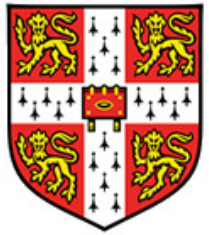

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CKM angle γ at LHCb

Matthew Kenzie
on behalf of the LHCb Collaboration

BEAUTY 2018, Elba

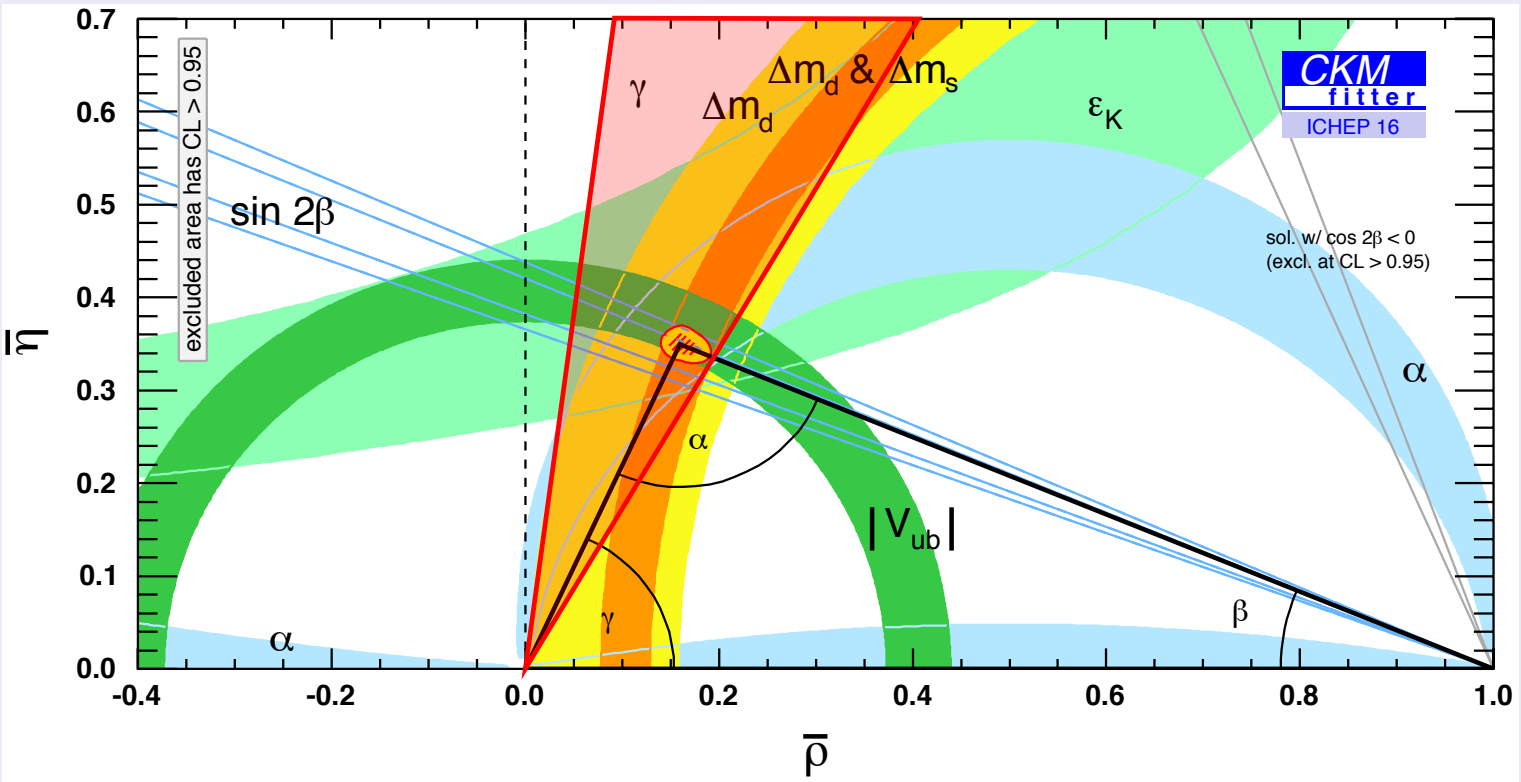
May 7, 2018

CKM picture is now well verified

- Angle γ is the *least well known* CKM constraint (*although now only just*)
  - **SM benchmark** - only CKM angle accessible at **tree level**

Current Status

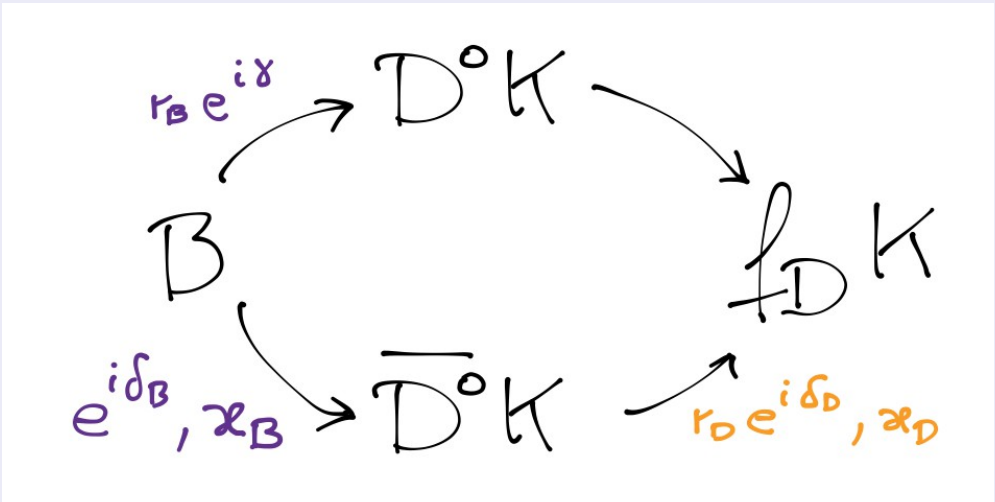
Direct: $\gamma = (73.5^{+4.3}_{-5.0})^\circ$ **Indirect:** $\gamma = (65.3^{+1.0}_{-2.5})^\circ$ **Pre-LHCb:** $\gamma = (73^{+22}_{-25})^\circ$



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 $B^\pm \to {}^{(-)}D^0 K^\pm$:
  - Transitions themselves have different final states (D^0 and $\overline{D}^0$)
  - Interference occurs when D^0 and $\overline{D}^0$ decay to the same final state f

Reconstruct the $D^0/\overline{D}^0$ in a final state accessible to both to acheieve 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]

γ from theory

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

- 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

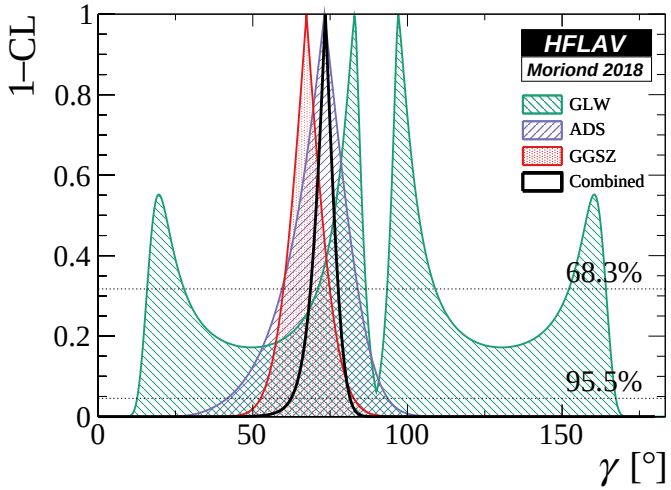
$$BR(B^- \to DK^-, D \to \pi K) \approx 2 \times 10^{-7}$$

- Small interference effect typically $\sim 10\%$
- Fully hadronic decays - hard to trigger on
- Many channels have a K^0_S 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
- External inputs for some beauty and charm parameters are needed

Measuring 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

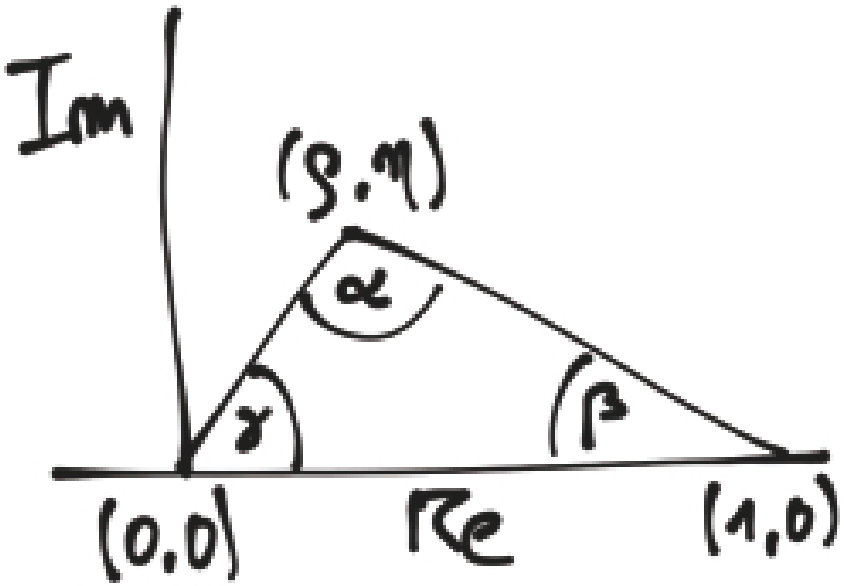


- GLW
  - CP eigenstates e.g. $D \to KK$, $D \to \pi\pi$
  - [Phys. Lett. B253 (1991) 483]
  - [Phys. Lett. B265 (1991) 172]
- ADS
  - CF or DCS decays e.g. $D \to K\pi$
  - [Phys. Rev. D63 (2001) 036005]
  - [Phys. Rev. Lett. 78 (1997) 3257]
- GGSZ
  - 3-body final states e.g. $D \to K^0_S\pi\pi$
  - [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]

Overview

Today I will cover a small selection of recent results:

1. Model-independent measurement of γ with $B^+ \to DK^+$, $D \to K^0_S hh$ decays - [LHCb-PAPER-2018-017]
   - GGSZ analysis update with Run 2 data
2. Time-dependent analysis with $B^0 \to D^- \pi^+$ - [LHCb-PAPER-2018-009]
   - Very large statistics sample with decay / mixing interference
3. Updated LHCb combination - [LHCb-CONF-2018-002]
4. Recently updated World Average - [HFLAV]



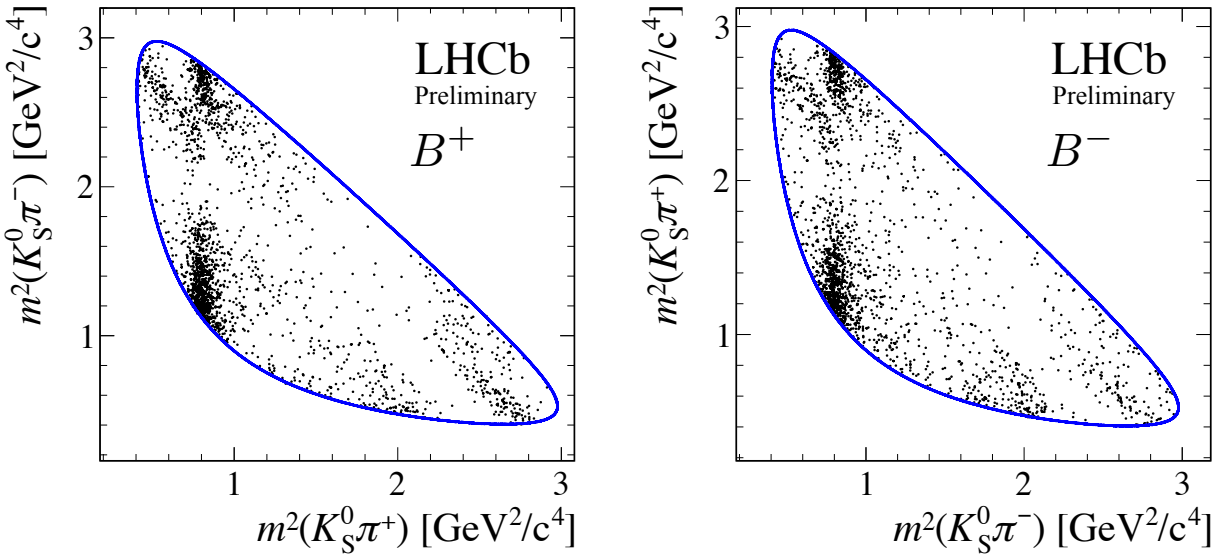
GGSZ Method

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

GGSZ observables (partial rate as function of Dalitz position)

$$d\Gamma_{B^\pm}(\mathbf{x}) = A^2_{(\pm,\mp)} + r_B^2 A^2_{(\mp,\pm)} + 2A_{(\pm,\mp)}A_{(\mp,\pm)}\left[r_B \cos(\delta_B \pm \gamma)\cos(\delta_{D(\pm,\mp)}) + r_B \sin(\delta_B \pm \gamma)\sin(\delta_{D(\pm,\mp)})\right] \quad (1)$$

From [LHCb-PAPER-2018-017]



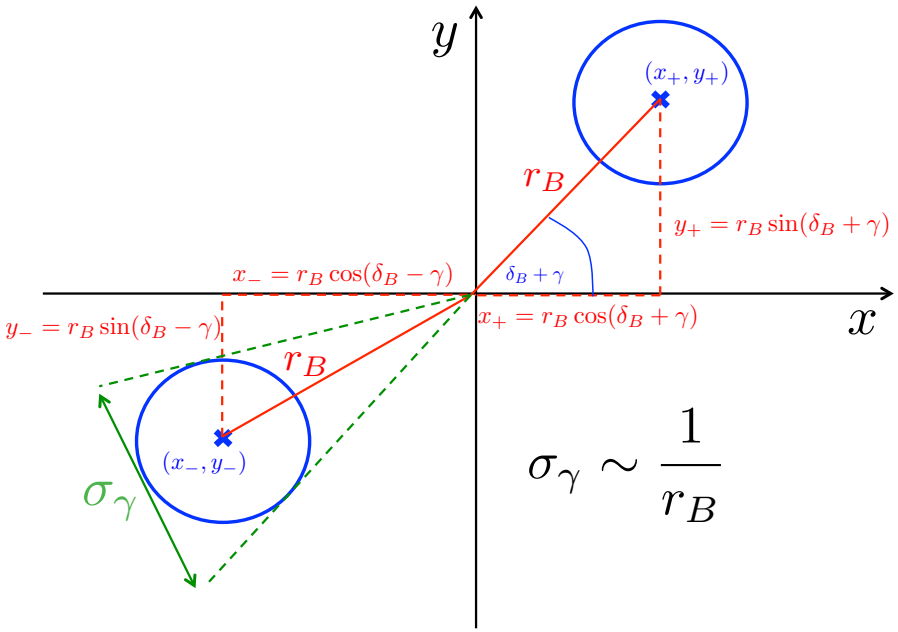
- Essentially a GLW/ADS type analysis across the D decay phase space
- Excellent sensitivity from interference between various contributions

GGSZ Method

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

GGSZ observables (partial rate as function of Dalitz position)

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

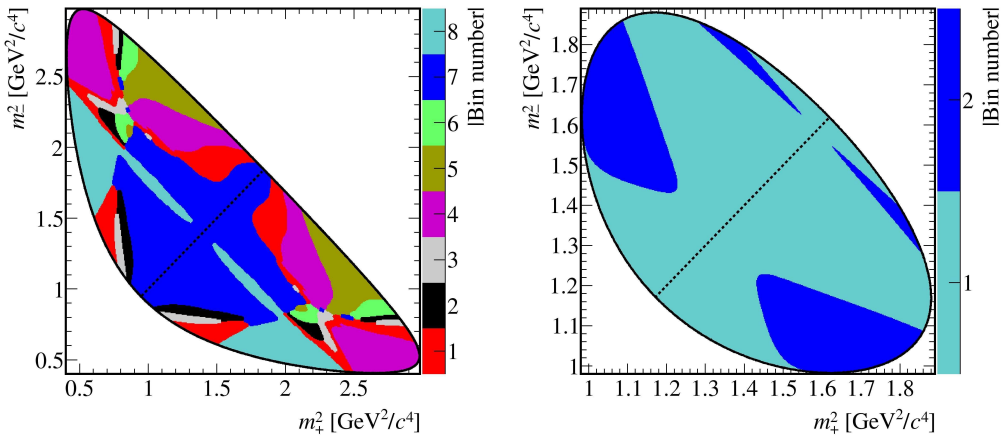


- $x_\pm + iy_\pm = r_B e^{i(\delta_B \pm \gamma)}$
- **Uncertainty on γ is inversely proportional to central value of hadronic unknown!!**
- Fluctuation in nuisance parameter = fluctuation in error on parameter of interest!

Model-independent GGSZ Analysis

[LHCb-PAPER-2018-017]

- NEW LHCb paper with Run 2 data
- Consider both $D \to K^0_S \pi\pi$ and $D \to K^0_S KK$ 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

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

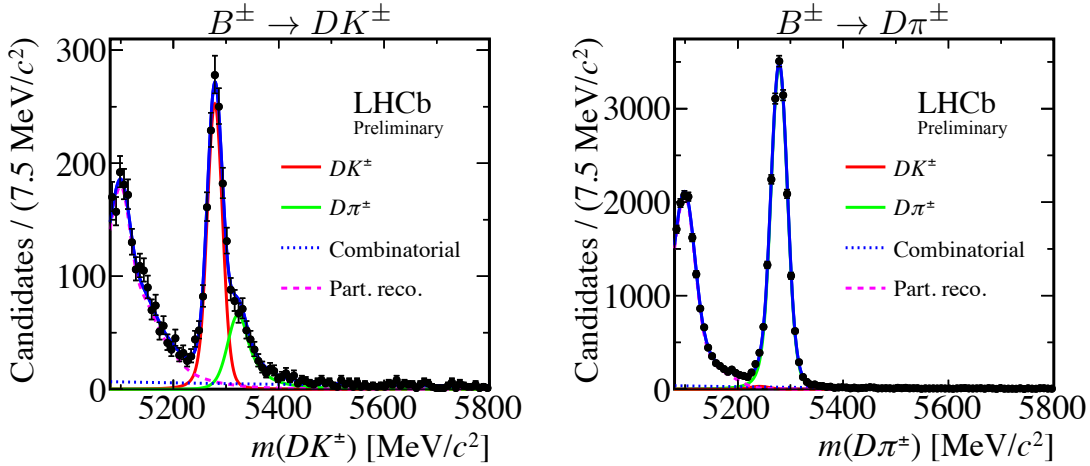
$$N^-_{\pm i} = h_{B^-}\left[F_{\pm i} + (x_-^2 + y_-^2)]F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} - y_- s_{\pm i})\right]$$

- $N^{\pm}_{\pm i}$ - 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

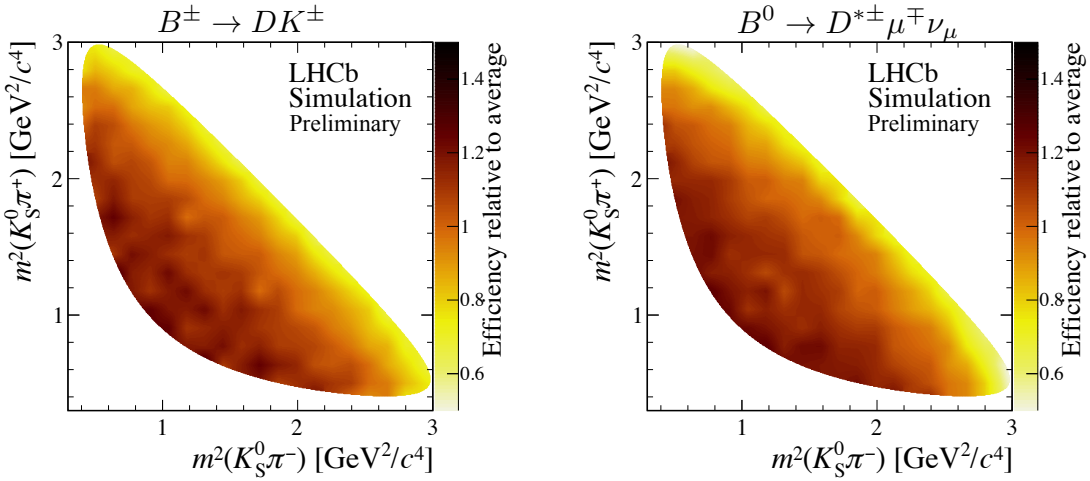
Model-independent GGSZ Analysis

[LHCb-PAPER-2018-017]

- Control mass shapes and cross-feed with $B^{\pm} \to D^0\pi^{\pm}$ decay mode



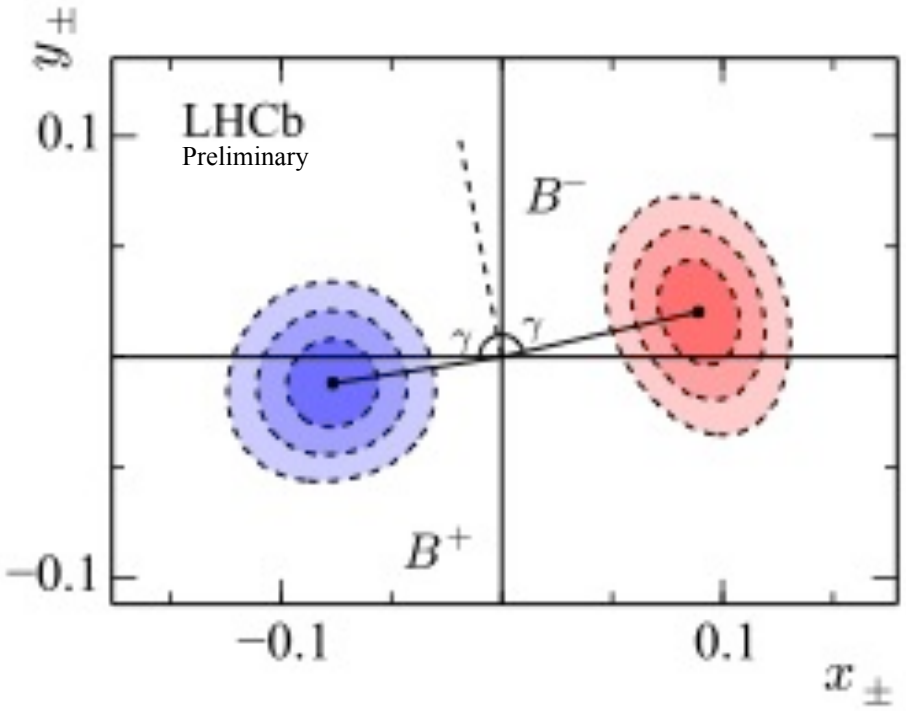
- Fractions of D^0 and $\overline{D}^0$ in each bin ($F_{\pm i}$) with $B \to D^{*\pm}\mu^{\mp}\nu_{\mu}X$ decay mode
- Efficiency difference between $B^{\pm} \to D^0K^{\pm}$ and $B \to D^{*\pm}\mu^{\mp}\nu_{\mu}X$ with simulation

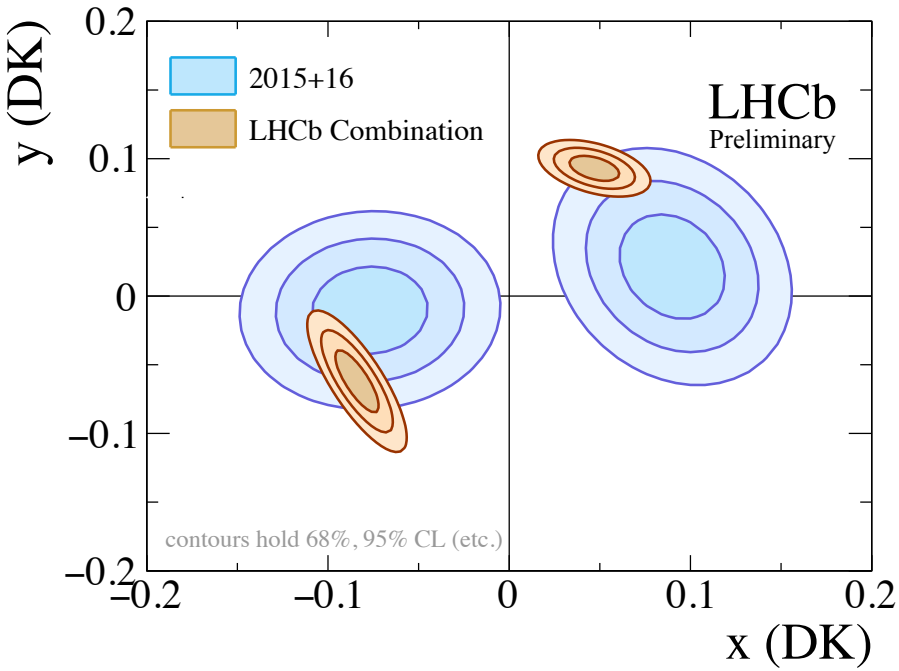


Model-independent GGSZ Analysis

[LHCb-PAPER-2018-017]

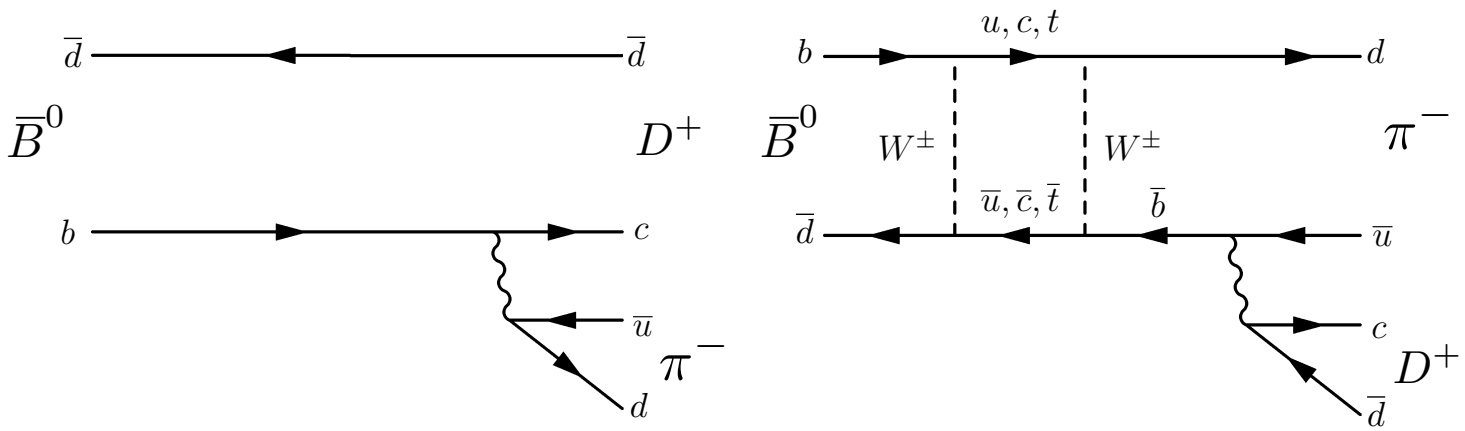
- Perform *CP*-fit to determine $x_\pm$ and $y_\pm$
- Combine with Run 1 analysis to determine $\gamma = (80^{+10}_{-9})^\circ$





Time-dependent Methods for γ

- B^0 and $\overline{B}^0$ can both decay to same final state $D^{\mp}\pi^{\pm}$ via $b \to cW$ or $b \to uW$ (analogous to $B_s^0 \to D_s^{\mp}K^{\pm}$)
- Inteference obtained between mixing and decay for neutral B^0
  - Weak phase difference is $(\gamma + 2\beta)$ for B^0 [analogous to $(\gamma - 2\beta_s)$ for B_s^0]



- Requires tagging the initial B^0 flavour
- Requires a time-dependent analysis to observe the meson oscillations
- Fit the decay-time-dependent decay rates
- Also requires knowledge of Γ_d, and Δm_d

Time-dependent method with $B^0 \to D^{\mp}\pi^{\pm}$

Time-dependent decay rates for initial B^0 at $t = 0$

$$\Gamma_{B^0 \to f}(t) \propto e^{-\Gamma t}\left[C_f \cos(\Delta m t) - S_f \sin(\Delta m t) \underbrace{+ \cosh\left(\frac{\Delta\Gamma t}{2}\right)}_{=1 \text{ for } B^0} + \underbrace{A_f \sinh\left(\frac{\Delta\Gamma t}{2}\right)}_{=0 \text{ for } B^0}\right]$$

$$\Gamma_{B^0 \to \bar{f}}(t) \propto e^{-\Gamma t}\left[C_{\bar{f}} \cos(\Delta m t) - S_{\bar{f}} \sin(\Delta m t) \underbrace{+ \cosh\left(\frac{\Delta\Gamma t}{2}\right)}_{=1 \text{ for } B^0} + \underbrace{A_{\bar{f}} \sinh\left(\frac{\Delta\Gamma t}{2}\right)}_{=0 \text{ for } B^0}\right]$$

CP-observables

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

$$S_f = -\frac{2r \sin[\delta - (2\beta + \gamma)]}{1 + r^2}$$

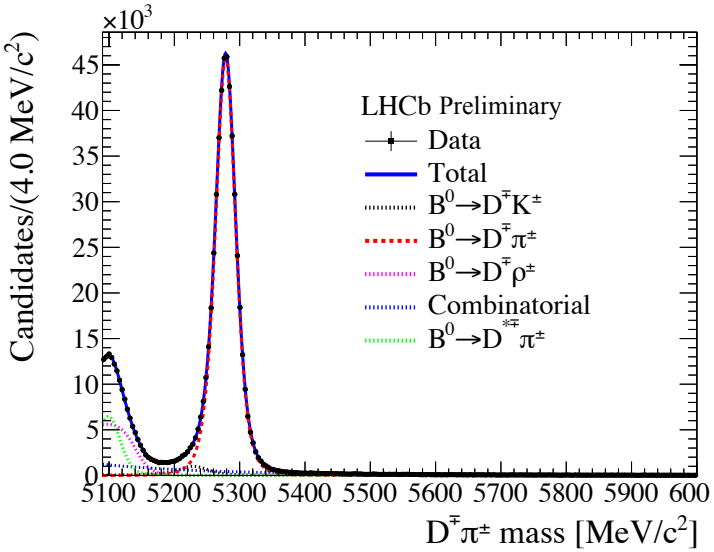
$$S_{\bar{f}} = \frac{2r \sin[\delta + (2\beta + \gamma)]}{1 + r^2}$$

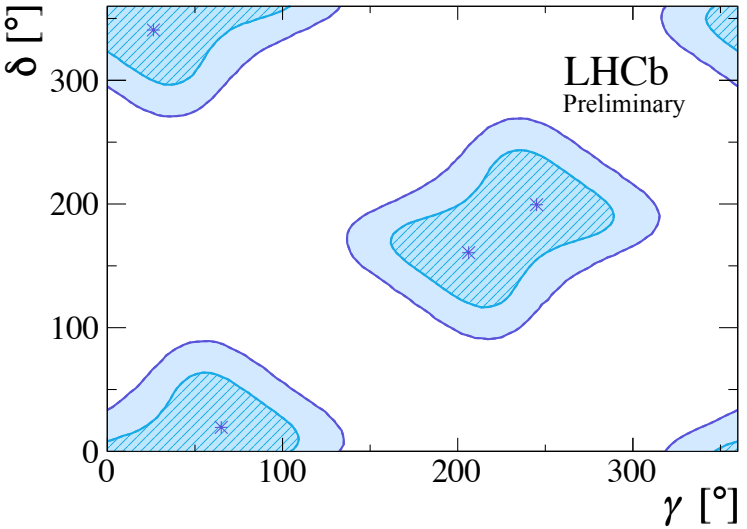
- r - constrained from BaBar [Phys. Rev. D78 (2008) 032005] and Belle [Phys. Rev. D82 (2010) 051103]
- β - constrained from HFLAV
- δ, γ - measured by this analysis - [LHCb-PAPER-2018-009]

Time-dependent method with $B^0 \to D^{\mp}\pi^{\pm}$

[LHCb-PAPER-2018-009]

- Incredibly high statistics channel - $\sim$ 500K signal events
- Allows for simultaneous calibration of flavour tagging parameters





CP-observable results (PRELIMINARY)

$$S_f = 0.058 \pm 0.020\,(\text{stat}) \pm 0.11\,(\text{syst})$$

$$S_{\bar{f}} = 0.038 \pm 0.020\,(\text{stat}) \pm 0.007\,(\text{syst})$$

Comparable to (with better precision):

Belle: [Phys. Rev. D84 (2011) 021101] [Phys. Rev. D73 (2006) 092003]

BaBar: [Phys. Rev. D71 (2005) 112003] [Phys. Rev. D73 (2006) 111101]

Combined constraints on γ

- Ultimate sensitivity is only acheived when several modes are used together
- NEW version of the LHCb γ combination for this conference - [LHCb-CONF-2018-002]

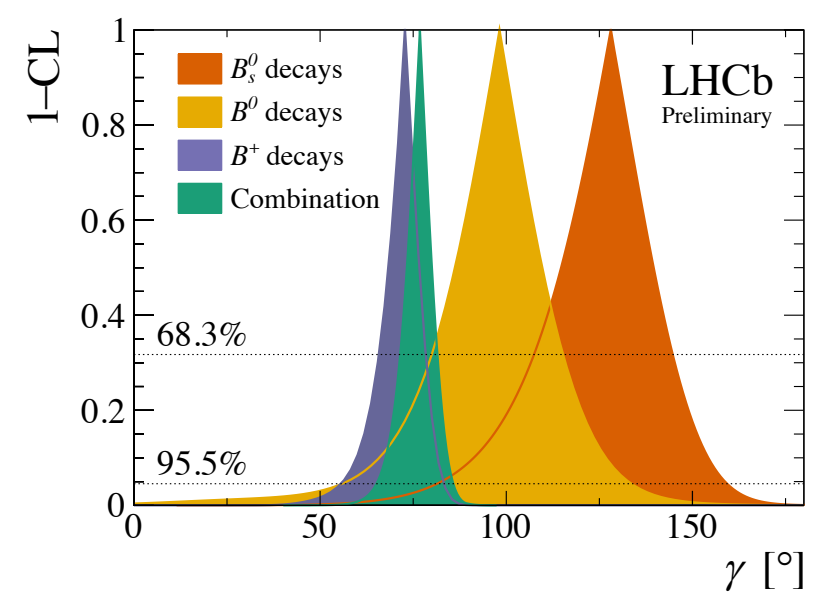
B decay	D decay	Method	Ref.	Dataset[†]	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2	New
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD	[25]	Run 1	Updated results
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1	New

[†] Run 1 corresponds to an integrated luminosity of $3\,\text{fb}^{-1}$ taken at centre-of-mass energies of 7 and 8 TeV. Run 2 corresponds to an integrated luminosity of $2\,\text{fb}^{-1}$ taken at a centre-of-mass energy of 13 TeV.

Combined constraints on γ

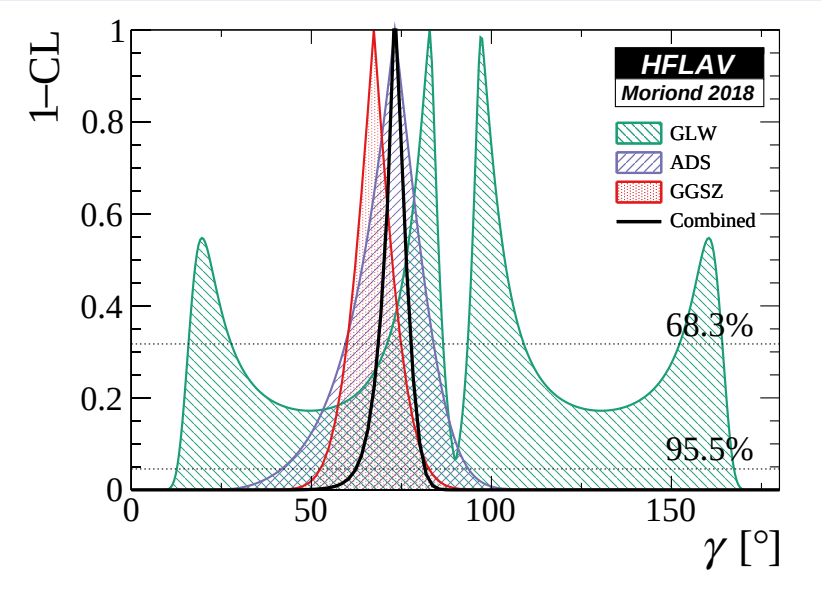
LHCb Average - [LHCb-CONF-2018-002]

$$\gamma = (74.0^{+5.0}_{-5.8})^\circ$$



World Average (HFLAV) - [Spring update]

$$\gamma = (73.5^{+4.2}_{-5.1})^\circ$$

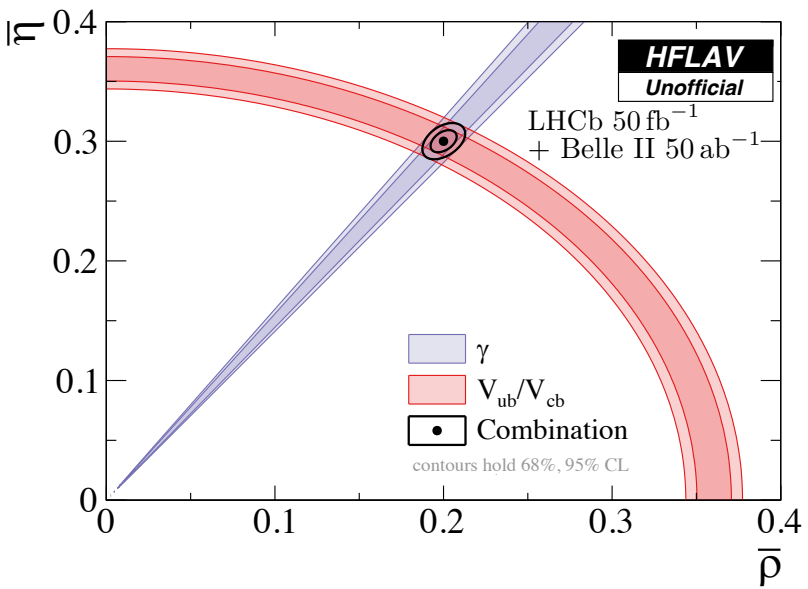


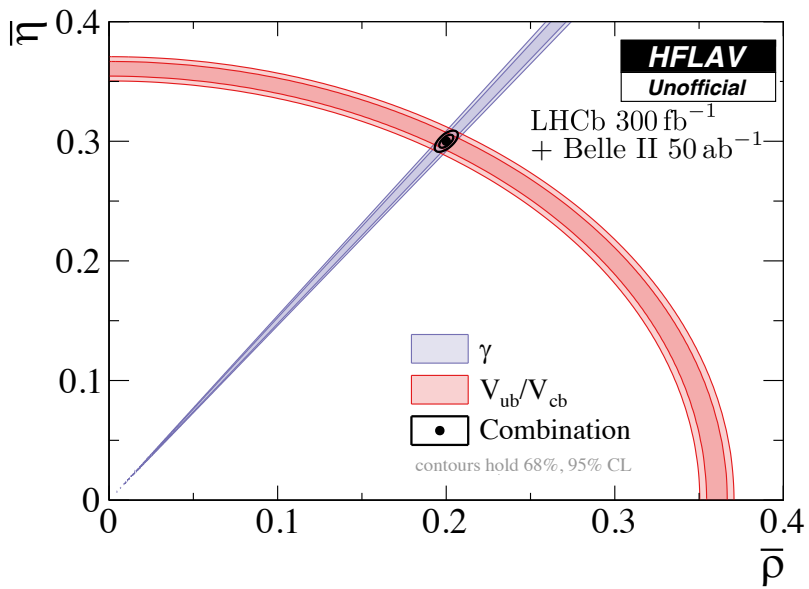
Indirect constraints are: $\gamma = (65.3^{+1.0}_{-2.5})^\circ$ $(\sim 2\sigma)$

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

Ultimate Precision

- Reaching an exciting time for measurements of γ
- In the next decade we will see its transition to **the** precision benchmark for SM CKM measurements
- With $50\,\text{ab}^{-1}$ at Belle-II and a possible $300\,\text{fb}^{-1}$ at LHCb precision will reach $\sim 0.3^\circ$
- And this can be enhanced by many new kids on the block
- Can we become sensitive to differences between initial states (B^+, B^0, B_s^0)?
- Can we get sufficient precision to probe tree-level Wilson coefficients C_1, C_2 [arXiv:1412.1446]?

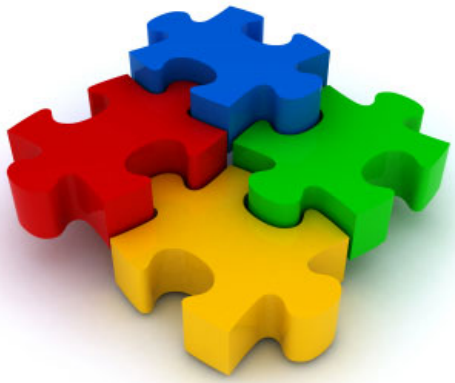




Summary

- CKM angle γ an incredibly **clean** benchmark for the SM
  - A cornerstone of flavour physics experiments' programs
  - Theoretical uncertainty so low the emphasis is on experimental determination
- Sensitive both directly and indirectly to NP
- **Ultimate precision only acheived via combination of multiple decay modes**
- Have shown the latest developments from LHCb with Run 2 analysis of $B^+ \to DK^+$ with GGSZ decays
- Have shown a novel approach with a large statistics sample of $B \to D\pi$ TD decays
- Have shown the latest combination from LHCb - $\gamma = (74.0^{+5.0}_{-5.8})^\circ$
  - **The most precise single experiment determination of γ to date**

THANK YOU!



Back Up

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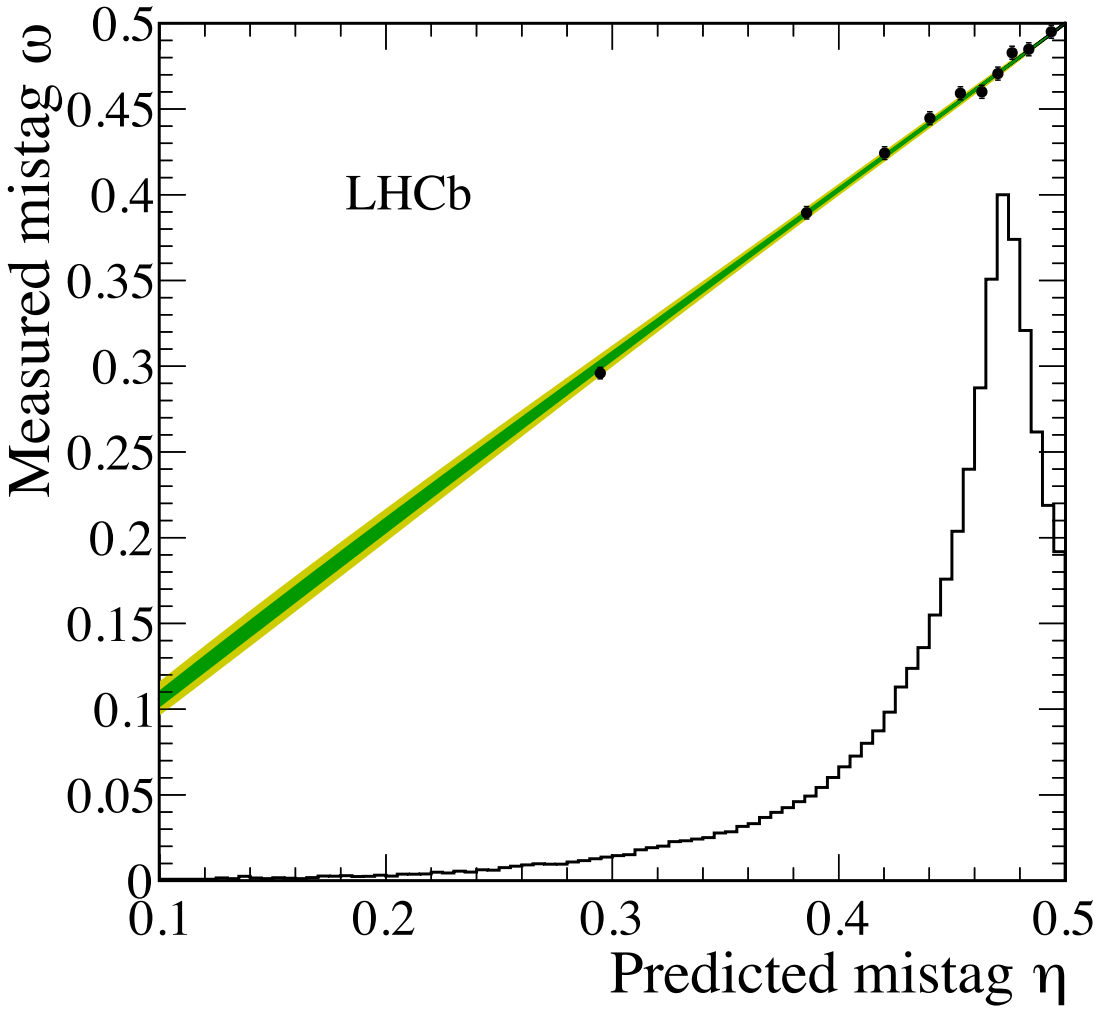
BACK UP

$B^0 \to D^- \pi^+$ tagging



Changes in combination