{B}^0_s \to f) + \Gamma(B^0_s \to f)} = \eta_f \sin(\phi_s) \sin(\Delta m_s t)$$

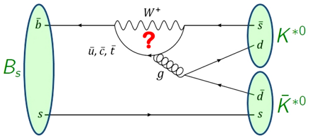
- Experimentally

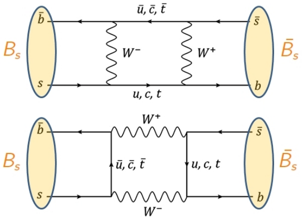
$$A_{CP}(t) \approx (1 - 2w) e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2} \eta_f \sin(\phi_s) \sin(\Delta m_s t)$$

  - w: Probability the initial B flavour was tagged incorrectly
  - σ_t: Decay-time resolution
  - η_f: CP-eigenvalue $\implies$ angular analysis
- **Important requirements**
  - Good decay time resolution
  - Good flavour tagging
  - Sufficient statistics for an angular analysis
  - Good particle identification

The $B_s^0 \to K^{*0}\overline{K}^{*0}$ decay

- **Interference between $B_s^0 \to K^{*0}\overline{K}^{*0}$ and $B_s^0 \to \overline{B}_s^0 \to K^{*0}\overline{K}^{*0}$**
  - where $K^{*0} \to K^+\pi^-$ and $\overline{K}^{*0} \to K^-\pi^+$
- **Gives access to *CP*-violating phase $\phi_s^{d\bar{d}}$**
- First discovered by LHCb in [Phys. Lett. **B709** (2012) 50]
  - Update in [JHEP **07** (2015) 166]
- Discussed extensively in the literature as a promising mode for New Physics
  - Fleisher et. al. [Phys. Lett. **B660** (2008) 212]
  - Ciuchini et. al. [Phys. Rev. Lett. **100** (2008) 031802]
  - Descotes-Genon et. al. [Phys. Rev. **D85** (2012) 034010]
  - Bhattacharya et. al. [Phys. Lett. **B717** (2012) 403]





SM expectation:

- $|\lambda| = \dfrac{p}{q}\dfrac{\bar{A}_f}{A_f} \approx 1$
- $\phi_s^{d\bar{d}} = \phi_{\text{mix}} - 2\phi_{\text{decay}} \approx 0$

Current key responsibilties in LHCb

Physics working group convenor (Jan 2017 - Jan 2019)

- Nominated "B to open charm" (γ analysis) WG convenor in November 2016
- **One of the eight top level physics analysis groups in LHCb**
- Member of the Physics Planning Group $\rightarrow$ liase between WG and management
- Manage ~ 80 physicists studying CP-violation (including all γ analyses) in B decays

Statistics expert

- Develop and manage the "`GammaCombo`" statistical package [gammacombo.github.io]
- Advise and liase with several analysis groups

Trigger expert on call

- Developed lifetime unbiased triggering in LHCb