UNIVERSITY OF CAMBRIDGE

Measurement of the CKM angle γ at LHCb

Jordi Garra Ticó
on behalf of the LHCb collaboration

Outline

- Description of formalisms
- 2014 combination
- GLW / ADS $B \to D K \pi \pi$.
- qGLW / ADS $B \to Dh$, $D \to h h' \pi^0$.

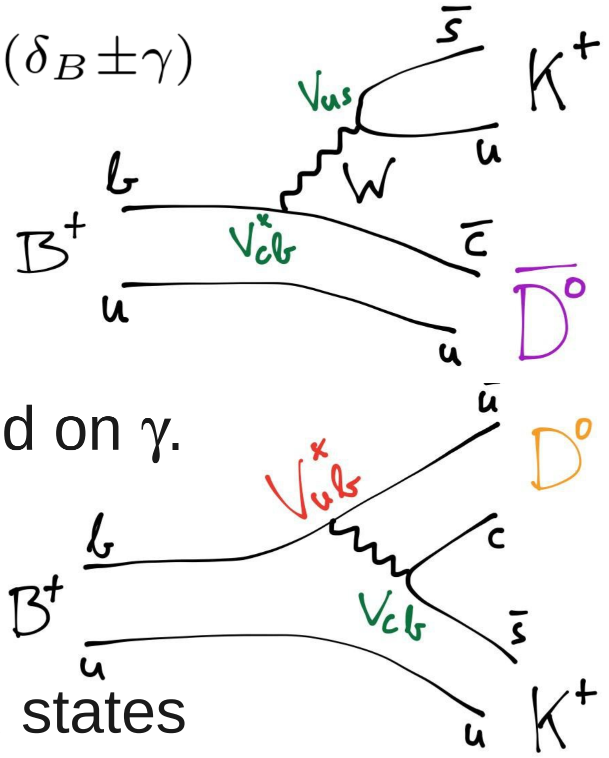
Formalisms

Formalisms

- D meson produced in $B^{\pm} \to D\, h^{\pm}$ decay is

$$|D_-\rangle \sim |D^0\rangle + z_-\, |\bar{D}^0\rangle \qquad z_{\pm} = r_B\, e^{i(\delta_B \pm \gamma)}$$

- r_B, δ_B specific for each B decay.
- Observable based measurements
  - Measure several magnitudes that depend on γ.
  - GLW: decays with CP final states
    - Parameters r_B, δ_B, γ
  - ADS: decays to favored and suppressed states
    - Parameters $r_B, \delta_B, \gamma, \rho = r_D\, e^{i\delta_D}$
- Amplitude analysis (GGSZ)
- Time dependent analysis



My small tribute to
Moritz Karbach
(1979-2015)

Formalisms

- GLW **PLB265 (1991) 172, PLB253 (1991) 483**
  - Ratio of CP to flavor widths

$$R_{\mathrm{CP}}^{\pm} = \frac{\Gamma\left(B^- \to D_{\pm}^{\mathrm{CP}} K^-\right) + \Gamma\left(B^+ \to D_{\pm}^{\mathrm{CP}} K^+\right)}{\Gamma\left(B^- \to D^0 K^-\right) + \Gamma\left(B^+ \to \bar{D}^0 K^+\right)}$$

  - Asymmetry between CP widths

$$A_{\mathrm{CP}}^{\pm} = \frac{\Gamma\left(B^- \to D_{\pm}^{\mathrm{CP}} K^-\right) - \Gamma\left(B^+ \to D_{\pm}^{\mathrm{CP}} K^+\right)}{\Gamma\left(B^- \to D_{\pm}^{\mathrm{CP}} K^-\right) + \Gamma\left(B^+ \to D_{\pm}^{\mathrm{CP}} K^+\right)}$$

  - Other intermediate observables to avoid uncertainty due to precision on the D branching fractions and different selections

Formalisms

- ADS **hep-ph/9612433, hep-ph/0008090**
  - Ratio between suppressed and favored widths

$$R_{\mathrm{ADS}}^{\pm} = \frac{\Gamma\left(B^{\pm} \to D_{\pm}^{\mathrm{sup}} K^{\pm}\right)}{\Gamma\left(B^{\pm} \to D_{\pm}^{\mathrm{fav}} K^{\pm}\right)}$$

$$R_{\mathrm{ADS}} = \frac{\Gamma\left(B^{-} \to D_{-}^{\mathrm{sup}} K^{-}\right) + \Gamma\left(B^{+} \to D_{+}^{\mathrm{sup}} K^{+}\right)}{\Gamma\left(B^{-} \to D_{-}^{\mathrm{fav}} K^{-}\right) + \Gamma\left(B^{+} \to D_{+}^{\mathrm{fav}} K^{+}\right)}$$

  - Asymmetry of the suppressed modes

$$A_{\mathrm{ADS}} = \frac{\Gamma\left(B^{-} \to D_{-}^{\mathrm{sup}} K^{-}\right) - \Gamma\left(B^{+} \to D_{+}^{\mathrm{sup}} K^{+}\right)}{\Gamma\left(B^{-} \to D_{-}^{\mathrm{sup}} K^{-}\right) + \Gamma\left(B^{+} \to D_{+}^{\mathrm{sup}} K^{+}\right)}$$

  - Need to use D decay information from elsewhere

Formalisms

- Amplitude analysis of 3-body decays (GGSZ)

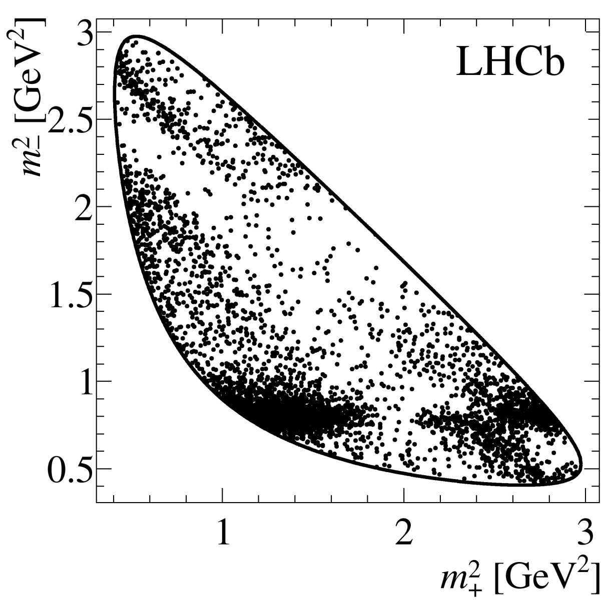
hep-ph/0303187

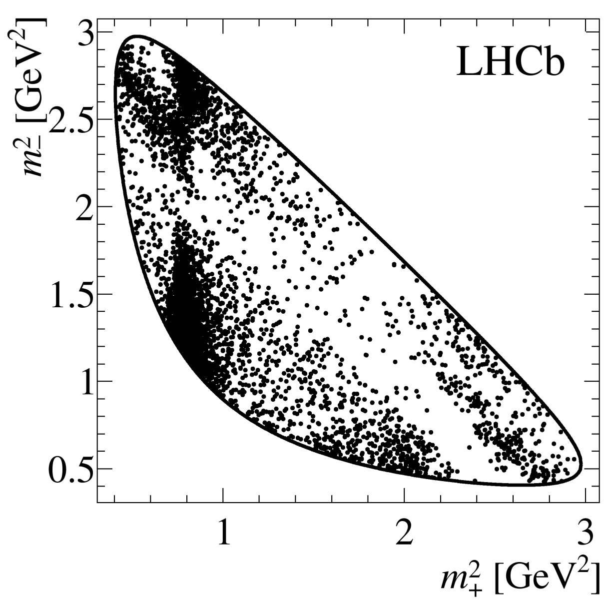
  - $z_\pm = r_B e^{i(\delta_B \pm \gamma)} = x_\pm + i\, y_\pm$
  - Unbinned, model-dependent

$$p_-(m^2_{12}, m^2_{13}) \sim |A_f|^2 + |z_-|^2 \left|\bar{A}_f\right|^2 + 2\,\mathrm{Re}\left(A^\star_f \bar{A}_f z_-\right)$$

  - Binned, model-independent

$$p_b^- \sim N_b + |z_-|^2\, \bar{N}_b + 2\sqrt{N_b \bar{N}_b}\,\mathrm{Re}\left(X_b z_-\right)$$





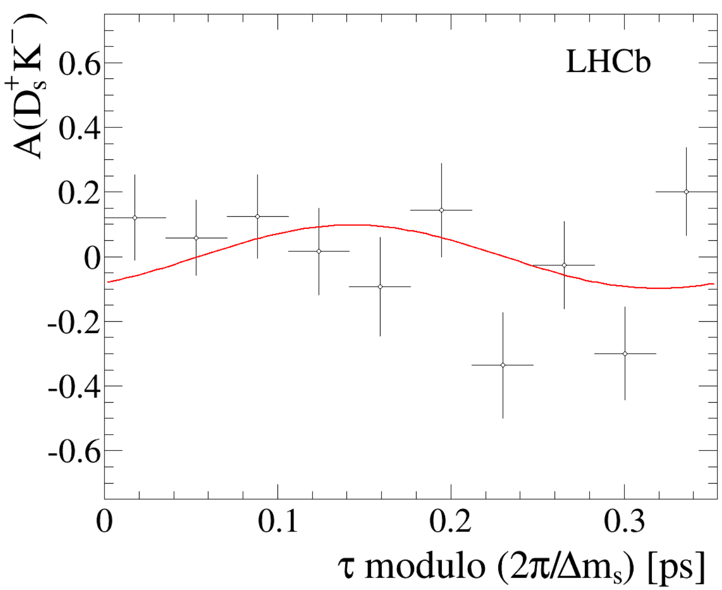
arXiv:1407.6211
1 ifb

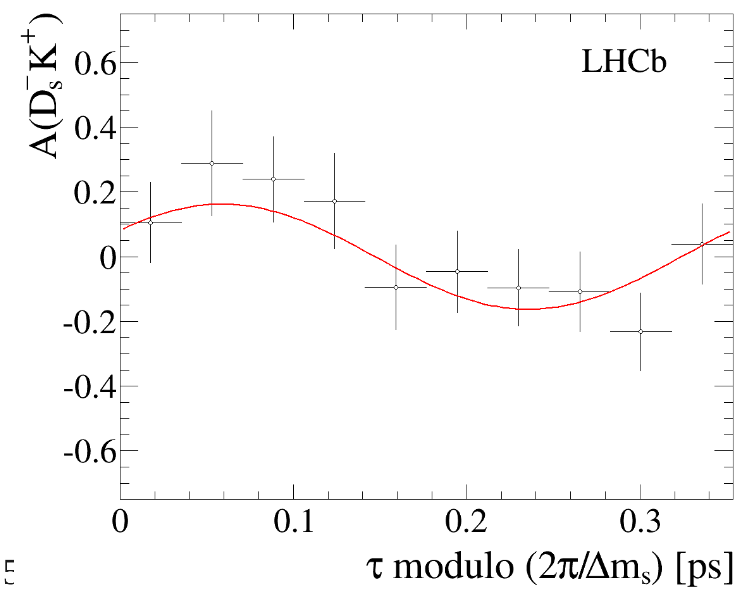
Formalisms

- Time dependent measurement $B_s^0 \to D_s^{\mp} K^{\pm}$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = z_- e^{-i\phi_q} \qquad x = -\frac{\Delta\Gamma}{2\Gamma} \qquad y = \frac{\Delta m}{\Gamma}$$

$$e^{-\Gamma t}\frac{1+|\lambda_f|^2}{2}\left[\cosh(x\Gamma t) + \underbrace{\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}}_{C_f}\cos(y\Gamma t) - \underbrace{\frac{-2\,\mathrm{Re}\,(\lambda_f)}{1+|\lambda_f|^2}}_{A_f^{\Delta\Gamma}}\sinh(x\Gamma t) - \underbrace{\frac{2\,\mathrm{Im}\,(\lambda_f)}{1+|\lambda_f|^2}}_{S_f}\sin(y\Gamma t)\right]$$





arXiv:1407.6127
1 ifb

2014 combination

2014 combination

LHCb-CONF-2014-004

- Measurements considered:

B decay	D decay	lumi	type	reference
$B^{\pm} \to D\, h^{\pm}$	$D \to h\, h$	$1\,\mathrm{fb}^{-1}$	GLW/ADS	arXiv:1203.3662
$B^{\pm} \to D\, h^{\pm}$	$D \to K\, \pi\, \pi\, \pi$	$1\,\mathrm{fb}^{-1}$	ADS	arXiv:1303.4646
$B^{\pm} \to D\, K^{\pm}$	$D \to K_s K\, \pi$	$3\,\mathrm{fb}^{-1}$	ADS	arXiv:1402.2982
$B^{\pm} \to D\, K^{\pm}$	$D \to K_s h\, h$	$3\,\mathrm{fb}^{-1}$	GGSZ	arXiv:1408.2748
$B^0 \to D\, K^{\star 0}$	$D \to h\, h$	$3\,\mathrm{fb}^{-1}$	GLW/ADS	arXiv:1407.8136
$B_s^0 \to D_s^{\mp}\, K^{\pm}$	$D \to h\, h\, h'$	$1\,\mathrm{fb}^{-1}$	TD	arXiv:1407.6127

- Two combinations:
  - **Robust**, excluding $B \to D\pi$
  - **Full**, including all the channels

2014 combination

LHCb-CONF-2014-004

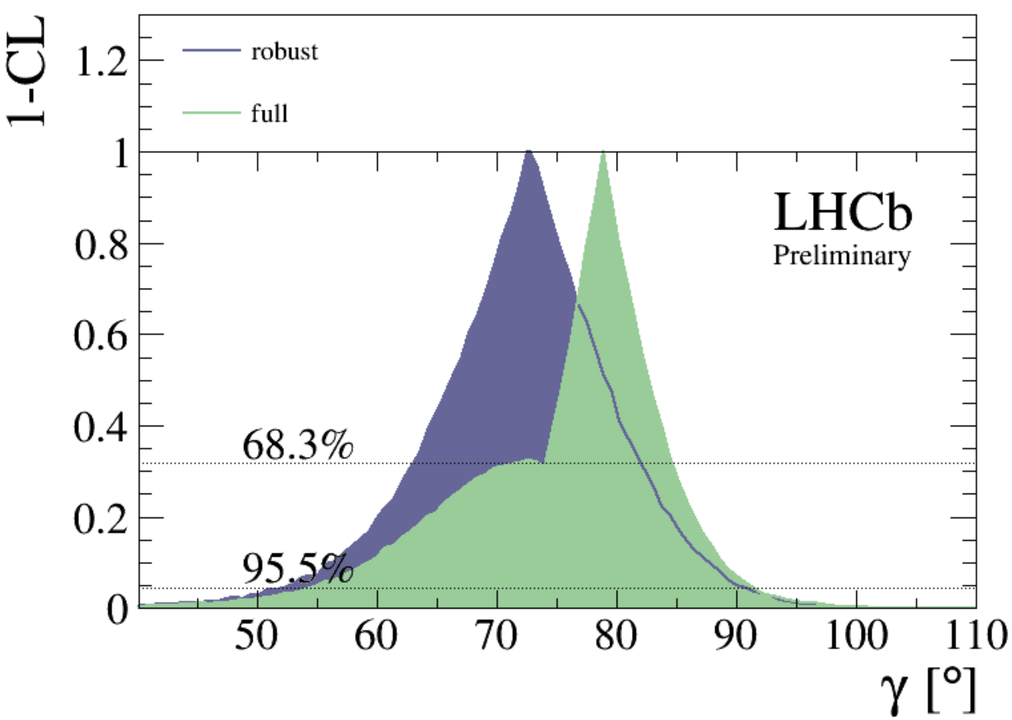
- D amplitude ratios taken from CLEO-c
- Charm mixing parameters taken from HFAG
- $\phi_s = -2\beta_s$ taken from arXiv:1304.2600 (LHCb)
- **Robust** result

$$\gamma = (72.9^{+9.2}_{-9.9})^\circ$$

- **Full** results (2 minima)

$$\gamma = (78.9^{+5.8}_{-7.4})^\circ$$

$$\gamma = (72.8^{+11.9}_{-1.3})^\circ$$



GLW / ADS measurements

GLW / ADS B → D K π π

LHCb-PAPER-2015-020
arXiv:1505.07044v1

- GLW modes $D \to \pi\,\pi \quad D \to K\,K$
- ADS mode $D \to K\,\pi$

$$R^{+}_{\rm CP} = \frac{\Gamma\left(B^- \to D^{\rm CP}_{+} X^-_s\right) + \Gamma\left(B^+ \to D^{\rm CP}_{+} X^+_s\right)}{\Gamma\left(B^- \to D^0 X^-_s\right) + \Gamma\left(B^+ \to \bar{D}^0 X^+_s\right)}$$

$$R^{\pm}_{\rm ADS} = \frac{\Gamma\left(B^\pm \to D^{\rm sup}_{\pm} K^\pm\right)}{\Gamma\left(B^\pm \to D^{\rm fav}_{\pm} K^\pm\right)}$$

- Express $R^{+}_{\rm CP}$ in terms of double ratio $R^{+}_{\rm CP} \simeq \frac{R^{hh}_{s/d}}{R^{K\pi}_{s/d}}$

$$R^{hh}_{s/d} = \frac{\Gamma\left(B^- \to D^{\rm CP}_{+} X^-_s\right) + \Gamma\left(B^+ \to D^{\rm CP}_{+} X^+_s\right)}{\Gamma\left(B^- \to D^{\rm CP}_{+} X^-_d\right) + \Gamma\left(B^+ \to D^{\rm CP}_{+} X^+_d\right)}$$

GLW / ADS $B \to D K \pi \pi$

LHCb-PAPER-2015-020
arXiv:1505.07044v1

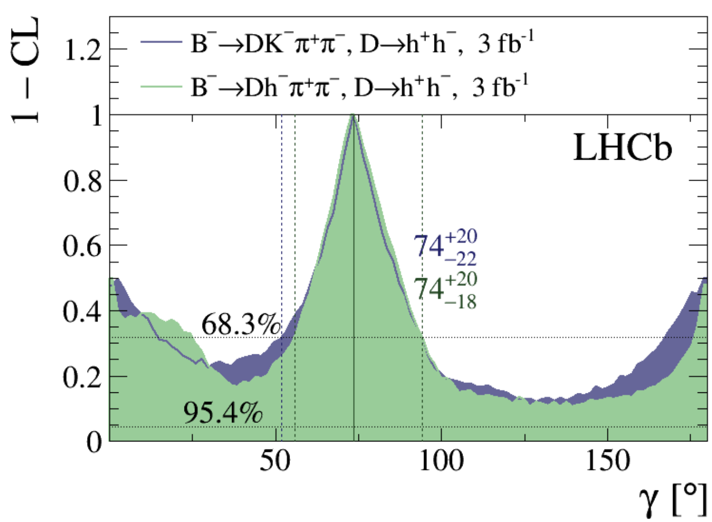
$$R_{\mathrm{CP}}^{+} = 1.040 \pm 0.064$$

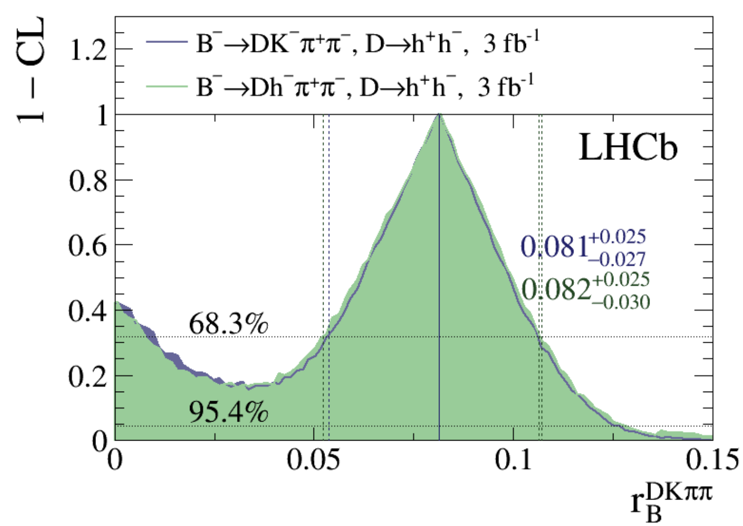
$$R_{\mathrm{ADS}} = (0.82^{+0.38}_{-0.30}) \cdot 10^{-4}$$

$$A_{\mathrm{ADS}} = -0.32^{+0.27}_{-0.34}$$

$$\gamma = (74^{+20}_{-18})^{\circ}$$

As expected, most of the sensitivity comes from $B^{\pm} \to D X_s^{\pm}$





GLW / ADS $B^{\pm} \to D h^{\pm}$, $D \to h h' \pi^0$

LHCb-PAPER-2015-014
arXiv:1504.05442v2

- Integration over D phase space dilutes sensitivity
  - But, dilution effects in $D \to hh'\pi^0$ are small
- GLW involving almost CP-even eigenstates
  - F_+ is the fractional CP-even content of $|D_{F_+}\rangle$

$$R_{\mathrm{qGLW}} = \frac{\Gamma(B^- \to D_{F_+} K^-) + \Gamma(B^+ \to D_{F_+} K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to \bar{D}^0 K^+)}$$

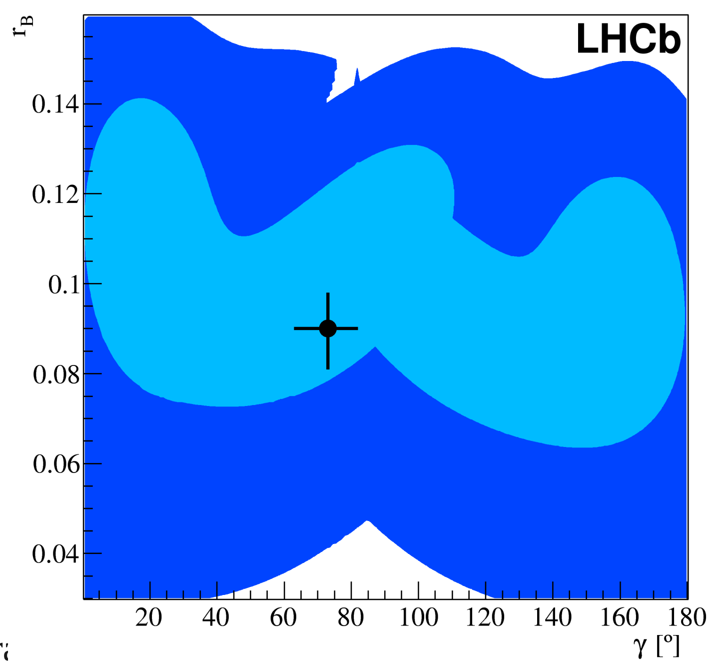
- Express R_{qGLW} in terms of double ratio

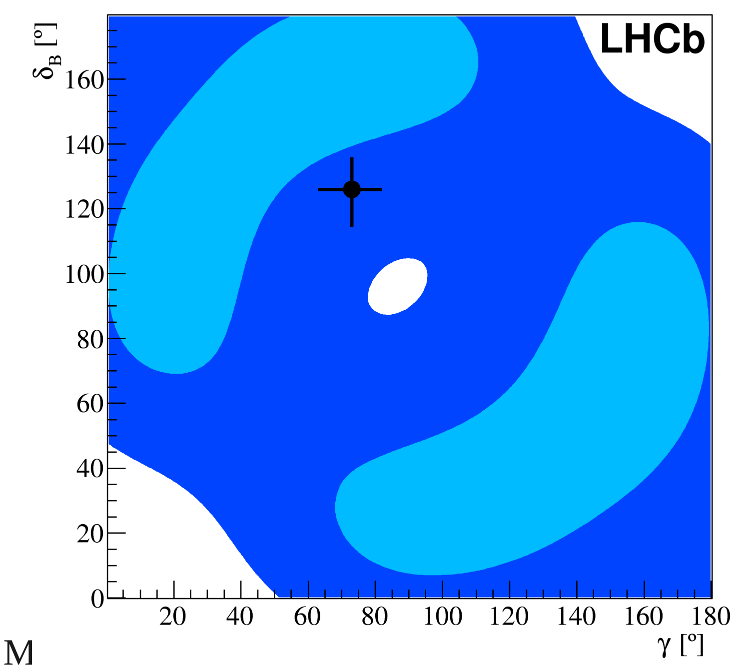
$$R_{\mathrm{qGLW}} \simeq \frac{R^{hh\pi^0}_{K/\pi}}{R^{K\pi\pi^0}_{K/\pi}}$$

GLW / ADS $B^{\pm} \to D h^{\pm}$, $D \to h h' \pi^{0}$

LHCb-PAPER-2015-014
arXiv:1504.05442v2

- Most precise measurements of qGLW and ADS parameters in these channels so far
- No evidence of CPV with current precision
  - Measurements valuable for combination





Conclusions

Conclusions

- LHCb very active in many measurements involving γ
- Current precision on γ of O(10º), but its uncertainty is narrowing really fast
- The run 2 LHCb data will provide unprecedented precision of O(4º)
- LHCb improves on the precision of B factories and it will dominate the precision in the following years