Constraining the CKM Angle γ at LHCb

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on behalf of the LHCb Collaboration

Rencontres de Moriond EW 2014

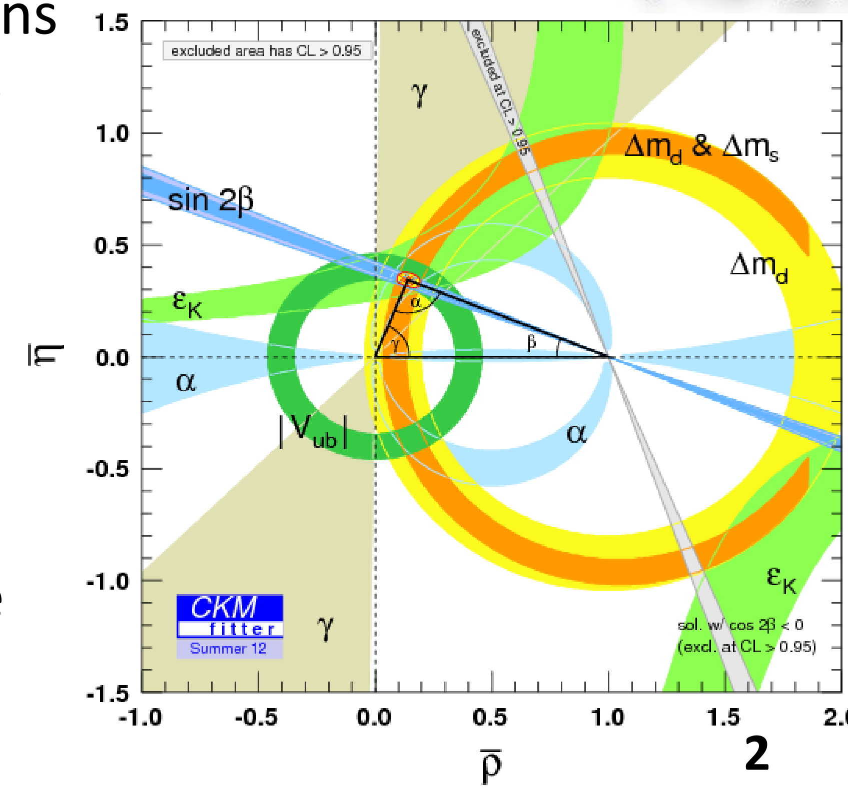
γ in Tree-Level *B* Decays

- γ is the least well-constrained angle of the CKM triangle.
- Fits in summer 2012 (before the inclusion of LHCb data) gave:

  γ = 66±12° *(CKMFitter)*, **γ = 76±10°** *(UTFit)*

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

- Measurements of γ from *B* decays mediated only by tree-level transitions provide an “standard candle” for the Standard Model.
- This can be compared with γ values from *B* decays involving loop-level transitions
  - For example $B^0_{(s)} \rightarrow hh'$ decays
- Significant difference between these would indicate New Physics contribution to the loop process.

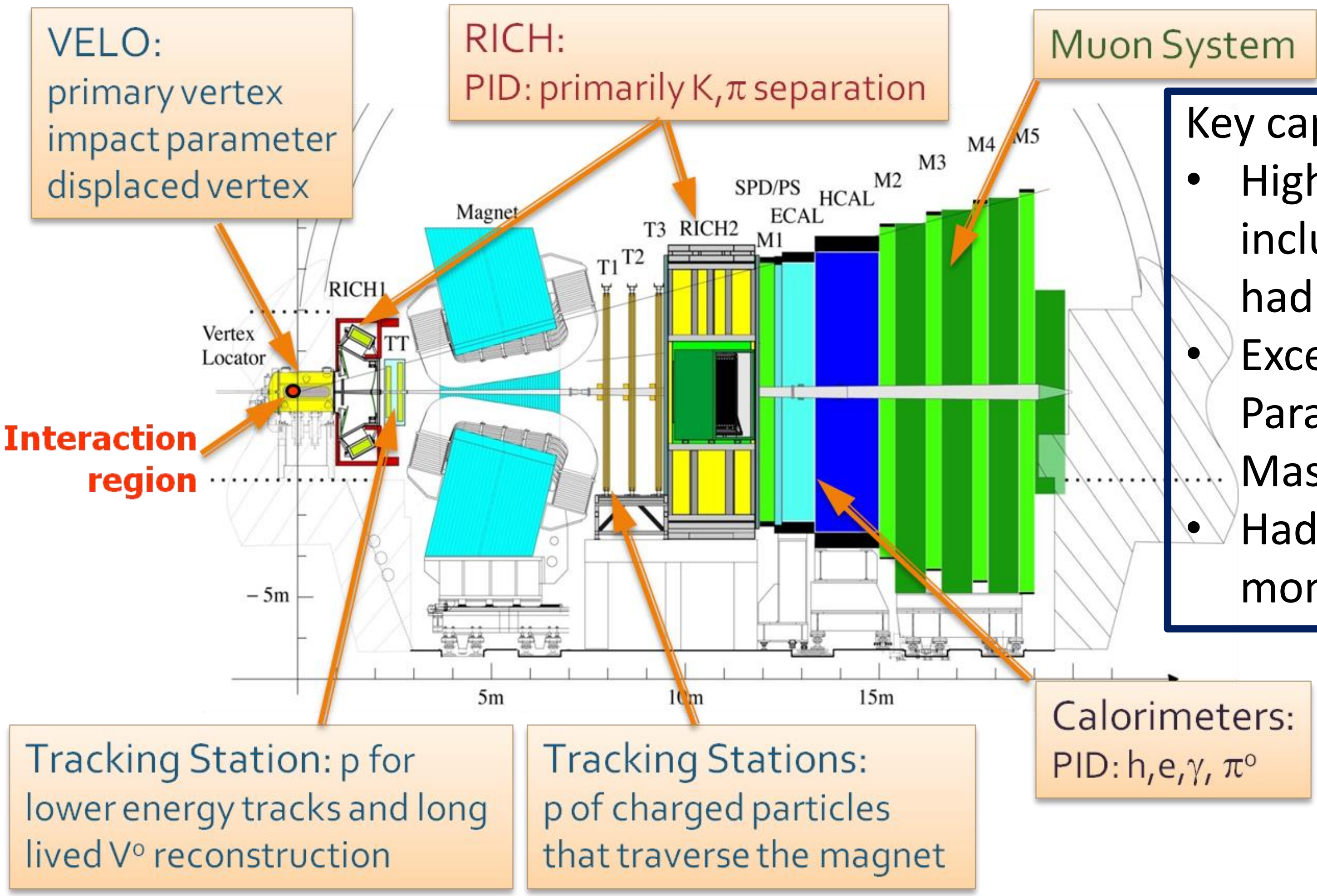


Menu of Results

- LHCb gamma combination from time-independent methods, using $B^+ \to D^0 K^+$ and $B^+ \to D^0 \pi^+$ (Phys. Lett. **B 726** (2013) 151), and updated preliminary combination using $B^+ \to D^0 K^+$ only (LHCb-CONF-2013-006)
- Time-independent γ measurement with 3/fb, using $B^+ \to D^0 K^+$ and $B^+ \to D^0 \pi^+$ with $D^0 \to K_S K \pi$ (LHCb-PAPER-2013-068, submitted to Phys. Lett. **B**) NEW!
- First observation of $B_s \to \overline{D}^0 \varphi$ (Phys. Lett. **B 727** (2013) 403)
- Studies of beauty baryon decays to $D^0 ph$ and $\Lambda_c h$ (Phys. Rev. **D 89** (2014) 032001)
- Studies of beauty baryon decays to pairs of charm hadrons (LHCb-PAPER-2014-002, submitted to Phys. Rev. Lett.) NEW!

The LHCb Experiment

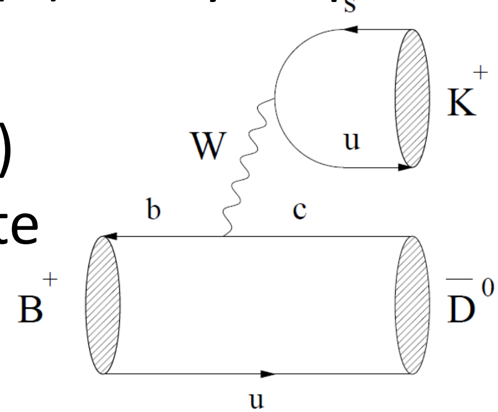
- Forward arm spectrometer, optimised for study of *B* and *D* decays.
- Collected 1/fb of data at E_{CM} = 7 TeV in 2011 and 2/fb at 8 TeV in 2012

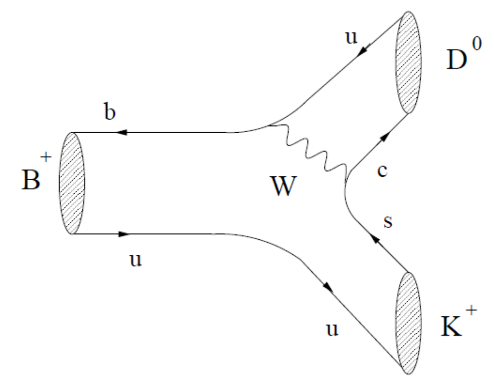


Key capabilities:
- High trigger efficiency, including on purely hadronic final states.
- Excellent Impact Parameter (IP) and Mass Resolution
- Hadronic PID over wide momentum range

Time-Integrated Methods

- Sensitivity to γ from interference between $b \to c$ and $b \to u$ transitions at tree level, when D final state is accessible to both D^0 and $\overline{D}^0$
- Aside from γ, have hadronic unknowns $r_{B(D)}$, $\delta_{B(D)}$, where ratio of suppressed to favoured $B(D)$ decay amplitudes is $r_B\, e^{i(\delta_B - \gamma)}$ ($r_D\, e^{i\delta_D}$)
- Method to extract these hadronic unknowns (and γ) depends on the D final state

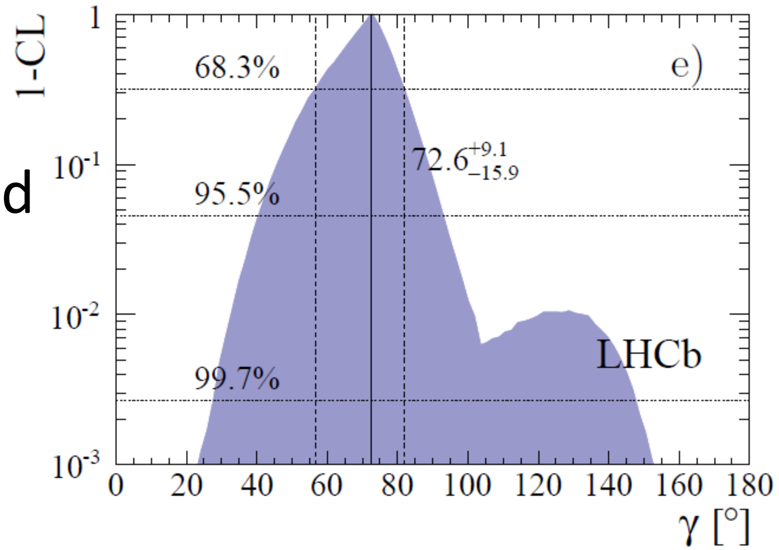




- Three main methods:
- ***GLW***: $D \to$ CP-eigenstate, e.g. $\pi\pi$, KK (Phys. Lett. **B 253** (1991) 483, Phys. Lett. **B 265** (1991) 172)
- ***ADS***: $D \to$ quasi-flavour-specific state, e.g. $K\pi$, $K\pi\pi\pi$ (Phys. Rev. Lett. **78** (1997) 257, Phys. Rev. **D 63** (2001) 036005)
- ***GGSZ***: $D \to$ self-conjugate 3-body final state, e.g. $K_S\pi\pi$, K_SKK (Phys. Rev. **D 68** (2003) 054018, Phys. Rev. **D 70** (2004) 072003)

Gamma Combination

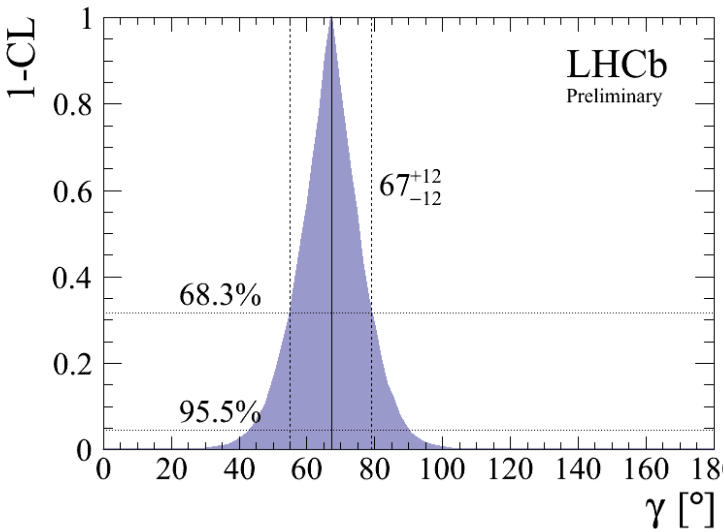
- The published LHCb combination uses analyses of $B \to Dh$ with:
  - $D \to K\pi$, KK or $\pi\pi$ using 1/fb (Phys. Lett. **B 712** (2012) 203),
  - D $\to K\pi\pi\pi$ using 1/fb (Phys. Lett. **B 723** (2012)) 44),
  - $D \to K_S KK$ or $K_S\pi\pi$ using 1/fb (Phys. Lett. **B 718** (2012) 43),
  - Plus CLEO data on $D \to K\pi\pi\pi$ strong phase (Phys. Rev. **D 80** (2009) 031105)
- The experimental likelihoods are combined as $\mathcal{L}(\vec{\alpha}) = \prod_i f_i(\vec{A}_i^{\rm obs}|\vec{A}_i(\vec{\alpha}_i))$, where A are the experimental observables (R_{CP}, x_+, etc) and α are the physics parameters (γ, r_B, etc).
- Confidence intervals are rescaled, to account for undercoverage and neglected correlations between systematics.

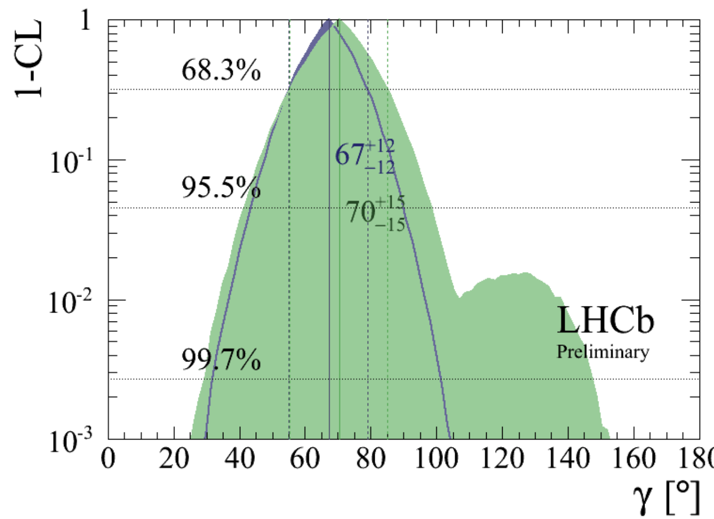


- The effects of D^0-$\overline{D}^0$ mixing, and of possible CPV in the D decays, are taken into account.
- 68% CL confidence interval using DK and Dπ is: $\gamma \in [55.4, 82.3]^\circ$

Gamma Combination

- There is also a more recent, preliminary LHCb combination.
- This uses analyses of $B \to DK$ from the same analyses as the published combination, adding the information from an updated analysis with $D \to K_S KK$ or $K_S \pi\pi$ using the 3/fb dataset (LHCb-CONF-2013-004).
- Preliminary result is **γ = 67±12°**





Comparison of 1/fb-only and updated confidence intervals for DK

- These results lead to updated CKM fits:

$\gamma = 68.0^{+8.0}_{-8.5}$° *(CKMFitter, FPCP 2013)*,

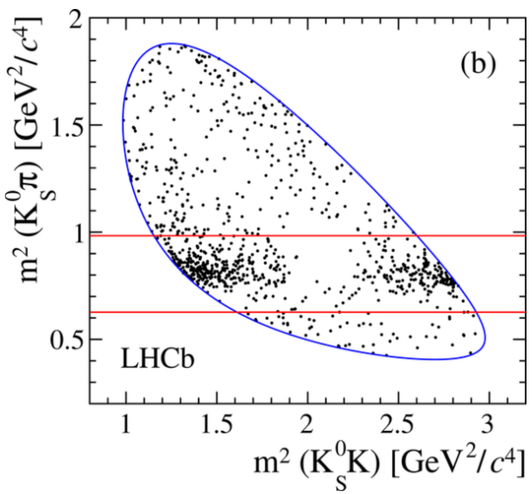
γ = 70.1±7.1° *(UTFit, EPS 2013)*.

Observables for $B^+ \to D^0(\to K_S K \pi)h^+$

NEW!

- This is the first ADS-like analysis to use Singly-Cabibbo-Suppressed (SCS) modes. Label final states as OS or SS comparing $K^\pm$ with $B^\pm$
- Analysing three-body *D* final state requires knowledge of how the average interference amplitude ($\kappa_{K_S K\pi}$) and strong phase difference ($\delta_{K_S K\pi}$) vary across the *D* Dalitz plot
  - This is taken from a CLEO-c measurement, Phys. Rev. **D 85** (2012) 092016
- Decay rates for $B^+ \to D^0 K^+$ are:

$$\Gamma^{\pm}_{\mathrm{SS},\ DK} = z[\ 1 + r_B^2 r_D^2 + 2 r_B r_D \kappa_{K_S^0 K\pi} \cos(\delta_B \pm \gamma - \delta_{K_S^0 K\pi})\ ]$$
$$\Gamma^{\pm}_{\mathrm{OS},\ DK} = z[\ r_B^2 + r_D^2 + 2 r_B r_D \kappa_{K_S^0 K\pi} \cos(\delta_B \pm \gamma + \delta_{K_S^0 K\pi})\ ]$$

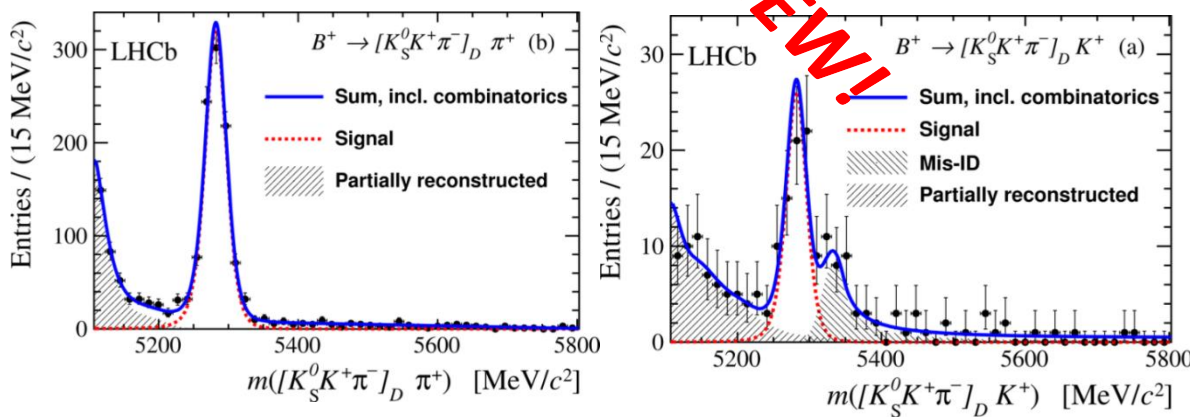


- Measure yield ratios (e.g. $\mathcal{R}_{DK/D\pi,\ SS}$) and charge asymmetries (e.g. $\mathcal{A}_{SS,DK}$) between the OS and SS samples, and between *DK* and $D\pi$ final states.
- Analysis is done across whole Dalitz plane, and in a restricted region around the $K^{*\pm}$ resonance, where the coherence factor $\kappa_{K_S K\pi}$ is higher (≈1.0 vs ≈0.7).

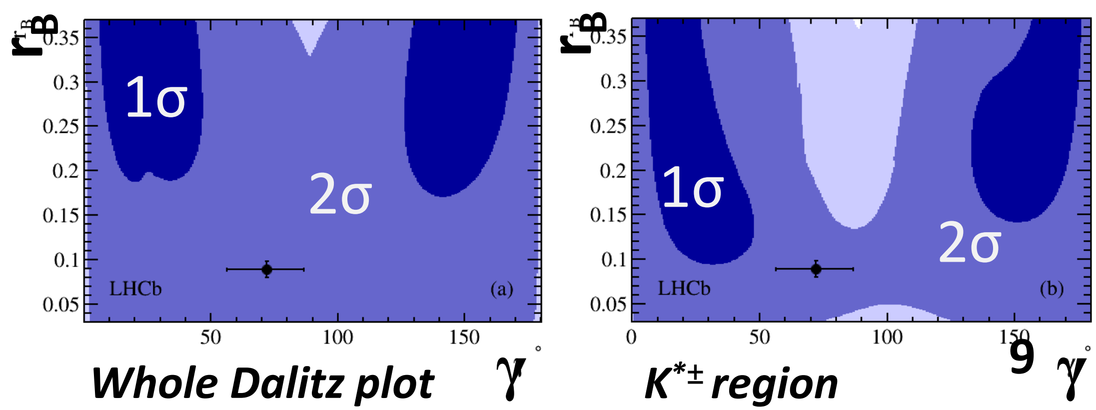
Results for $B^+ \to D^0(\to K_S K \pi)h^+$

NEW!

- Measure 8 yields, with $B^+ \to D^0K^+$ and $B^+ \to D^0\pi^+$ separated by OS/SS and charge of $B^\pm$
- Charge-summed yields for OS and SS D^0K^+ are 71 and 145 respectively.
- Sensitivity to γ appears to be improved by taking $K^{*\pm}$ region, due to higher coherence factor.
- Good prospects for future analysis of $K^{*\pm}$ region with more statistics.



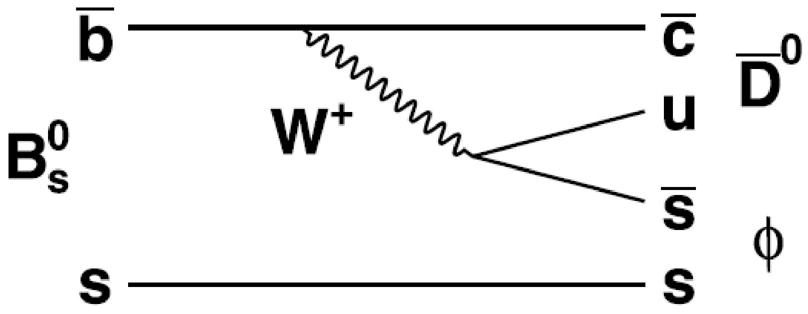
Observable	Whole Dalitz plot	$K^*(892)^\pm$ region
$\mathcal{R}_{SS/OS}$	$1.528 \pm 0.058 \pm 0.025$	$2.57 \pm 0.13 \pm 0.06$
$\mathcal{R}_{DK/D\pi,\ SS}$	$0.092 \pm 0.009 \pm 0.004$	$0.084 \pm 0.011 \pm 0.003$
$\mathcal{R}_{DK/D\pi,\ OS}$	$0.066 \pm 0.009 \pm 0.002$	$0.056 \pm 0.013 \pm 0.002$
$\mathcal{A}_{SS,\ DK}$	$0.040 \pm 0.091 \pm 0.018$	$0.026 \pm 0.109 \pm 0.029$
$\mathcal{A}_{OS,\ DK}$	$0.233 \pm 0.129 \pm 0.024$	$0.336 \pm 0.208 \pm 0.026$
$\mathcal{A}_{SS,\ D\pi}$	$-0.025 \pm 0.024 \pm 0.010$	$-0.012 \pm 0.028 \pm 0.010$
$\mathcal{A}_{OS,\ D\pi}$	$-0.052 \pm 0.029 \pm 0.017$	$-0.054 \pm 0.043 \pm 0.017$

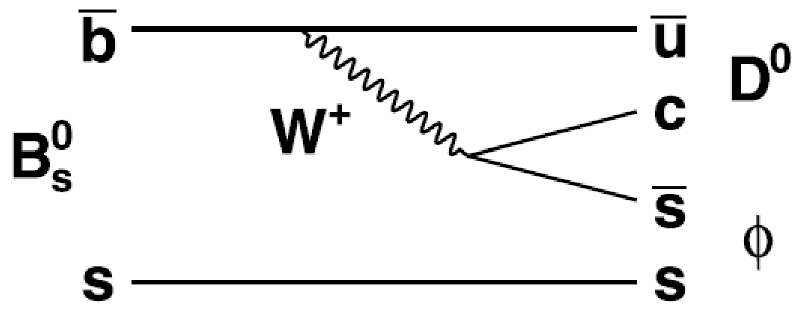


Whole Dalitz plot *$K^{*\pm}$ region*

Observation of $B_s \rightarrow \overline{D}^0 \varphi$

- Time-dependent analysis of the $B_s \rightarrow \overline{D}^0 \varphi$ decay can measure γ and φ_s (Phys. Lett. **B 253** (1991) 483).
- Using the now-known sign of $\Delta\Gamma_s$, this determination can be made unambiguous (Phys. Rev. **D 85** (2012) 114015).
- A time-***in***dependent analysis can also measure γ, provided enough D^0 final states are included (Phys. Rev. **D 69** (2004) 113003, Phys. Lett. **B 649** (2007) 61). This has advantages for LHCb, as it means flavour-tagging is not required.

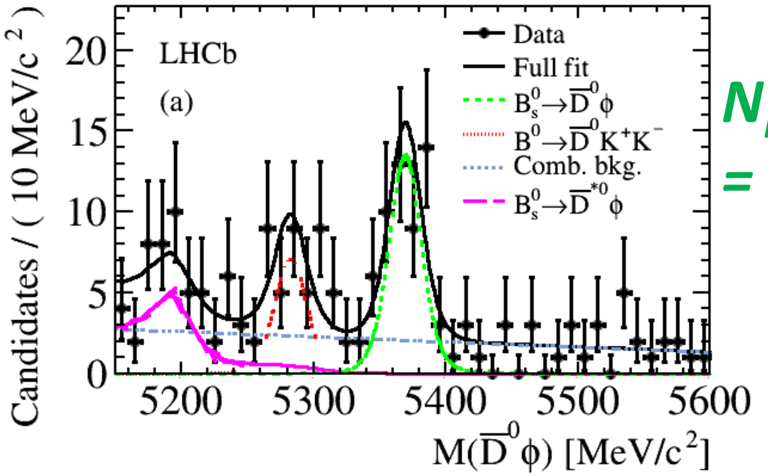




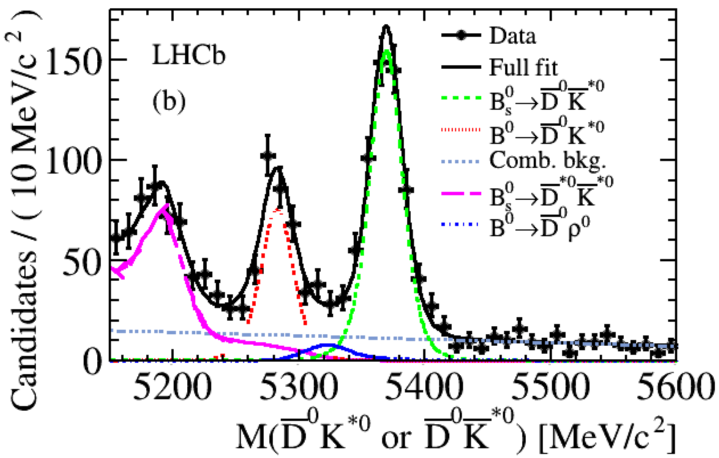
- First step is to make the first observation of the decay, using the Cabibbo-favoured $\overline{D}^0 \rightarrow K^+\pi^-$ decay mode.

Observation of $B_s \to \overline{D}^0 \varphi$

- LHCb searched for $B_s \to \overline{D}^0 \varphi$ with a blind analysis of 1/fb of data.
- First observation of $B_s \to \overline{D}^0 \varphi$ is made, with significance of 6.5σ.



$N_{B_s \to \overline{D}^0 \varphi} = 43 \pm 8$



- Branching fraction ($\mathcal{B}$) is measured relative to the $B_d \to \overline{D}^0 K^{*0}$ decay. Also improve the measurement of $\mathcal{B}(B_s \to \overline{D}^0 \overline{K}^{*0})$ relative to $B_d \to \overline{D}^0 K^{*0}$:

$$\mathcal{B}(B_s^0 \to \overline{D}^0 \phi) = [2.3 \pm 0.4\ (\text{stat}) \pm 0.2\ (\text{syst}) \pm 0.2\ (f_s/f_d)\ \pm 0.3\ (\mathcal{B}(B^0 \to \overline{D}^0 K^{*0}))] \times 10^{-5},$$

$$\mathcal{B}(B_s^0 \to \overline{D}^0 \overline{K}^{*0}) = [3.3 \pm 0.3\ (\text{stat}) \pm 0.1\ (\text{syst}) \pm 0.3\ (f_s/f_d) \pm 0.5\ (\mathcal{B}(B^0 \to \overline{D}^0 K^{*0}))] \times 10^{-4}.$$

- With more data, can add more D^0 final states, such as KK, $\pi\pi$, $K_S\pi\pi$, …

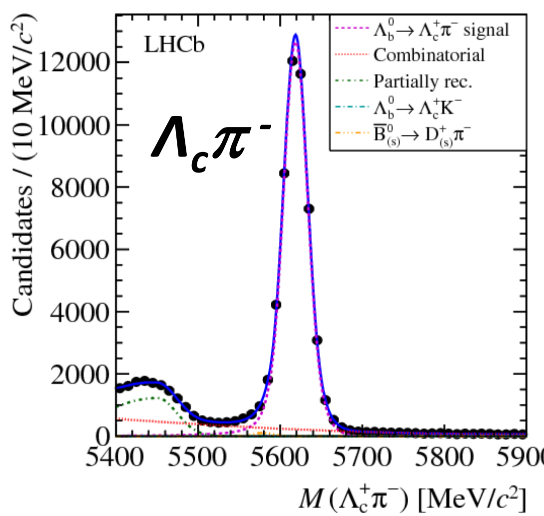
Baryon Decays to D^0ph, $\Lambda_c h$

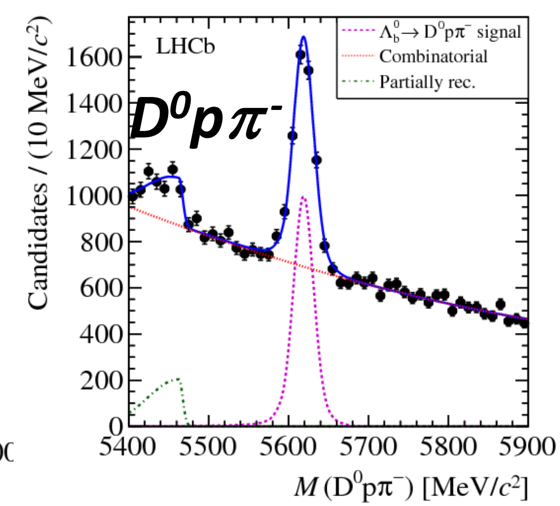
- Beauty baryon sector remains largely unexplored.
- Decays such as $\Lambda_b \rightarrow D^0\Lambda$ and $\Lambda_b \rightarrow D^0pK^-$ can be used to measure γ (Z. Phys. **C 56** (1992) 129, Mod. Phys. Lett. **A 14** (1999), Phys. Rev. **D 65** (2002) 073029)
- LHCb has studied beauty baryon decays to D^0ph^- and $\Lambda_c h^-$ final states, using 1/fb of data.
- The Caibibbo-favoured final states $D^0 \rightarrow K^-\pi^+$ and $\Lambda_c \rightarrow pK^-\pi^+$ are used.
- Common $pK^-\pi^+h$ final state reduces systematic uncertainties.
- Firstly, use a loose, cut-based selection to measure:

$$\equiv \frac{\mathcal{B}(\Lambda_b^0 \to D^0 p\pi^-) \times \mathcal{B}(D^0 \to K^-\pi^+)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-) \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}$$

$$= 0.0806 \pm 0.0023 \pm 0.0035$$

(factoring out poorly-known $\mathcal{B}(\Lambda_c \rightarrow pK^-\pi^+)$)



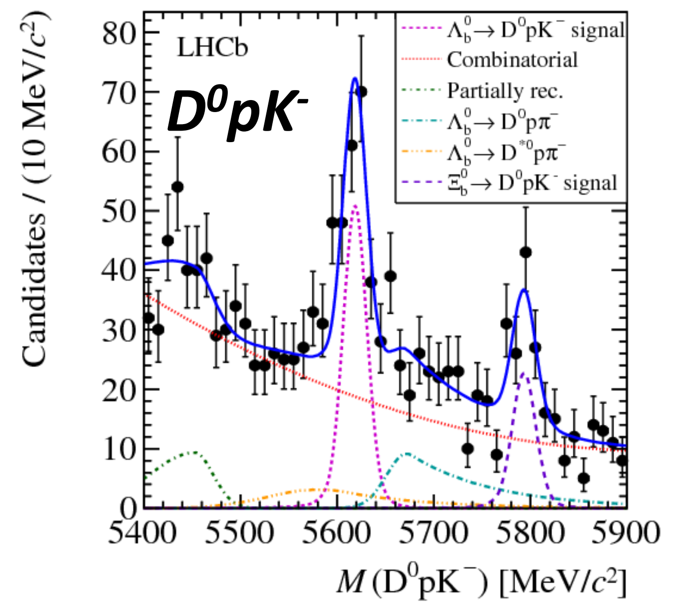


Baryon Decays to D^0ph, $\Lambda_c h$

- Tighter selection (with BDT) used to make the first observations of $\Lambda_b \to D^0pK^-$ (9.0σ) and $\Xi_b \to D^0pK^-$ (5.9σ), and measure:

$$\frac{\mathcal{B}(\Lambda_b^0 \to D^0 pK^-)}{\mathcal{B}(\Lambda_b^0 \to D^0 p\pi^-)} = 0.073 \pm 0.008^{+0.005}_{-0.006},$$

$$\frac{f_{\Xi_b^0} \times \mathcal{B}(\Xi_b^0 \to D^0 pK^-)}{f_{\Lambda_b^0} \times \mathcal{B}(\Lambda_b^0 \to D^0 pK^-)} = 0.44 \pm 0.09 \pm 0.06$$



- The D^0pK^- spectrum can also be used to measure the mass difference:

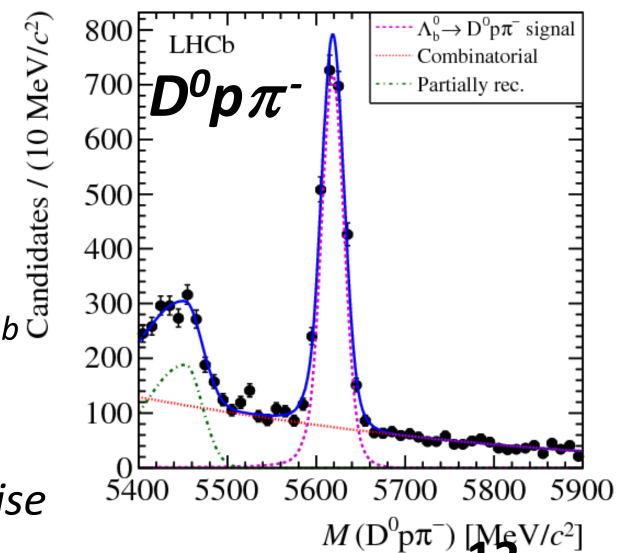
$$m_{\Xi_b^0} - m_{\Lambda_b^0} = 174.8 \pm 2.4 \pm 0.5\ \mathrm{MeV}/c^2$$

(Systematic is dominated by background modelling in mass fit)

- Combining with the LHCb measurement of $m_{\Lambda b}$ using $\Lambda_b \to J/\psi\Lambda$ (PRL 110 (2013) 182001) gives:

$$m_{\Xi_b^0} = 5794.3 \pm 2.4 \pm 0.7\ \mathrm{MeV}/c^2$$

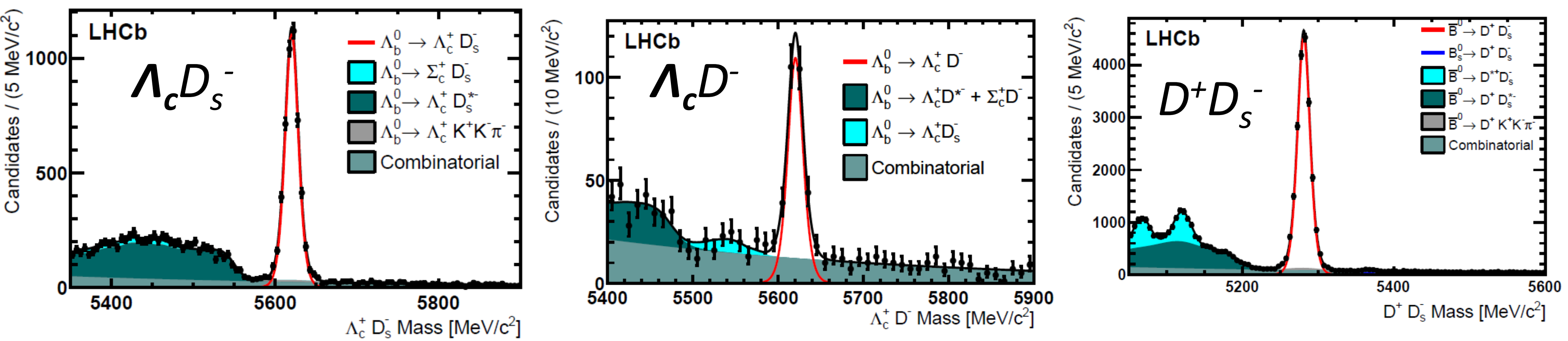
Most precise to date!



Baryon Decays to Two Charm Hadrons

NEW!

- Another showcase for LHCb's capabilities with beauty baryons is the analysis of their decays to pairs of charm hadrons, using 3/fb.
- Events are selected using a BDT trained on signal decays to the relevant single charm hadron: $B_d \to D^- \pi^+$, $B_s \to D_s^- \pi^+$ or $\Lambda_b \to \Lambda_c \pi^-$.
- Clear first observations are made of the decays $\Lambda_b \to \Lambda_c D_s^-$ (CF) and $\Lambda_b \to \Lambda_c D^-$ (SCS), with: $\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.042 \pm 0.003\,(\mathrm{stat}) \pm 0.003\,(\mathrm{syst})$.



- The Λ_b branching fractions can be normalised to $\bar{B}_d \to D^+ D_s^-$, but the fragmentation fraction ratio f_{Λ_b}/f_d is known to depend on the p_T of the b-hadron (LHCb, Phys. Rev. **D 85** (2012) 032008)…

Baryon Decays to Two Charm Hadrons

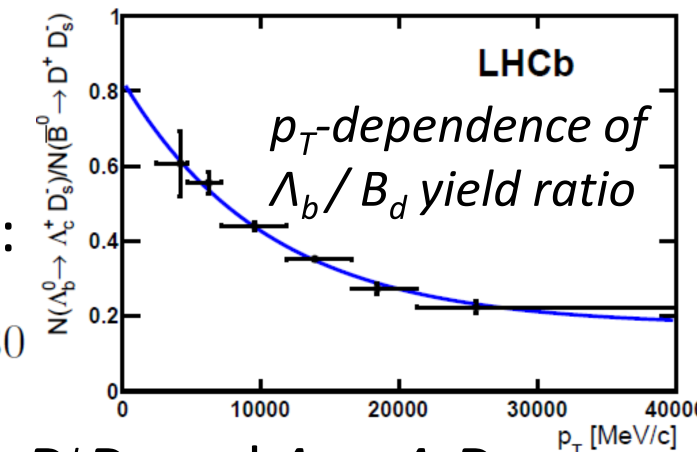
NEW!

- Adopting the p_T-dependence of $f_{\Lambda b}/f_d$ measured by LHCb using $B_d \to D^- \pi^+$ and $\Lambda_b \to \Lambda_c \pi^-$ (LHCb-PAPER-2012-004, in preparation), the double ratio is measured:

$$\left[\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}{\mathcal{B}(\overline{B}^0 \to D^+ D_s^-)}\right] \Big/ \left[\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)}{\mathcal{B}(\overline{B}^0 \to D^+ \pi^-)}\right] = 0.96 \pm 0.02\,(\mathrm{stat}) \pm 0.06\,(\mathrm{syst}).$$

- In addition, the modes $B_{\{d,s\}} \to \Lambda_c^+ \Lambda_c^-$ are searched for, and no significant signal is found. The following 95% C.L. limits are set:

$$\frac{\mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \Lambda_c^-)}{\mathcal{B}(\overline{B}^0 \to D^+ D_s^-)} < 0.0022, \quad \frac{\mathcal{B}(B_s^0 \to \Lambda_c^+ \Lambda_c^-)}{\mathcal{B}(B_s^0 \to D^+ D_s^-)} < 0.30$$



- Finally, the very similar Q-values of the $\overline{B}_d \to D^+ D_s^-$ and $\Lambda_b \to \Lambda_c D_s^-$ decays allows a precise measurement of the mass difference:

$$M(\Lambda_b^0) - M(\overline{B}^0) = 339.72 \pm 0.24\,(\mathrm{stat}) \pm 0.18\,(\mathrm{syst})\,\mathrm{MeV}/c^2.$$

Dominant syst is due to $\tau(D^+) >>> \tau(\Lambda_c)$

- Using the World Average B_d mass gives the most precise result to date for the absolute Λ_b mass: $M(\Lambda_b^0) = 5619.30 \pm 0.34\,\mathrm{MeV}/c^2$

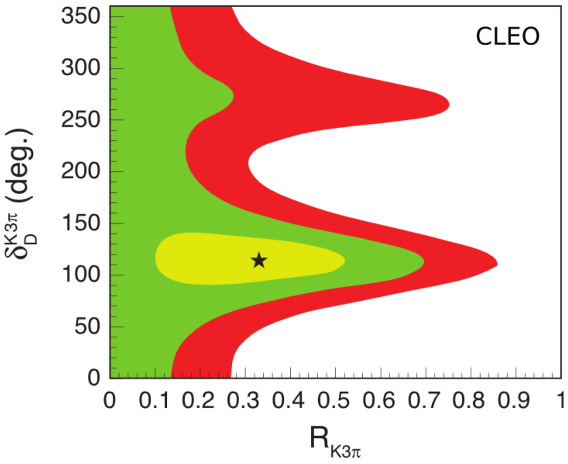
Summary & Prospects

- Preliminary LHCb γ combination with $B^+ \rightarrow D^0 K^+$ decays, using various methods (ADS, GLW, GGSZ) gives **γ = 67±12°**, more precise than the B-factory measurements.
- At the moment, no one method dominates the sensitivity.
- Always looking to add new *B* decays, and new *D* final states
  - First constraints on γ with $B^+ \rightarrow D^0(\rightarrow K_S K \pi)h^+$ just submitted to PLB
  - Promising new mode $B_s \rightarrow \overline{D}^0 \varphi$ now observed
- Wealth of measurements now being done with *b*-baryons, may throw up some interesting surprises.
- Stay tuned for more results in the future!
  - Many measurements are awaiting the inclusion of the 2.0/fb collected at 8 TeV in 2012

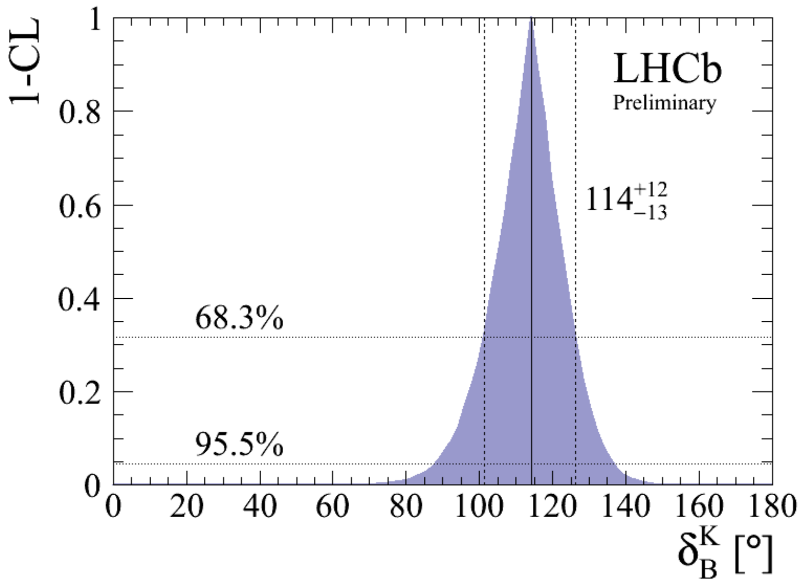
Backup

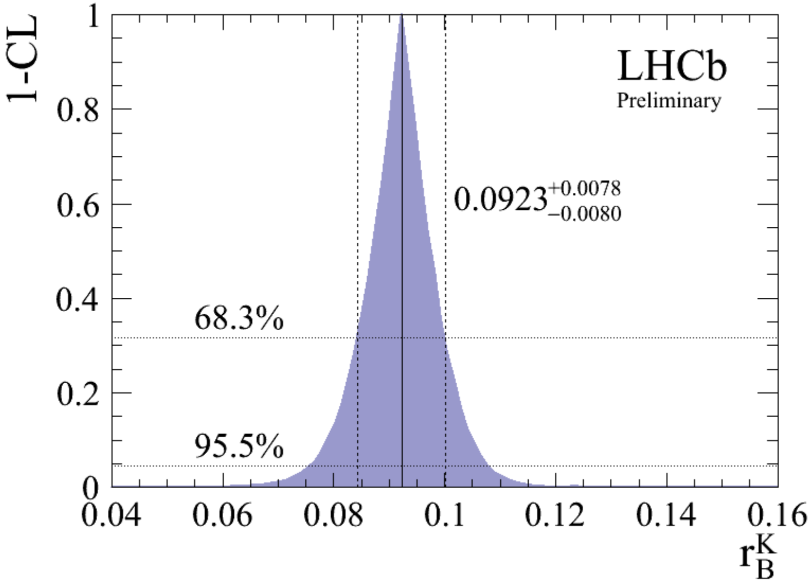
Gamma Combination

- CLEO-c result on $D \to K\pi\pi\pi$:



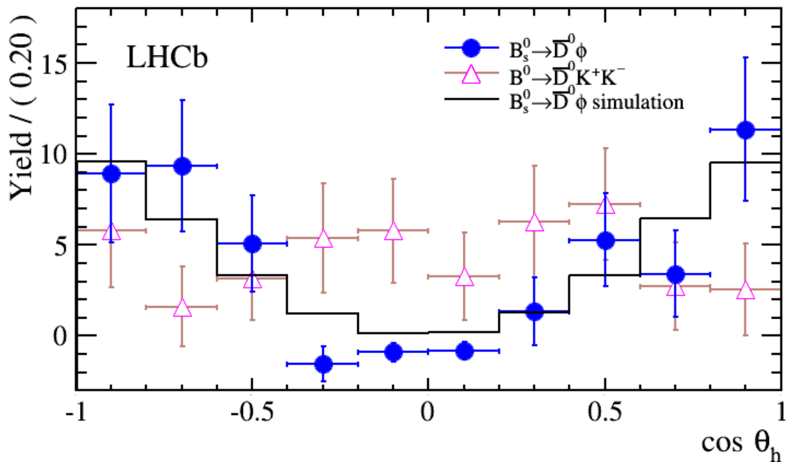
- Other parameters measured:





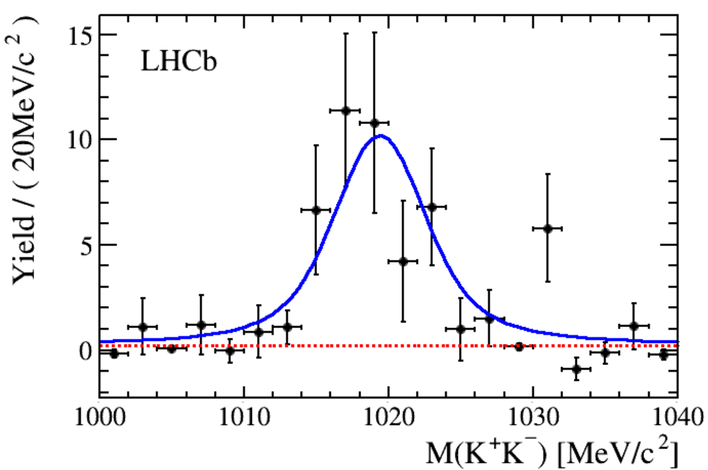
Helicity Structure for $B_s \rightarrow \overline{D}^0 \varphi$

- Distribution of the helicity angle for selected signal events shows that the B_s mass region is dominated by a vector resonance, as expected for a final state. In contrast in the B_d mass region is not.



- The B_d distribution supports what was seen in the LHCb paper on the discovery of the $B_d \rightarrow \overline{D}^0 K^+ K^-$ decay, Phys. Rev. Lett. **109** (2012) 131801.

- The B_s distribution is reinforced by the *m(KK)* distribution in the B_s region:

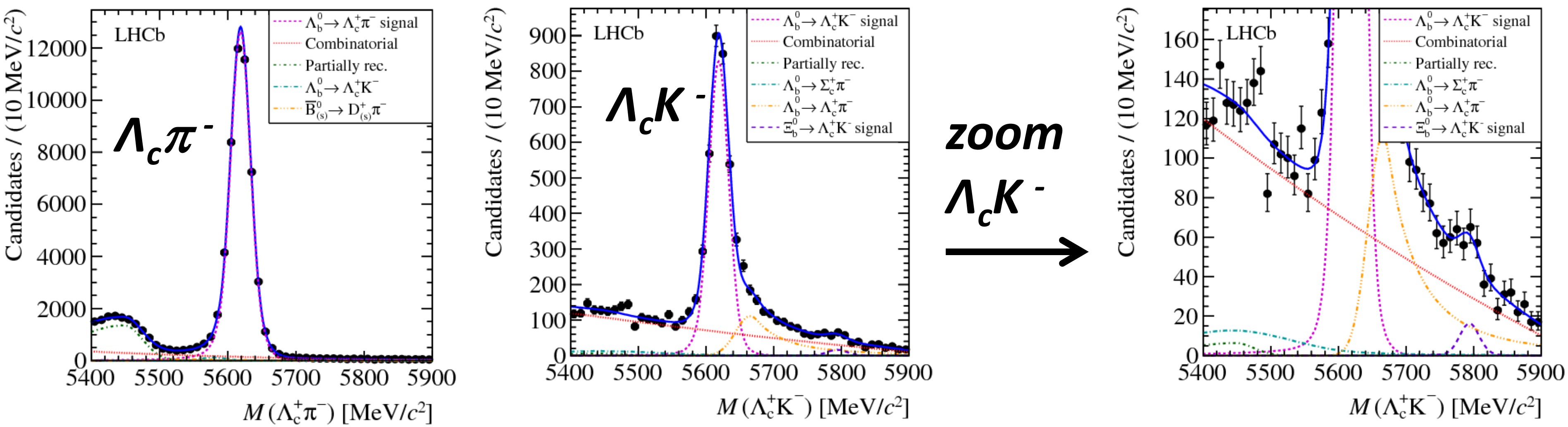


Baryon Decays to D^0ph, $\Lambda_c h$

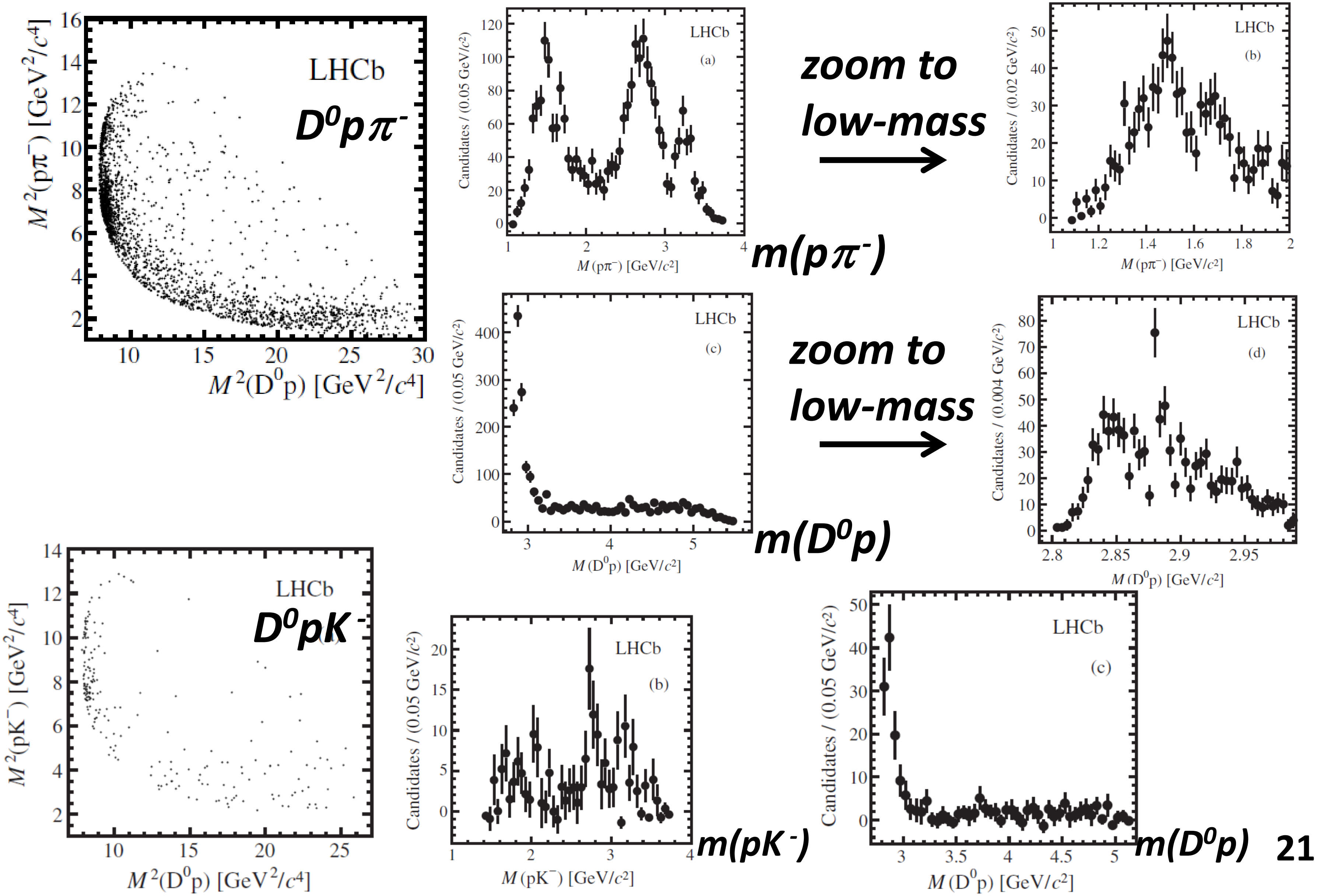
- The tighter selection is also applied to the $\Lambda_c h^-$ spectra, to clearly observe $\Lambda_b \to \Lambda_c K^-$, and find evidence for $\Xi_b \to \Lambda_c K^-$ (3.3σ):

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)} = 0.0731 \pm 0.0016 \pm 0.0016,$$

$$\frac{\mathcal{B}(\Xi_b^0 \to \Lambda_c^+ K^-) \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_b^0 \to D^0 pK^-) \times \mathcal{B}(D^0 \to K^-\pi^+)} = 0.57 \pm 0.22 \pm 0.21$$



$\Lambda_b \to D^0 p h^-$ Dalitz Plots



$\mathcal{B}(B_s \to D^+ D_s^-)$ Measurement

- The "two charm hadrons" analysis also makes the most precise measurement of $\mathcal{B}(B_s \to D^+ D_s^-)$:

$$\frac{\mathcal{B}(B_s^0 \to D^+ D_s^-)}{\mathcal{B}(\bar{B}^0 \to D^+ D_s^-)} = 0.038 \pm 0.004\,(\text{stat}) \pm 0.003\,(\text{syst}).$$

$$\mathcal{B}(B_s^0 \to D^+ D_s^-) = (2.7 \pm 0.5) \times 10^{-4}$$