Measurements of φ_3/γ at LHCb

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On behalf of the LHCb collaboration

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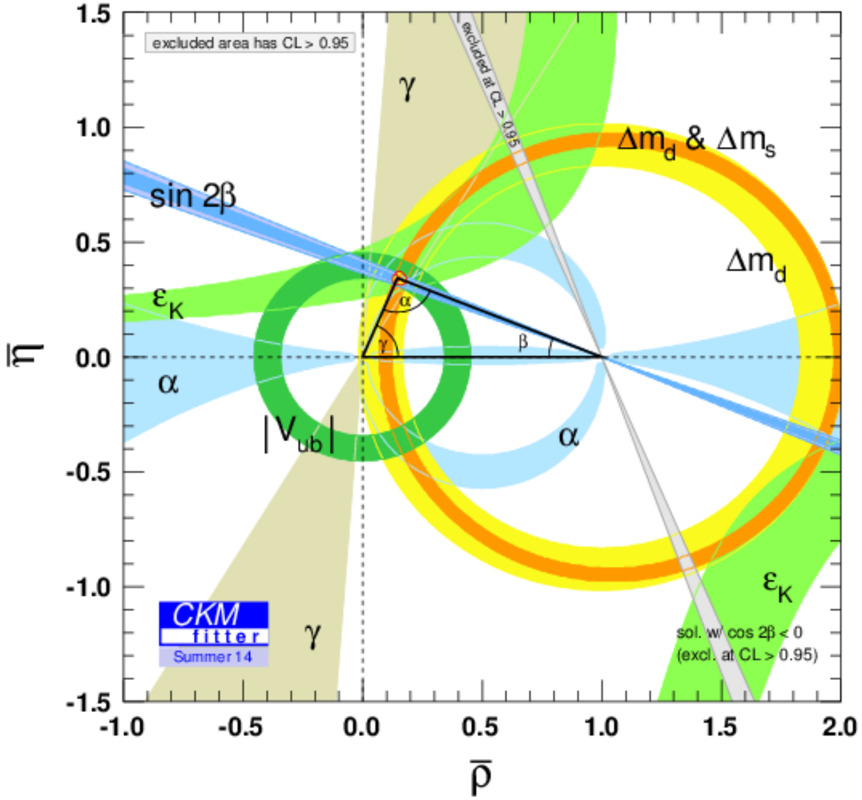
The CKM angle γ



CKM matrix parametrises quark couplings

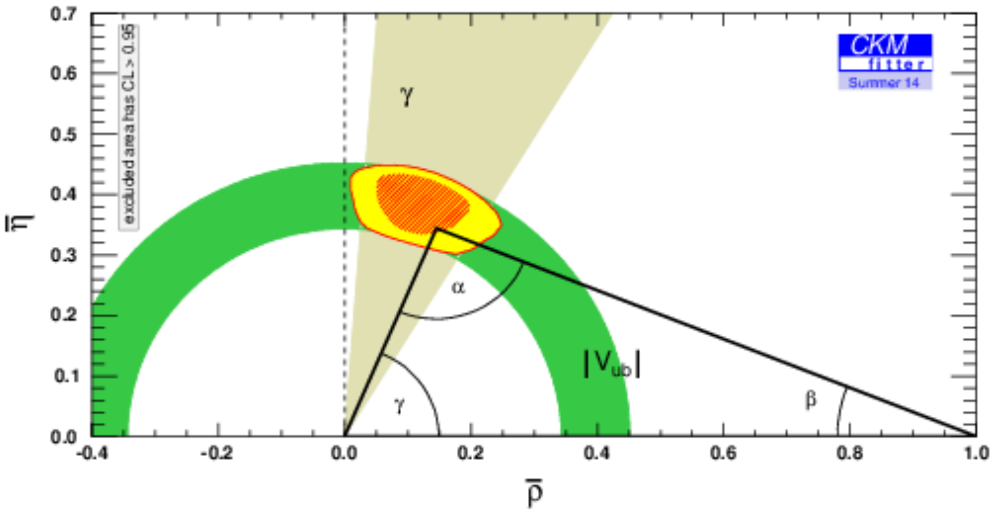
The matrix has one complex phase that results in CPV

Unitarity triangle is a representation of this CPV

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

γ is the least well known angle

Precision measurement → New Physics test bed



γ is the only angle directly accessible in tree decays

Measurement of the "Standard Model". Theoretical uncertainty: 10^{-7}

Direct measurement: $\gamma = 73.2^{+6.3\circ}_{-7.0}$

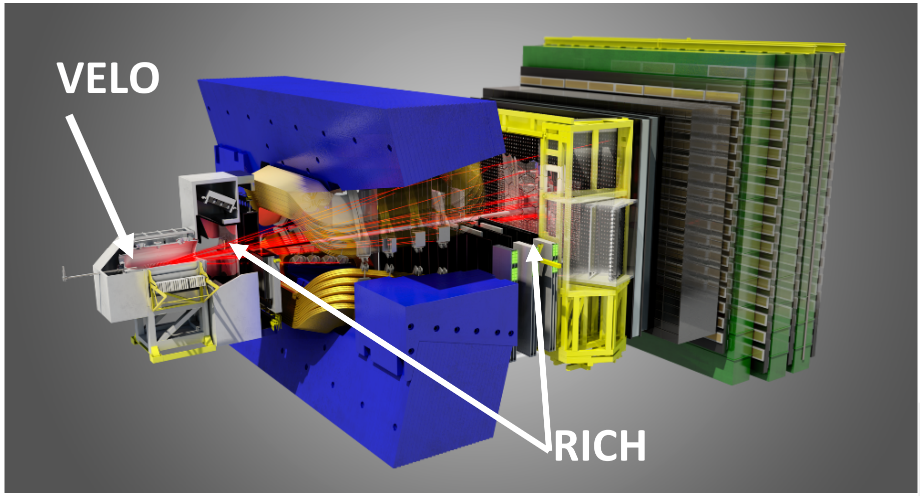
Indirect precision from global CKM fit – includes loop based measurements

$$\gamma = 66.9^{+1.0\circ}_{-3.7}$$

Despite recent progress in the direct measurements better precision still required to test for New Physics.

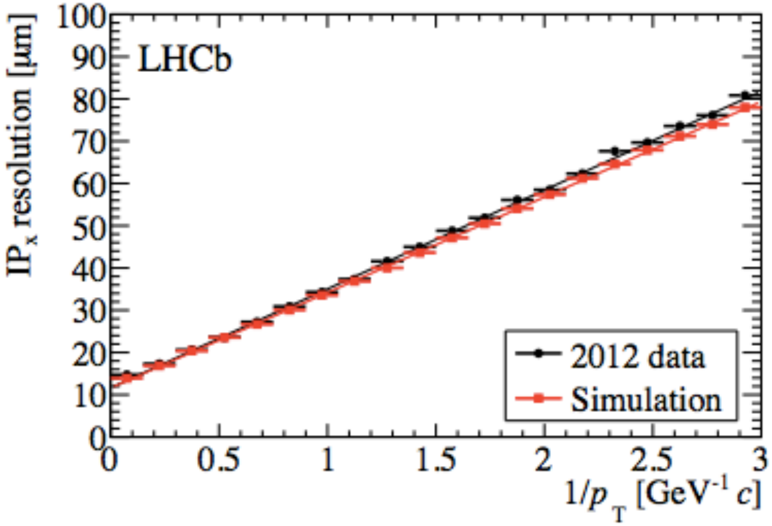
Goal : Improve the direct precision

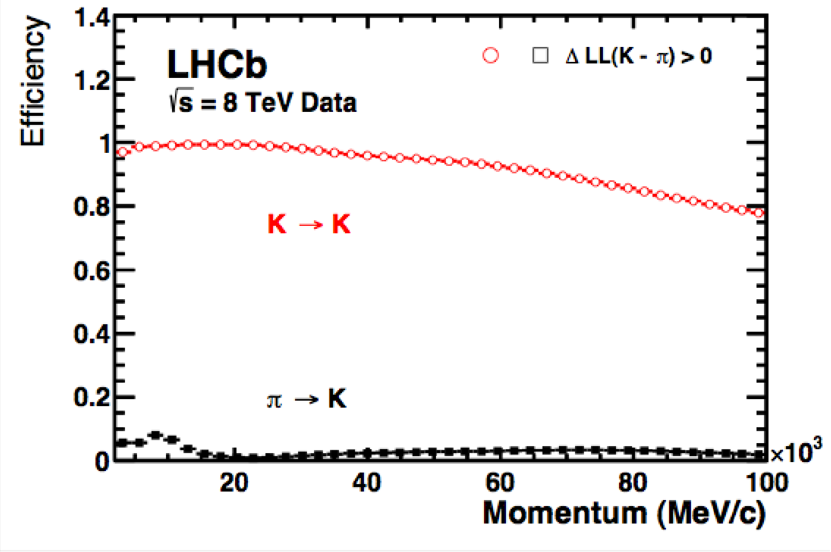
The LHCb detector



All measurements profit from the VELO for displaced vertices and the RICH for particle identification

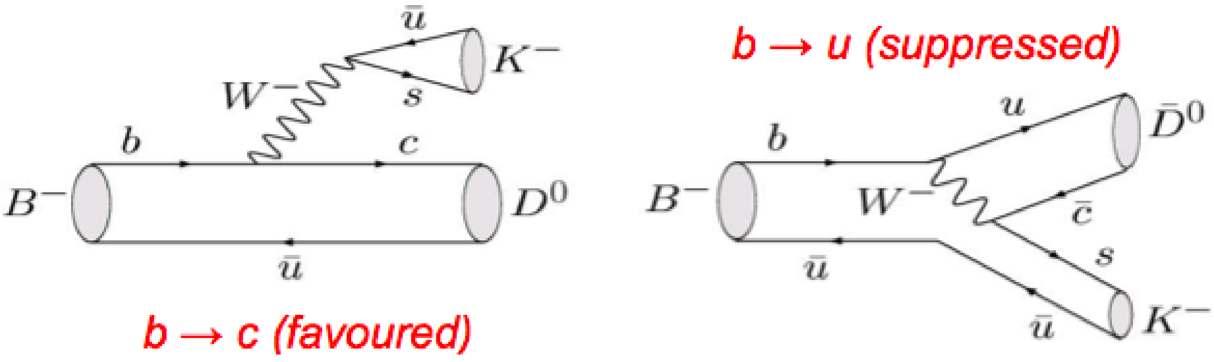
$B_s \rightarrow D_s K$ benefits in particular from the excellent time resolution.





Int. J Mod. Phys A 30 (2015) 1530022

B→DK



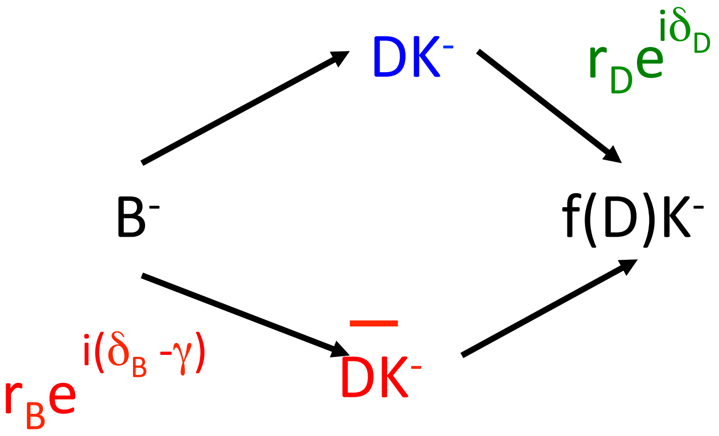
$b \to u$ (suppressed)

$b \to c$ (favoured)

Sensitivity to γ from b→c and b→u interference

Require D^0 and $\overline{D^0}$ to decay to same final state

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



DK^-

$r_D e^{i\delta_D}$

B^-

$f(D)K^-$

$r_B e^{i(\delta_B - \gamma)}$

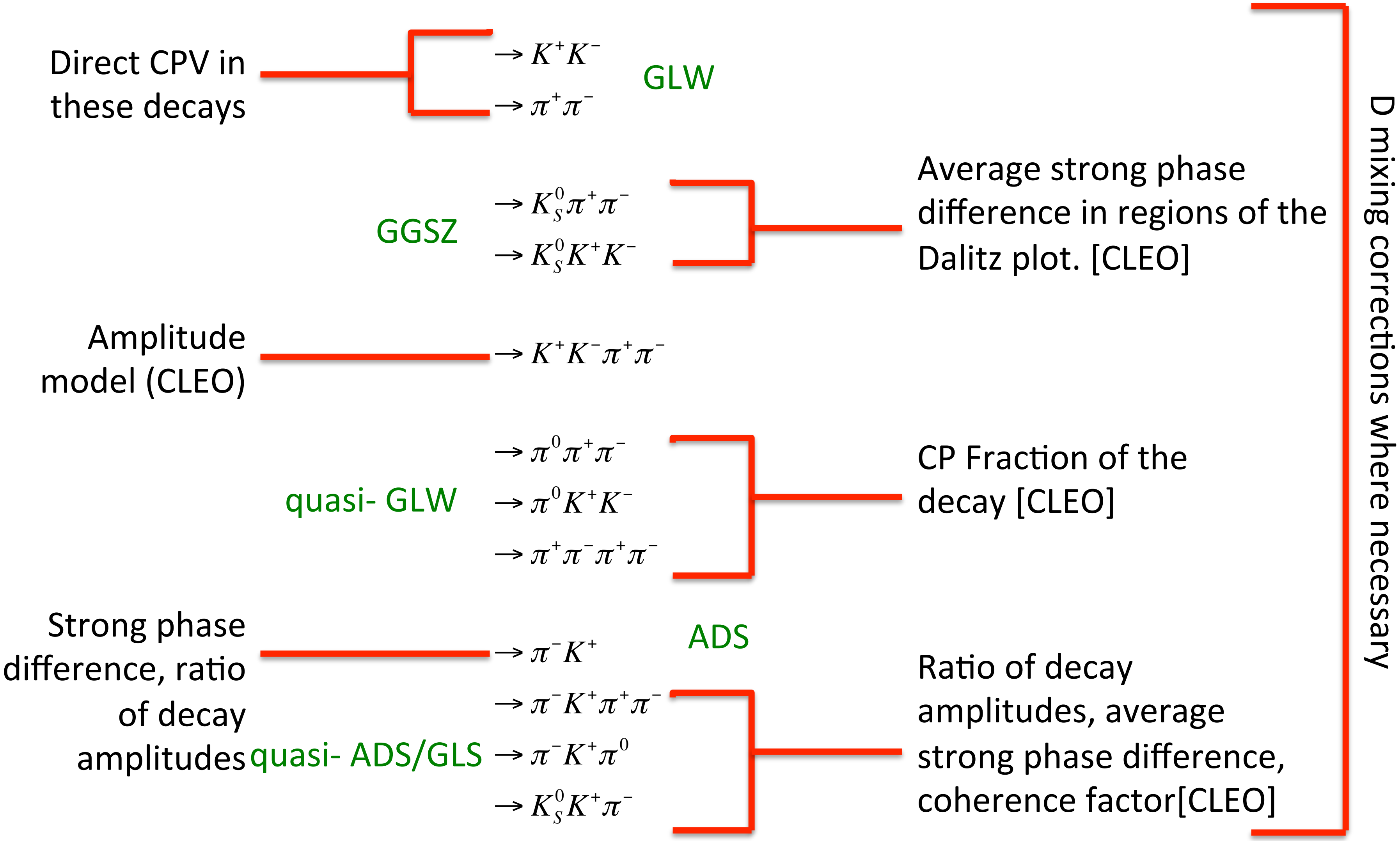
$\overline{D}K^-$

r_B ~ 0.1

B→Dπ also possible r_B ~0.01 but higher statistics.

Measured observables are asymmetries and ratio of yields.

Pick your D channel



Direct CPV in these decays

$\rightarrow K^+K^-$

$\rightarrow \pi^+\pi^-$

GLW

GGSZ

$\rightarrow K_S^0\pi^+\pi^-$

$\rightarrow K_S^0K^+K^-$

Average strong phase difference in regions of the Dalitz plot. [CLEO]

Amplitude model (CLEO)

$\rightarrow K^+K^-\pi^+\pi^-$

quasi- GLW

$\rightarrow \pi^0\pi^+\pi^-$

$\rightarrow \pi^0K^+K^-$

$\rightarrow \pi^+\pi^-\pi^+\pi^-$

CP Fraction of the decay [CLEO]

Strong phase difference, ratio of decay amplitudes

ADS

$\rightarrow \pi^-K^+$

quasi- ADS/GLS

$\rightarrow \pi^-K^+\pi^+\pi^-$

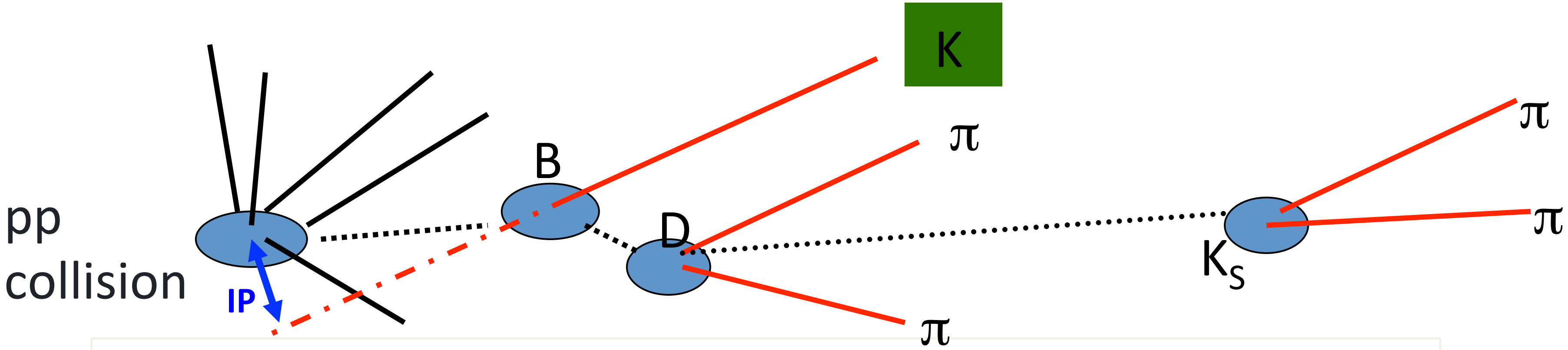
$\rightarrow \pi^-K^+\pi^0$

$\rightarrow K_S^0K^+\pi^-$

Ratio of decay amplitudes, average strong phase difference, coherence factor[CLEO]

D mixing corrections where necessary

Selection



Separate the topology of interest from random combinations

Useful variables include:

- Impact parameters
- Flight distances. (B travels a ~cm, K_s many cm)
- Vertex quality
- Particle ID

Specific vetos against particular backgrounds

π^0 reconstructed in decay to 2 photons

All analyses shown here employ similar strategies

Using multibody final states – $hh^{(\prime)}\pi^0$

Intermediate resonances dilute the impact of the observables.

$$\begin{aligned}
R^{K\pi\pi^0}_{\mathrm{ADS}(K)} &\approxeq (r_B)^2 + (r_D^{K\pi\pi^0})^2 + 2\kappa_D^{K\pi\pi^0} r_B r_D^{K\pi\pi^0} \cos(\delta_B + \delta_D^{K\pi\pi^0}) \cos\gamma \\
A^{K\pi\pi^0}_{\mathrm{ADS}(K)} &\approxeq \left[2\kappa_D^{K\pi\pi^0} r_B r_D^{K\pi\pi^0} \sin(\delta_B + \delta_D^{K\pi\pi^0}) \sin\gamma\right] / R^{K\pi\pi^0}_{\mathrm{ADS}(K)} \\
R^{h'h'\pi^0}_{\mathrm{qGLW}} &= 1 + (r_B)^2 + (2F_+^{h'h'\pi^0} - 1) \cdot 2 r_B \cos\delta_B \cos\gamma \\
A^{h'h'\pi^0}_{\mathrm{qGLW}(K)} &= (2F_+^{h'h'\pi^0} - 1) \cdot 2 r_B \sin\delta_B \sin\gamma / R^{h'h'\pi^0}_{\mathrm{qGLW}}
\end{aligned}$$

Dilution factors

Parameters of interest

Dilution factors all measured
They are large – all three decay modes pursued

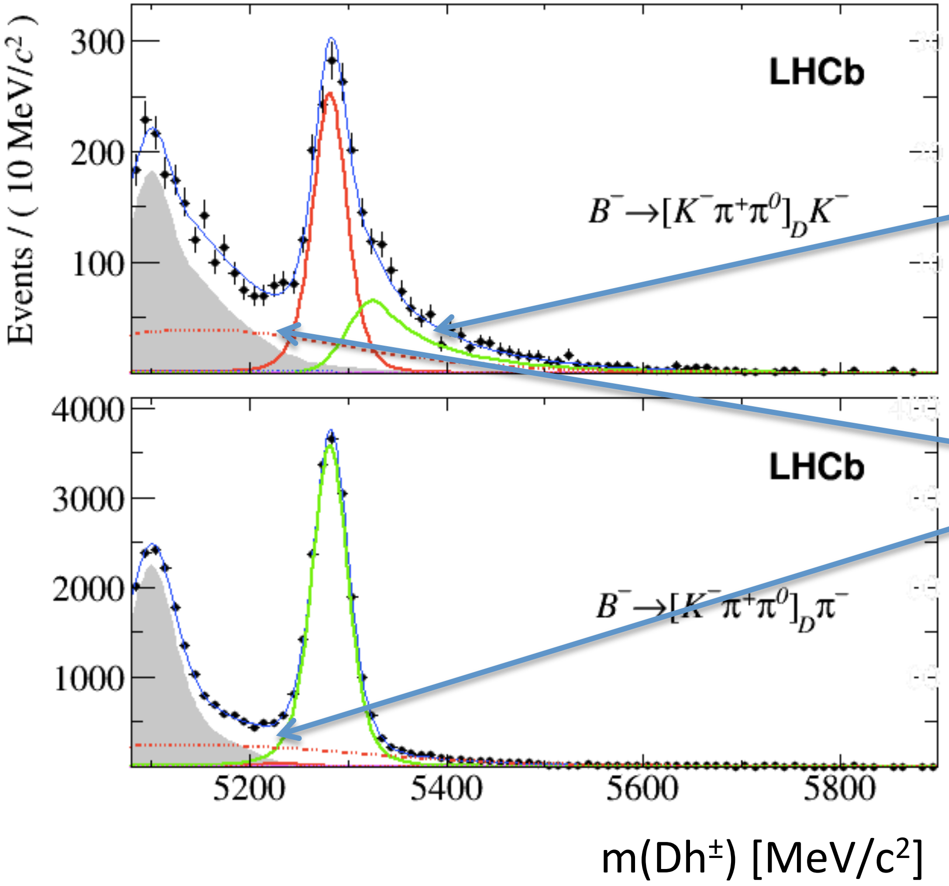
$$\kappa^{K\pi\pi^0} = 0.82 \pm 0.07$$

$$F^{\pi\pi\pi^0} = 0.973 \pm 0.017$$

$$F^{KK\pi^0} = 0.732 \pm 0.055$$

PLB 731 (2014) 197, arXiv :1504.05878

Favoured modes



Mass fit shapes driven by the favoured control channel

PID efficiencies constrain the fraction of B→Dπ in the B→DK channel

Presence of the π^0 reduces purity in comparison to all charged final states.

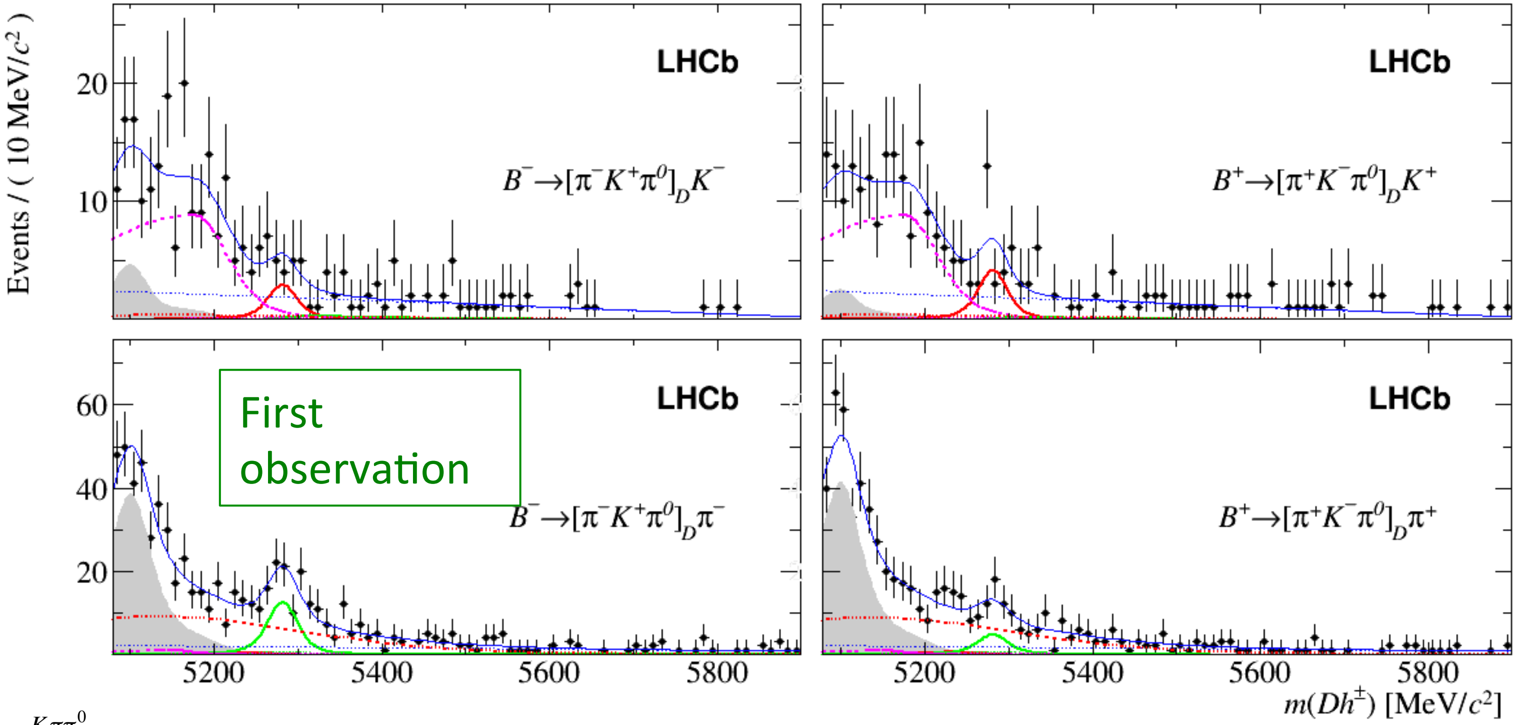
-Wrongly reconstructed D background

Detection and detector asymmetries input – fit observables corrected for these.

Production asymmetries is determined from the favoured decay.

arXiv:1504.05442

ADS-like modes



First observation

$$R_{ADS(K)}^{K\pi\pi^0} = 0.0140 \pm 0.0047 \pm 0.0021$$

$$R_{ADS(\pi)}^{K\pi\pi^0} = 0.00235 \pm 0.00049 \pm 0.00006$$

$$A_{ADS(K)}^{K\pi\pi^0} = -0.20 \pm 0.27 \pm 0.03$$

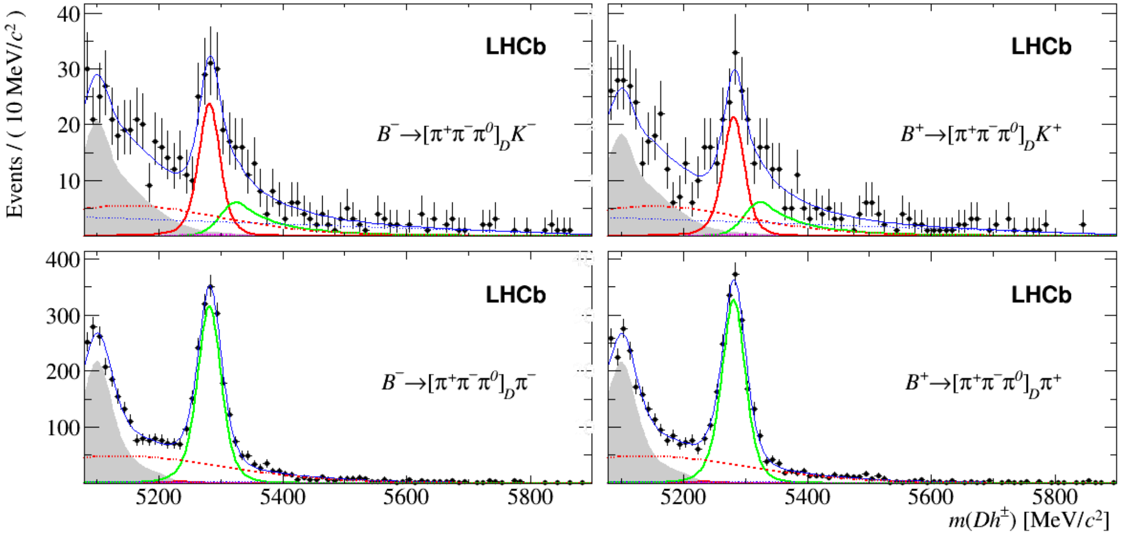
$$A_{ADS(\pi)}^{K\pi\pi^0} = 0.438 \pm 0.190 \pm 0.009$$

Uncertainties smaller than an analysis from Belle

Significance of B→DK signal is 2.8σ
Significance of B→Dπ signal is 5.3σ

arXiv:1504.05442

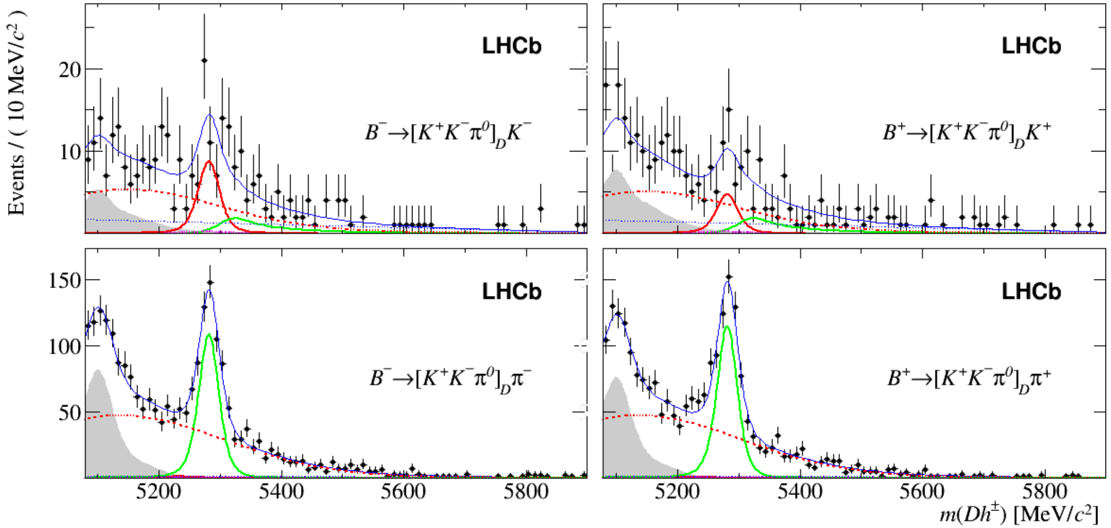
GLW-like modes



Statistics not sufficient for significant asymmetries

First observation of B→[KKπ^0] π. (>10 σ)

First evidence of B→[KKπ^0]K (4.5σ)



$$A_{qGLW(K)}^{\pi\pi\pi^0} = 0.054 \pm 0.091 \pm 0.011$$

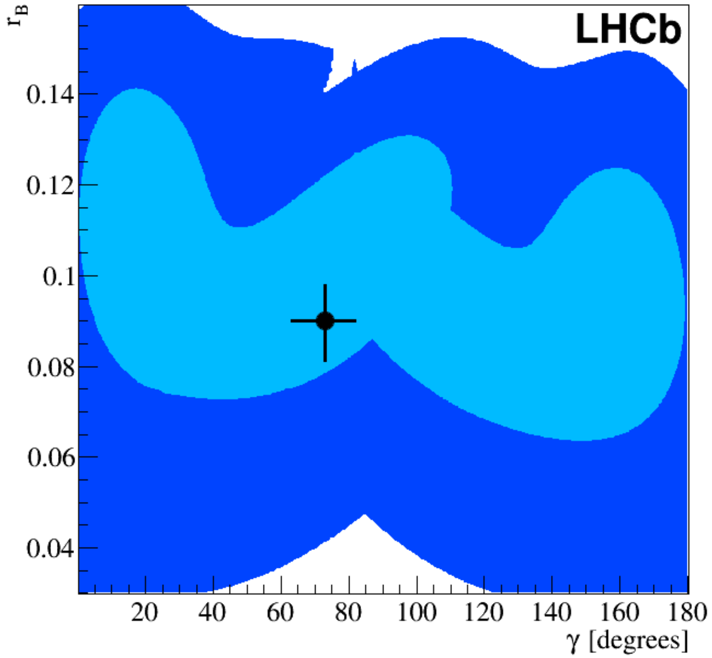
$$A_{qGLW(\pi)}^{\pi\pi\pi^0} = -0.016 \pm 0.020 \pm 0.004$$

$$A_{qGLW(K)}^{KK\pi^0} = 0.030 \pm 0.020 \pm 0.02$$

$$A_{qGLW(\pi)}^{KK\pi^0} = -0.030 \pm 0.040 \pm 0.005$$

arXiv:1504.05442

Interpretation of these results



2D likelihood scans of γ-r_B

1, 2 σ contours shown
Cross marks the best of of combination of other LHCb results

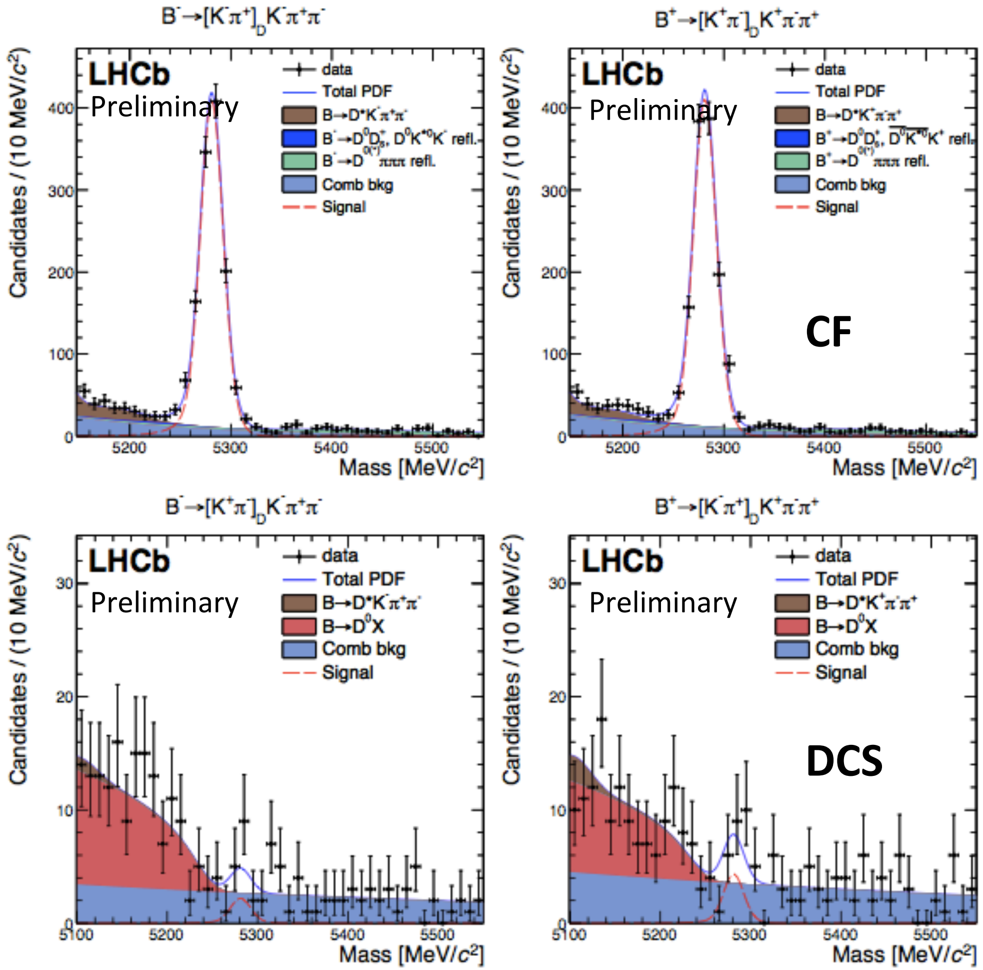
Although with this set of measurements γ is unconstrained $r_B = 0.11 +/- 0.03$

Will help further constrain γ, $r_{B,}$ δ_B when entered into the combination

arXiv:1504.05442

NEW

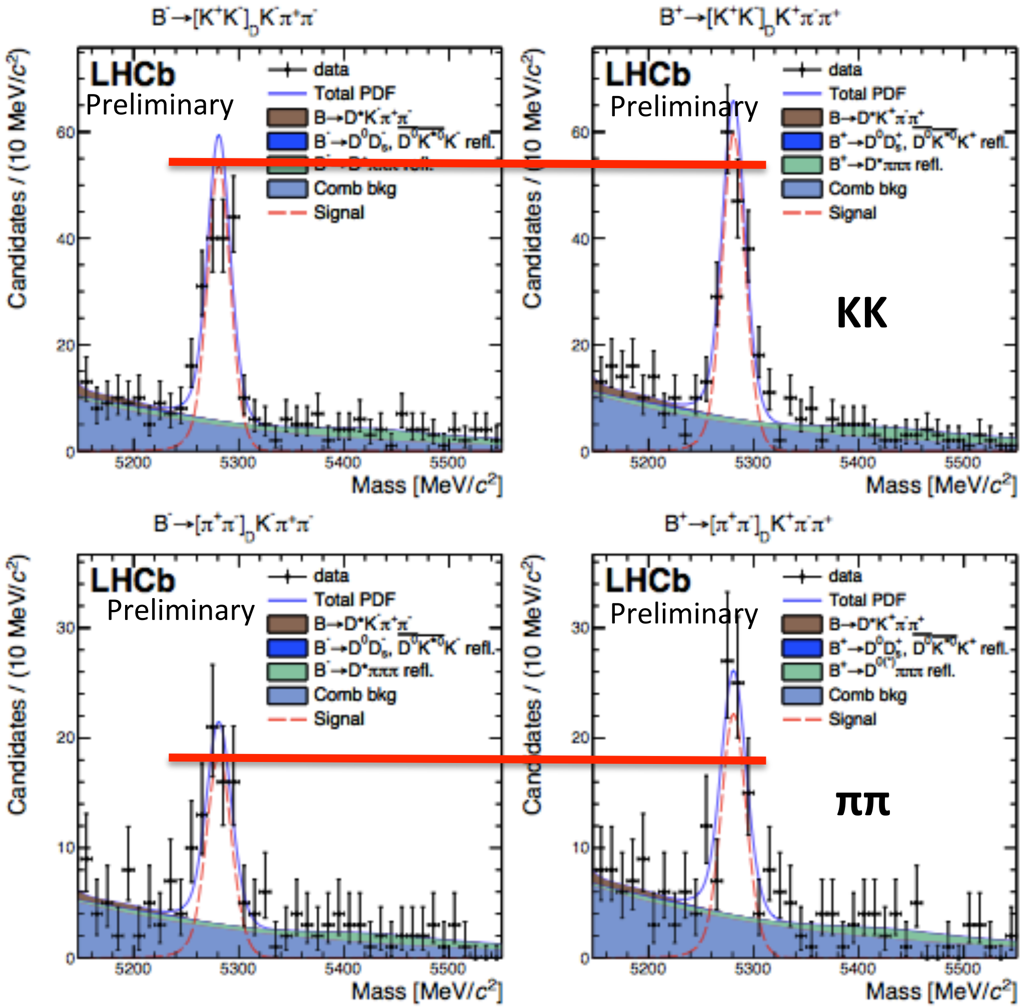
Other B decays: B→DKππ (1)



- Analyse KK, ππ, πK decay modes of the D
- r_B, δ_B are different to B→DK, γ is common
- Additional coherence factor due to different resonances in B →DKππ and B→$\bar{D}$Kππ
- Determined alongside the other physics parameters of interest
- Kππ system phasespace is restricted to enhance coherence
  - M(Kππ)<2 GeV/c^2
  - M(Kπ) within 100 MeV/c^2 of K*
- B→Dπππ also studied for CPV

LHCB-Paper-2015-020

NEW Other B decays: B→Dhππ (2)



Different selection used for the GLW and ADS modes

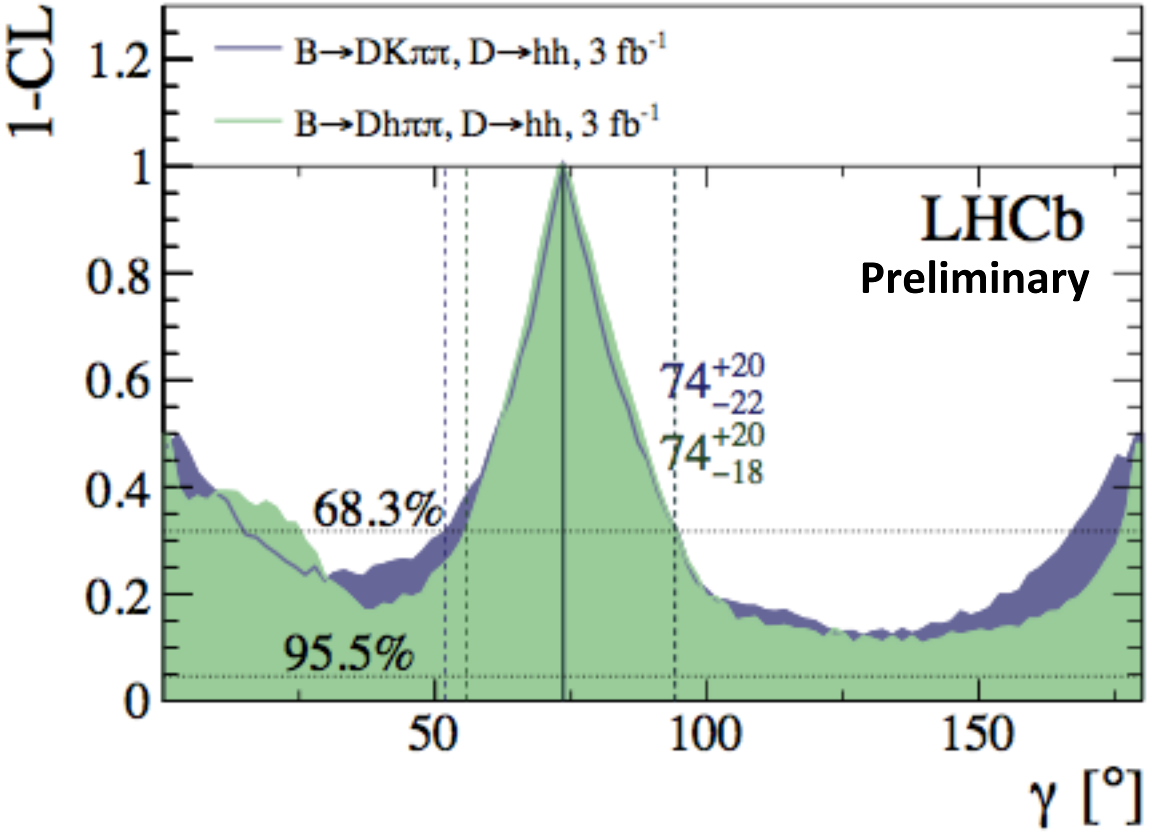
Looser selection possible in the GLW modes due to higher signal yields.

First observation of all these decays

LHCB-Paper-2015-020

NEW

Constraints on γ



Strong constraints set on γ at the 68.3% CL.

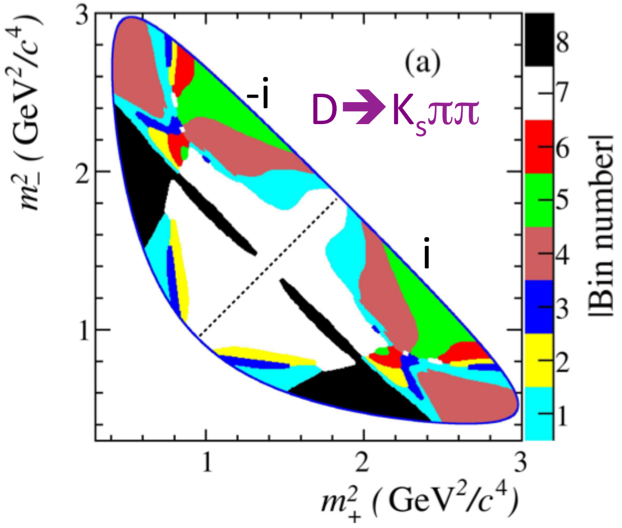
This decay channel has potential

Additional information from B→Dπππ adds a little sensitivity

Coherence factor close to 1 though no constraints set in the physical limit [0,1]

LHCB-Paper-2015-020

The golden modes – $K_s\pi\pi$, K_sKK



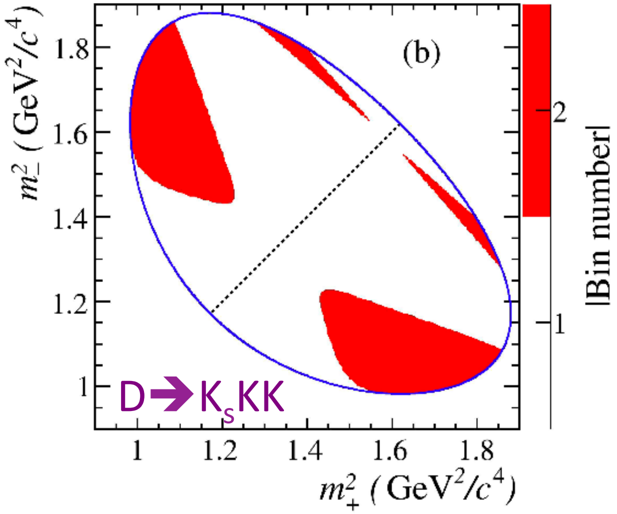
These decays analysed in regions of the Dalitz plot – not much sensitivity if analysed inclusively.

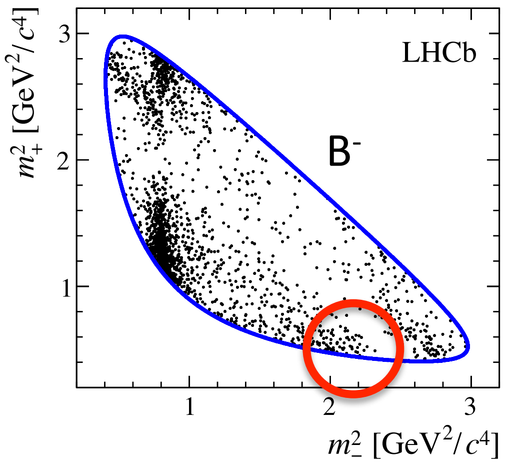
Binning shapes optimised for statistical sensitivity.

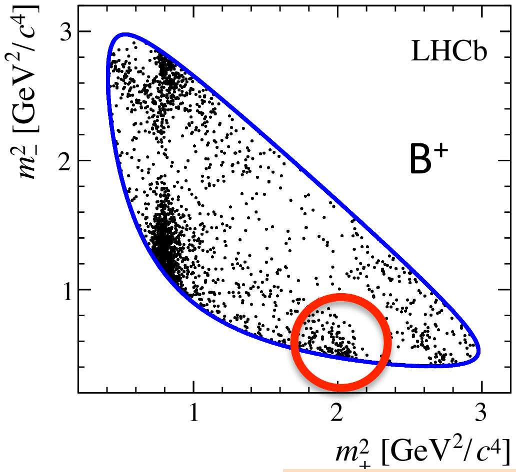
Symmetry of Dalitz plot defines positive and negative bins.

Reduces the analysis to a counting experiment in bins of the Dalitz plot - model independent

Data from D→K_SKK easily added as two additional bins.







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Analysis strategy

To determine γ : Count the number of observed events in a region of the Dalitz plot.

$$N_i^{\pm} = h\left(K_{\pm i} + r_B^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}\left[x_{\pm} c_i \pm y_{\pm} s_i\right]\right)$$

D from B± events in bin *i* of Dalitz plot

Fraction of events in bin for pure D^0 sample with the efficiency profile of signal

$x_{\pm}=r_B\cos(\delta_B \pm \gamma)$

$y_{\pm}=r_B\sin(\delta_B \pm \gamma)$

K_i are inputs from other LHCb decays - use $B^0 \rightarrow D^{*+}\mu^-\nu$, $D^{*+} \rightarrow D^0\pi^+$

Charge of the π tags the D^0 flavour.

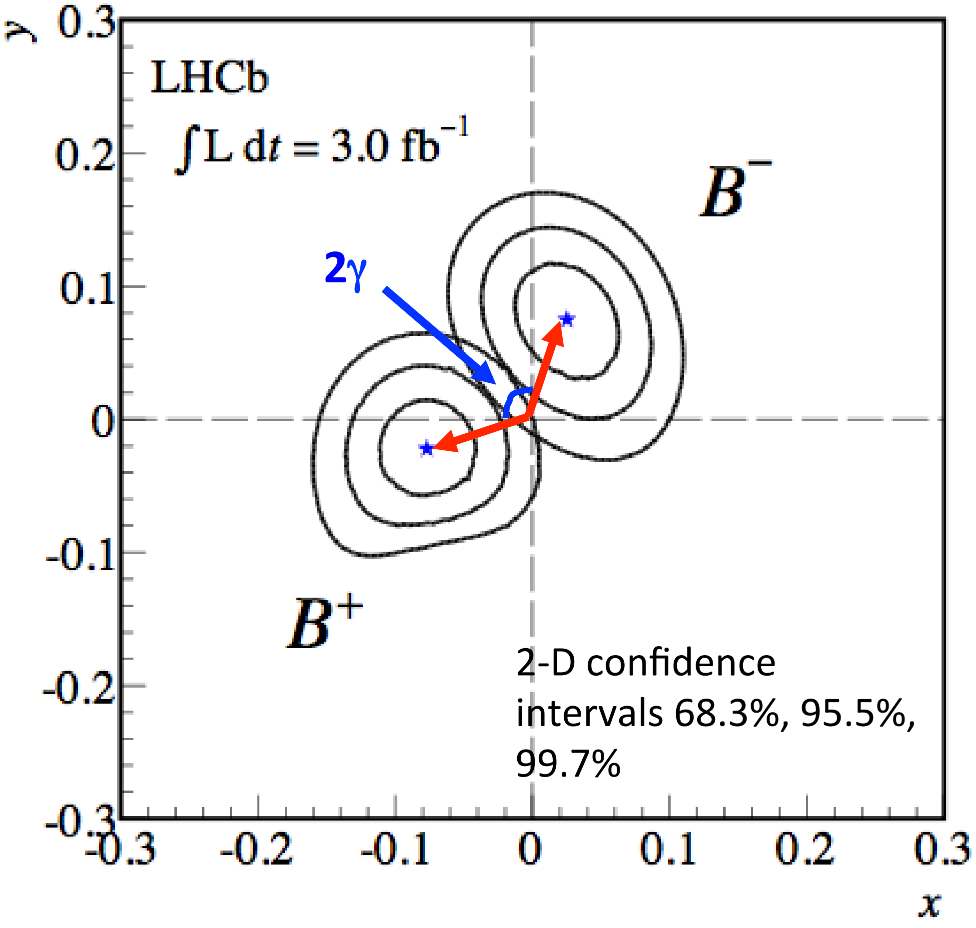
c_i and s_i are inputs from CLEO - the are measurements of the cosine and sine of the average strong phase difference

Simultaneous mass fit to candidates in all bins to extract best x,y

Combined measurement of 3 fb^{-1} data

Results

$$x_+ = (-7.7 \pm 2.4 \pm 1.0 \pm 0.4) \times 10^{-2},$$
$$x_- = (2.5 \pm 2.5 \pm 1.0 \pm 0.5) \times 10^{-2},$$
$$y_+ = (-2.2 \pm 2.5 \pm 0.4 \pm 1.0) \times 10^{-2},$$
$$y_- = (7.5 \pm 2.9 \pm 0.5 \pm 1.4) \times 10^{-2},$$



2-D confidence intervals 68.3%, 95.5%, 99.7%

Corrections for D mixing, K_s CPV ignored - negligible effect

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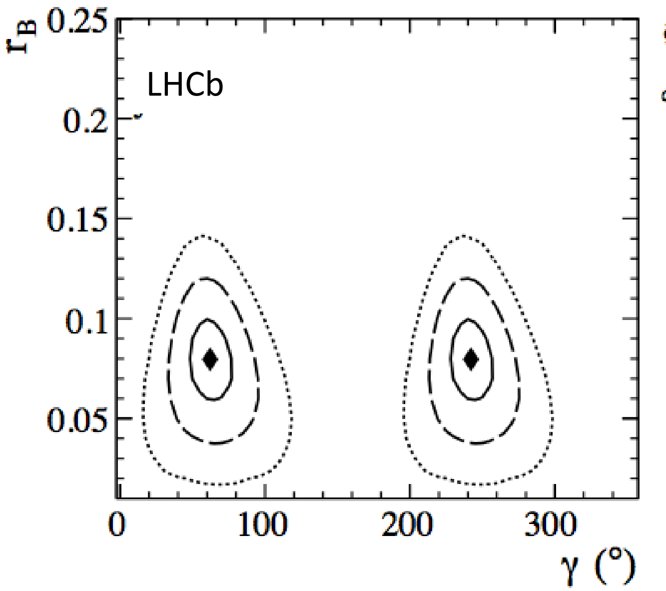
Constraints on γ

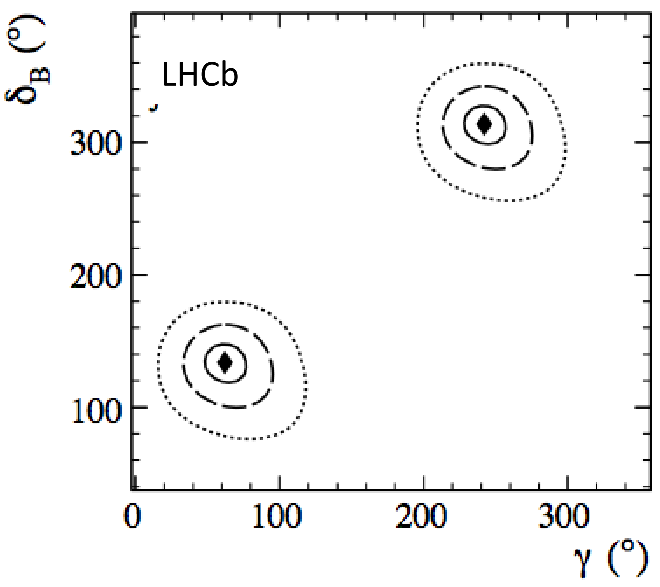
$$\gamma = (62^{+15}_{-14})^{\circ}$$

$$r_B = (8.0^{+1.9}_{-2.1}) \times 10^{-2}$$

$$\delta_B = (134^{+14}_{-15})^{\circ}$$

Precision matches that of either B factory γ combinations





Projection of contours onto 1-D gives 68.3, 95.5,99.7 % CL

Two-fold ambiguity from trigonometric relations

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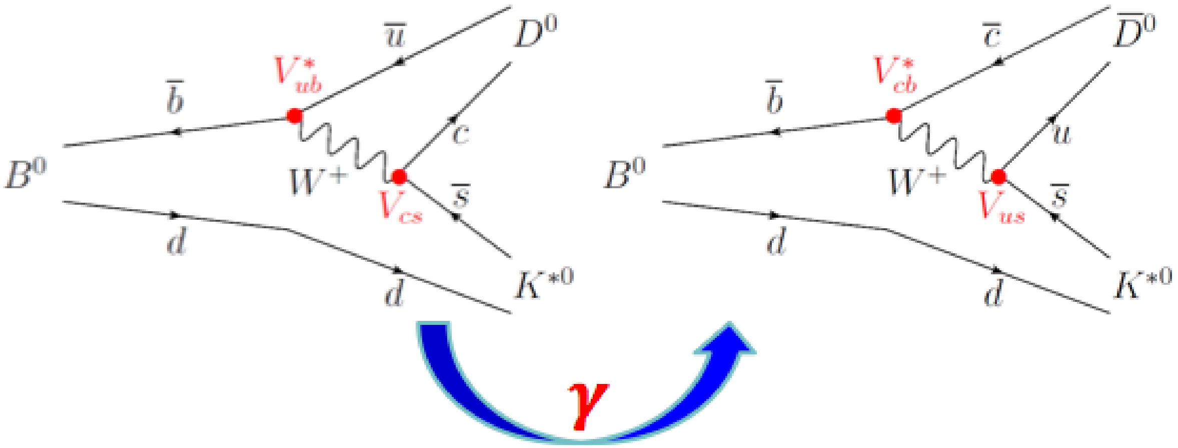
$B^0 \rightarrow DK^*$



Both diagrams colour suppressed ➔ large r_B (large interference)

Initial B^0 flavour tagged by the charge of the kaon in the K^{0*}➔$K\pi$

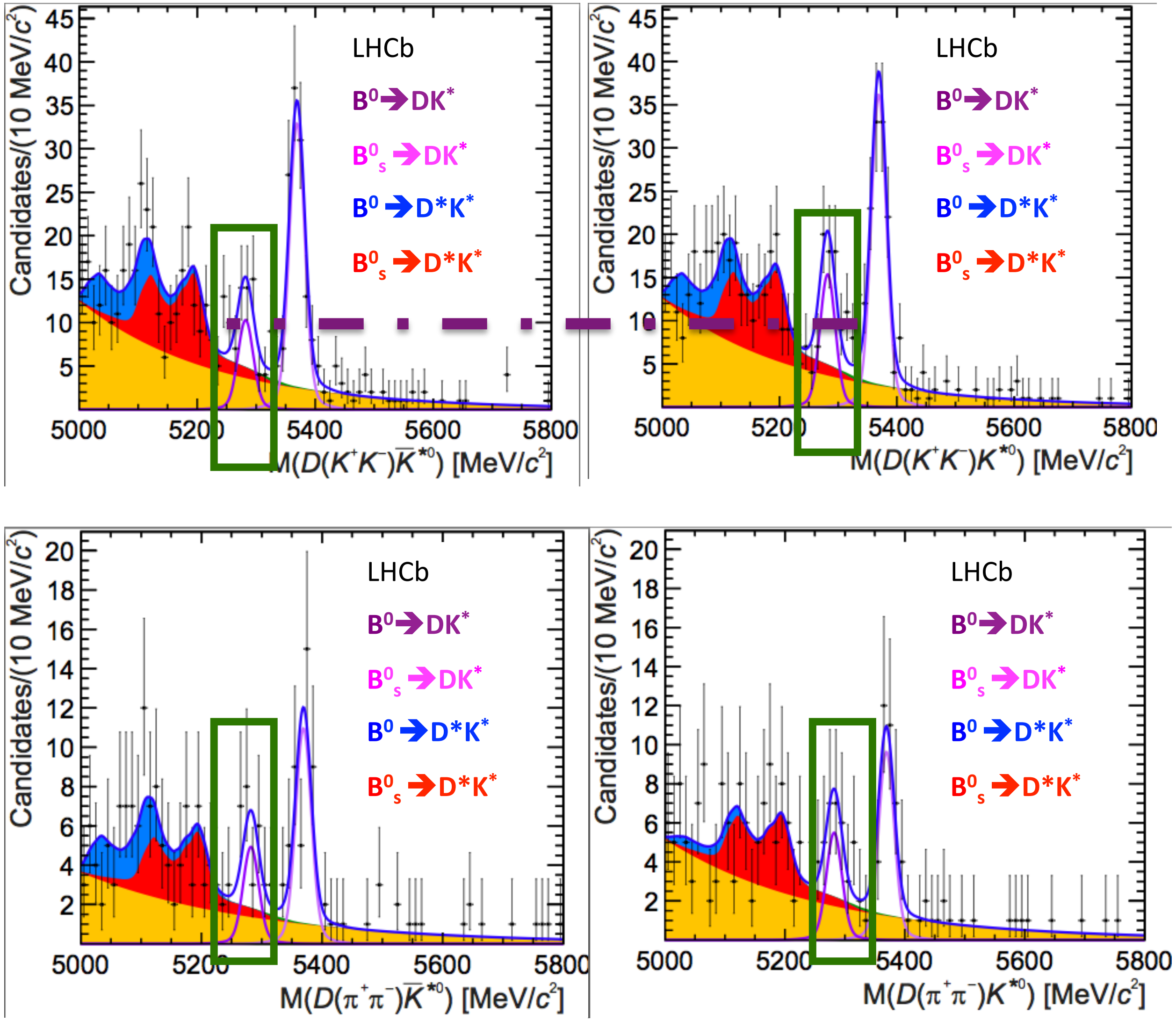
(no need for time-dependent analysis)

Interference requires same D final state

So far two-body D decay modes considered with 3 fb^{-1}

γ common to all analyses; here different B decay means different r_B and δ_B

KK, ππ in B⁰→DK*⁰



KK - significance of signal: 8.6σ

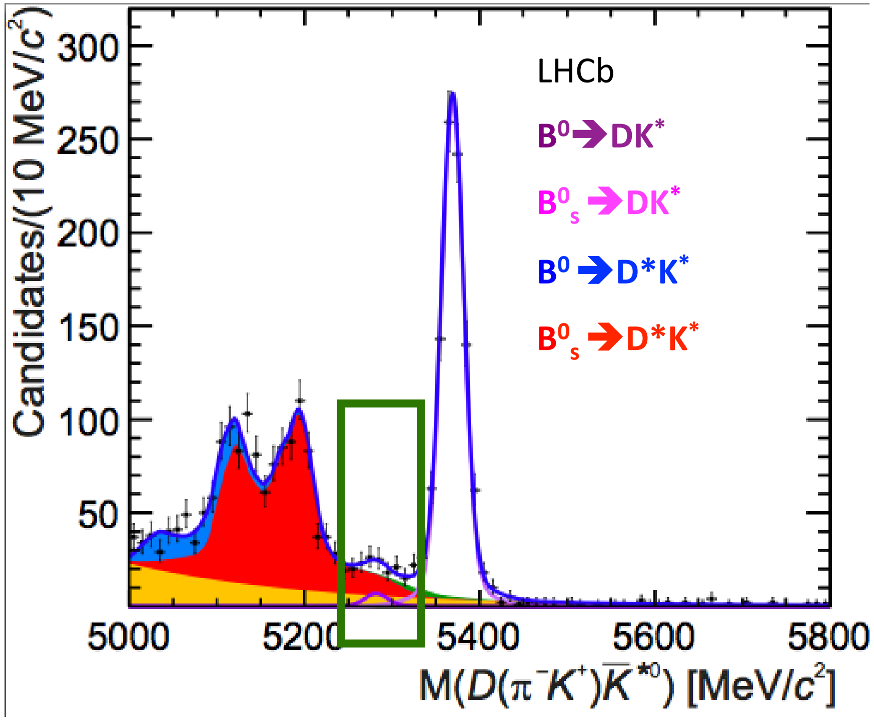
ππ - significance of signal: 5.8σ

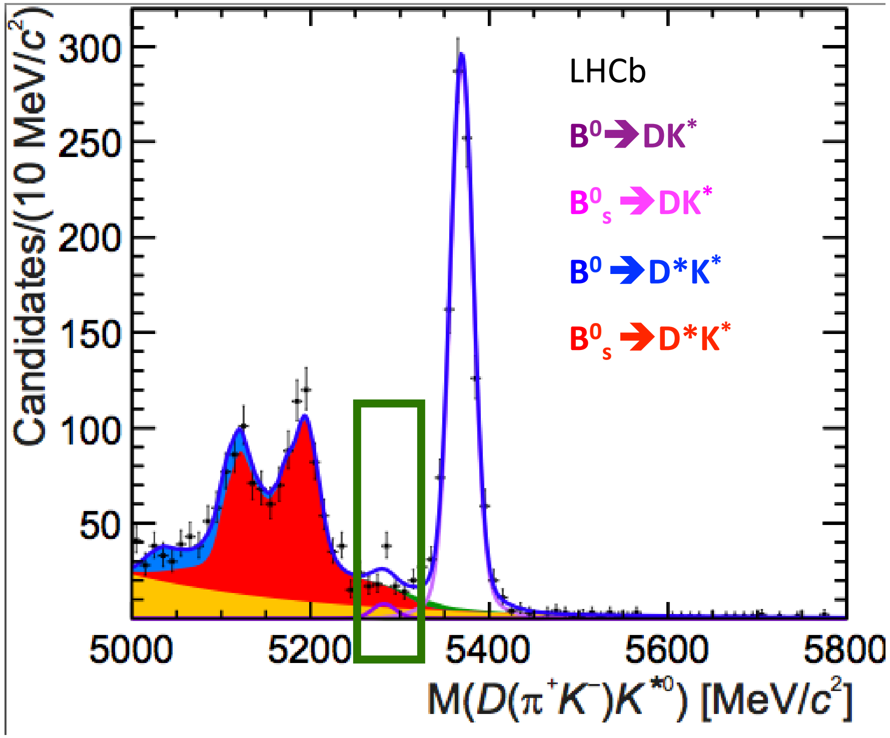
$$A_d^{KK} = -0.198^{+0.144+0.019}_{-0.145-0.020}$$

$$A_d^{\pi\pi} = -0.092^{+0.217+0.019}_{-0.217-0.019}$$

PRD 90 (2014) 112002

πK in $B^0 \rightarrow DK^{*0}$





$$R_d^+ = 0.057^{+0.029+0.009}_{-0.027-0.012}$$

Combined signal significance is 2.9σ.

$$R_d^- = 0.056^{+0.032+0.009}_{-0.030-0.012}$$

PRD 90 (2014) 112002

Interpretation

Coherence factor κ determined from simulation of a realistic model of the resonance content of $B^0 \to DK\pi$

$\kappa = 0.95 \pm 0.03$

Measurements of all observables combined to determine r_B, δ_B γ

Ambiguities from the trigonometric relations

Some constraints can be set at the 68.3% CL

r_B value larger than that for $B \to DK$

Promising decay to study further

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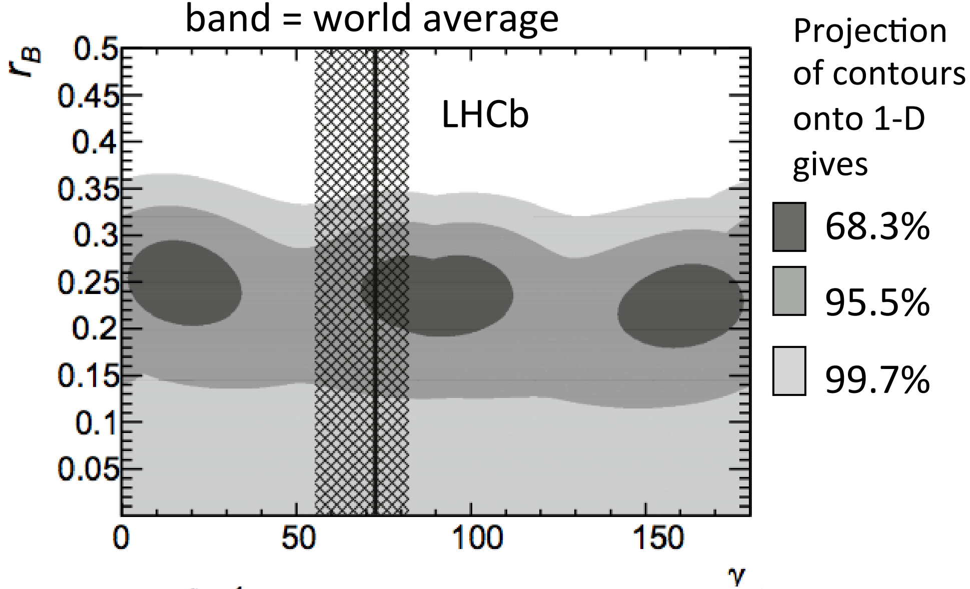
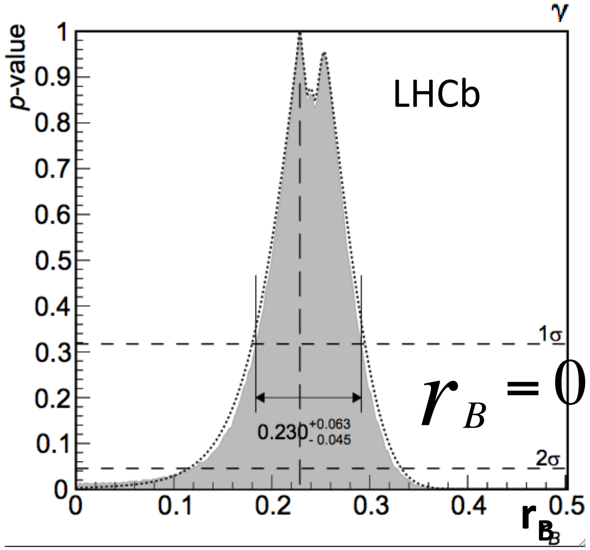

band = world average

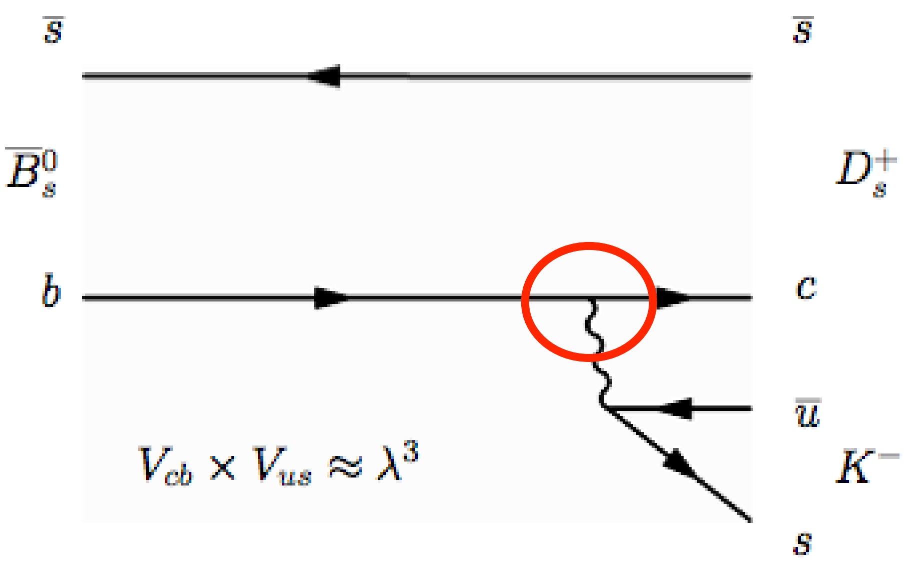
Projection of contours onto 1-D gives

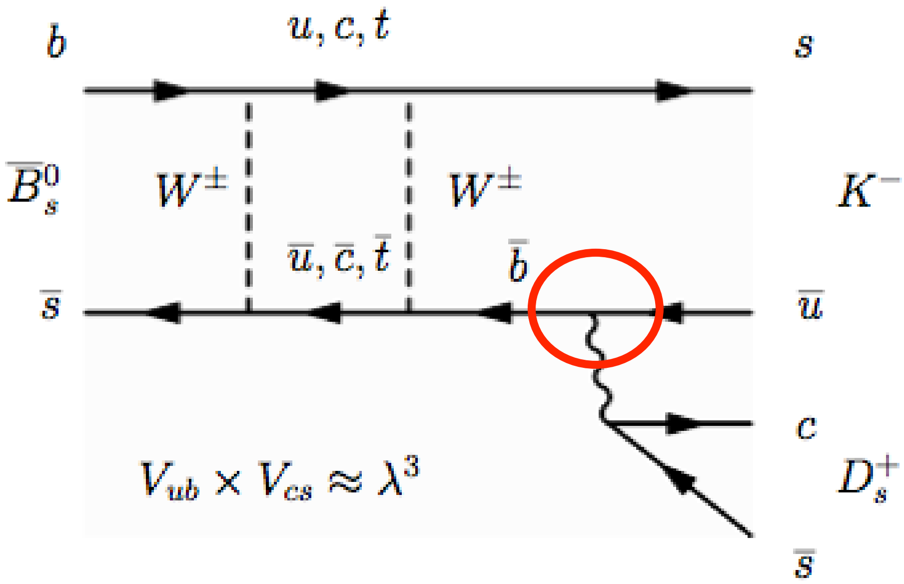


$$r_B = 0.230^{+0.063}_{-0.045}$$

Time dependent methods

Measure CP violation in the interference of mixing and decay





Both decay amplitudes ~λ^3 ➔ Large interference

Tree level process like other analyses shown

Time-dependence increases the complexity of the analysis

Decay rate relations

$$\frac{\mathrm{d}\Gamma_{B_s^0\to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f\cos(\Delta m_s t) - S_f\sin(\Delta m_s t)\right],$$

$$\frac{\mathrm{d}\Gamma_{\overline{B}_s^0\to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f\cos(\Delta m_s t) + S_f\sin(\Delta m_s t)\right],$$

$$\lambda_f \equiv \frac{q}{p}\left(\frac{\overline{A}_f}{A_f}\right)$$

A_f is the decay amplitude for B_S to decay to final state f

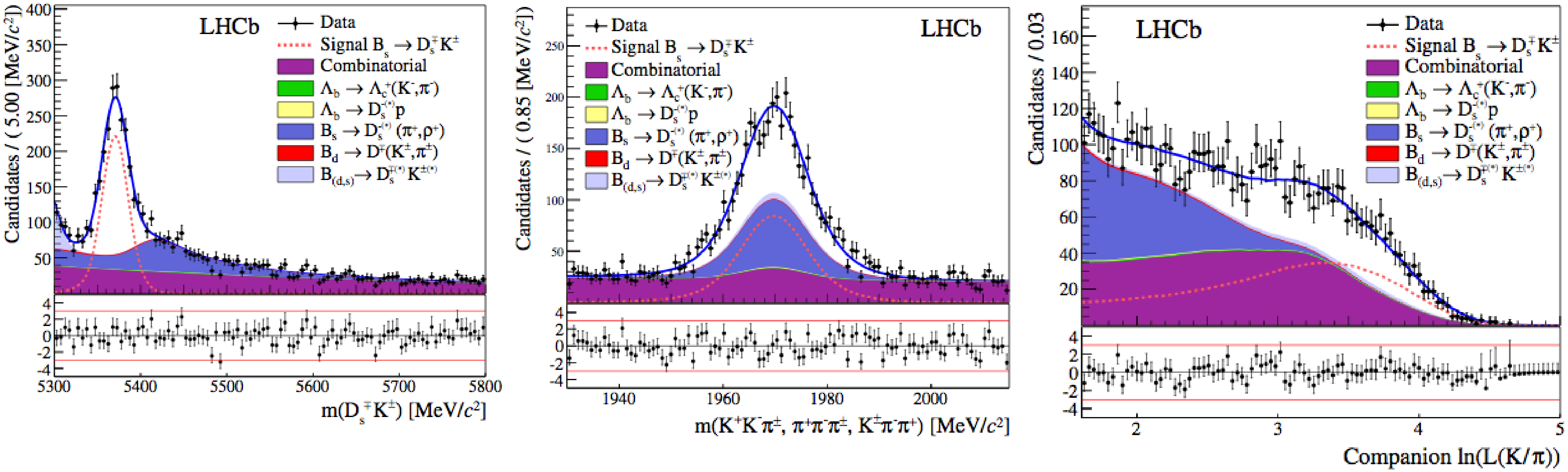
$$C_f = \frac{1-r_{D_sK}^2}{1+r_{D_sK}^2},$$

$$A_f^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}, \quad A_{\overline{f}}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2},$$

$$S_f = \frac{2r_{D_sK}\sin(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}, \quad S_{\overline{f}} = \frac{-2r_{D_sK}\sin(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2},$$

β_s - mixing phase

Parametrising signal



Three D_s^- decays considered: $K^-K^+\pi^-$, $\pi^-\pi^+\pi^-$, $K^-\pi^+\pi^-$: Plots show all D_s states combined

Simultaneous fit in 3 variables: $M(B_s)$, $M(D_s)$ and PID variable on the Kaon from the B

Allows for signal/background discrimination, and for determination of signal weights

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Tagging and decay time performance

Flavour tagging:

Combination of SS and OS taggers

Efficiency of tagging an event = 67.5%

Effective tagging power = 5.07%

Decay time acceptance:

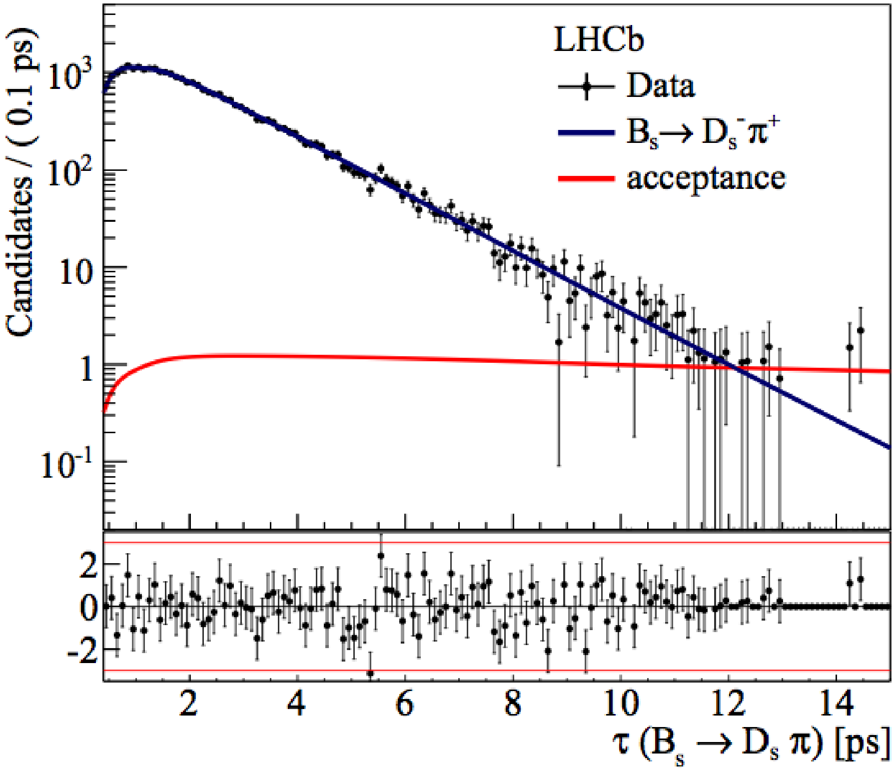
$B_s \rightarrow D_s\pi$ with additional corrections from simulation

Decay time resolution:

Use the per-event error. Average resolution is 47 fs

External Inputs:

Γ_s, $\Delta\Gamma_s$, Γ_d, $\Gamma_{\Lambda b}$ Δm_s all fixed from other measurements.



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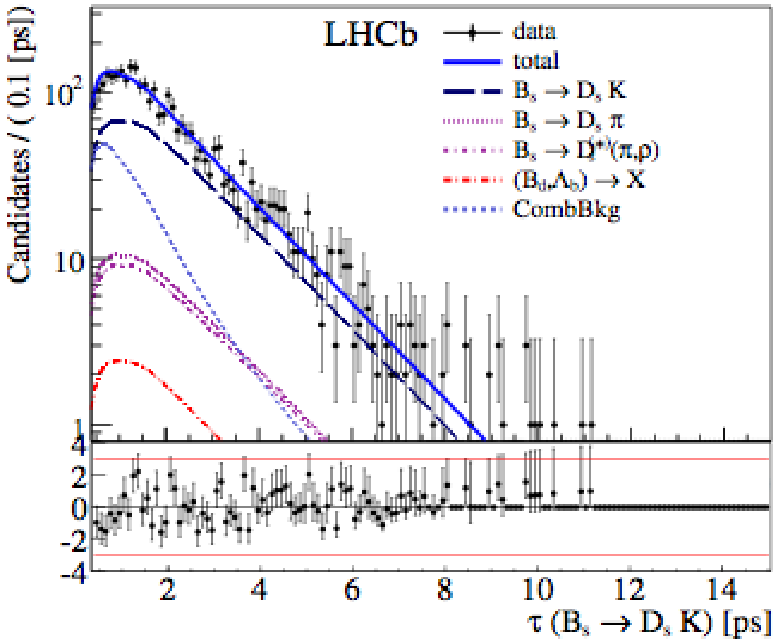
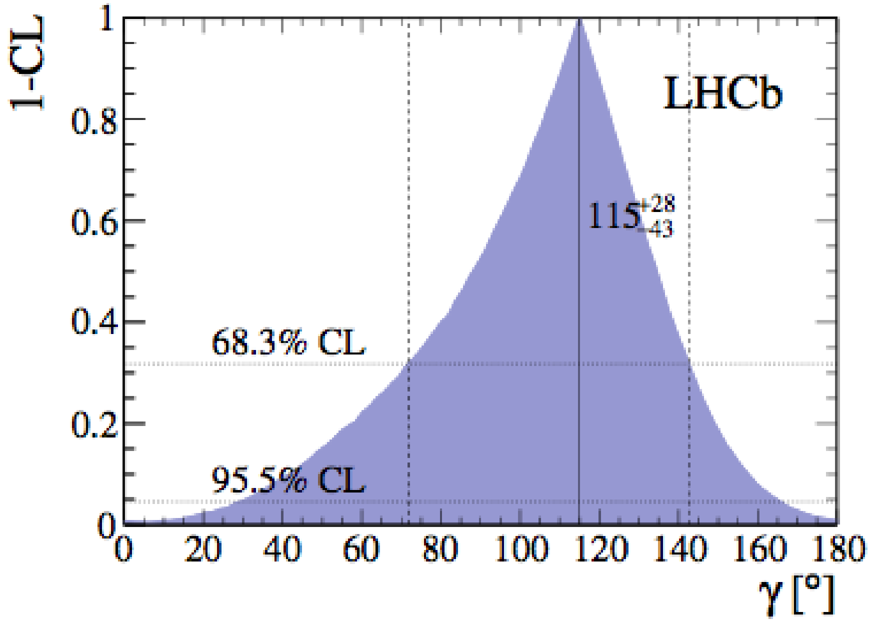
Results



Parameter	*cFit* fitted value
C_f	$0.53 \pm 0.25 \pm 0.04$
$A_f^{\Delta\Gamma}$	$0.37 \pm 0.42 \pm 0.20$
$A_{\bar{f}}^{\Delta\Gamma}$	$0.20 \pm 0.41 \pm 0.20$
S_f	$-1.09 \pm 0.33 \pm 0.08$
$S_{\bar{f}}$	$-0.36 \pm 0.34 \pm 0.08$



Observables converted to parameters of interest.

β_s external input.

First measurement from B_s ➔ D_sK

Only 1fb^{-1} - more available

$$\gamma = (115^{+28}_{-43})^\circ$$

$$r_{D_sK} = (0.53^{+0.17}_{-0.16})$$

$$\delta_{D_sK} = (3^{+19}_{-20})^\circ$$

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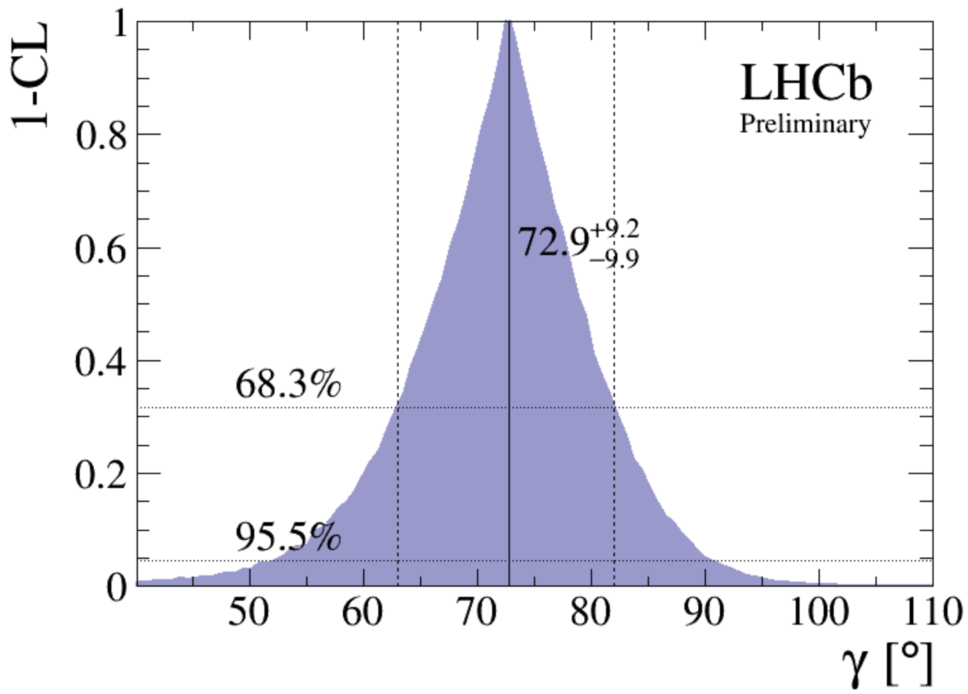
The sum is greater than the parts

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



Most observables treated Gaussian
Assume Gaussian systematic fluctuations

Non-physical regions excluded.

External parameters and D mixing taken into account

Does not yet include the D→$hh^{(')}\pi^0$, B→Dhππ results shown earlier.

Plugin method for nominal results – exclude B→Dπ measurements

Bayesian interpretation in good agreement.

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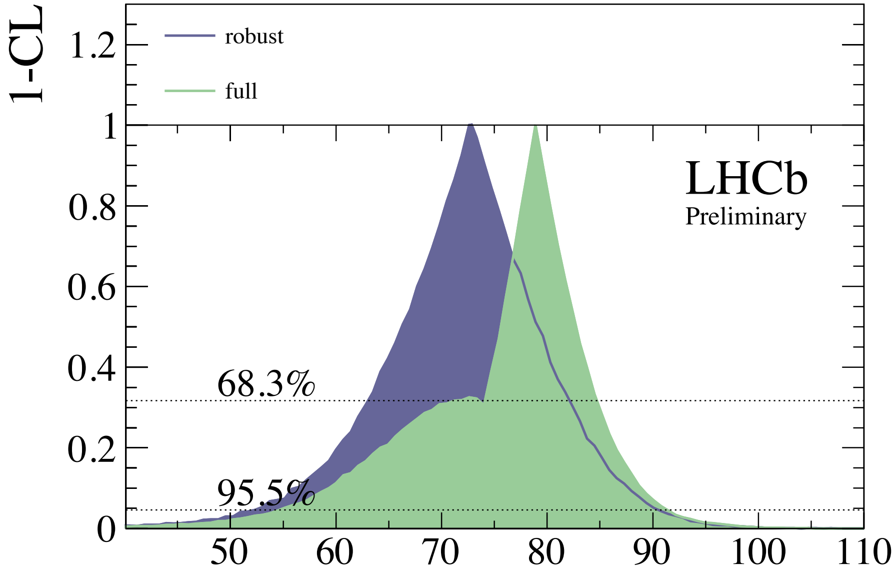
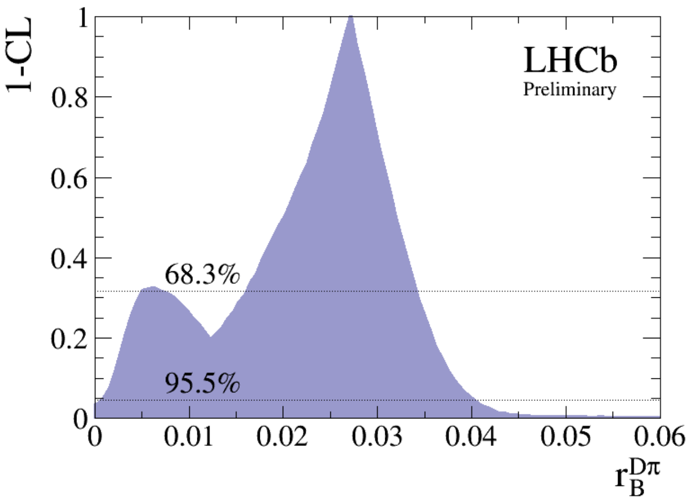
Including B→Dπ





Central value shifts up and peak sharpens when B→Dπ is added – ADS+GLW from $1fb^{-1}$

Second solution result understandable by looking at the r_B^{π} values.

Fit favours an unexpectedly high r_B^{π} value

More B→Dπ results soon – will help resolve this feature.

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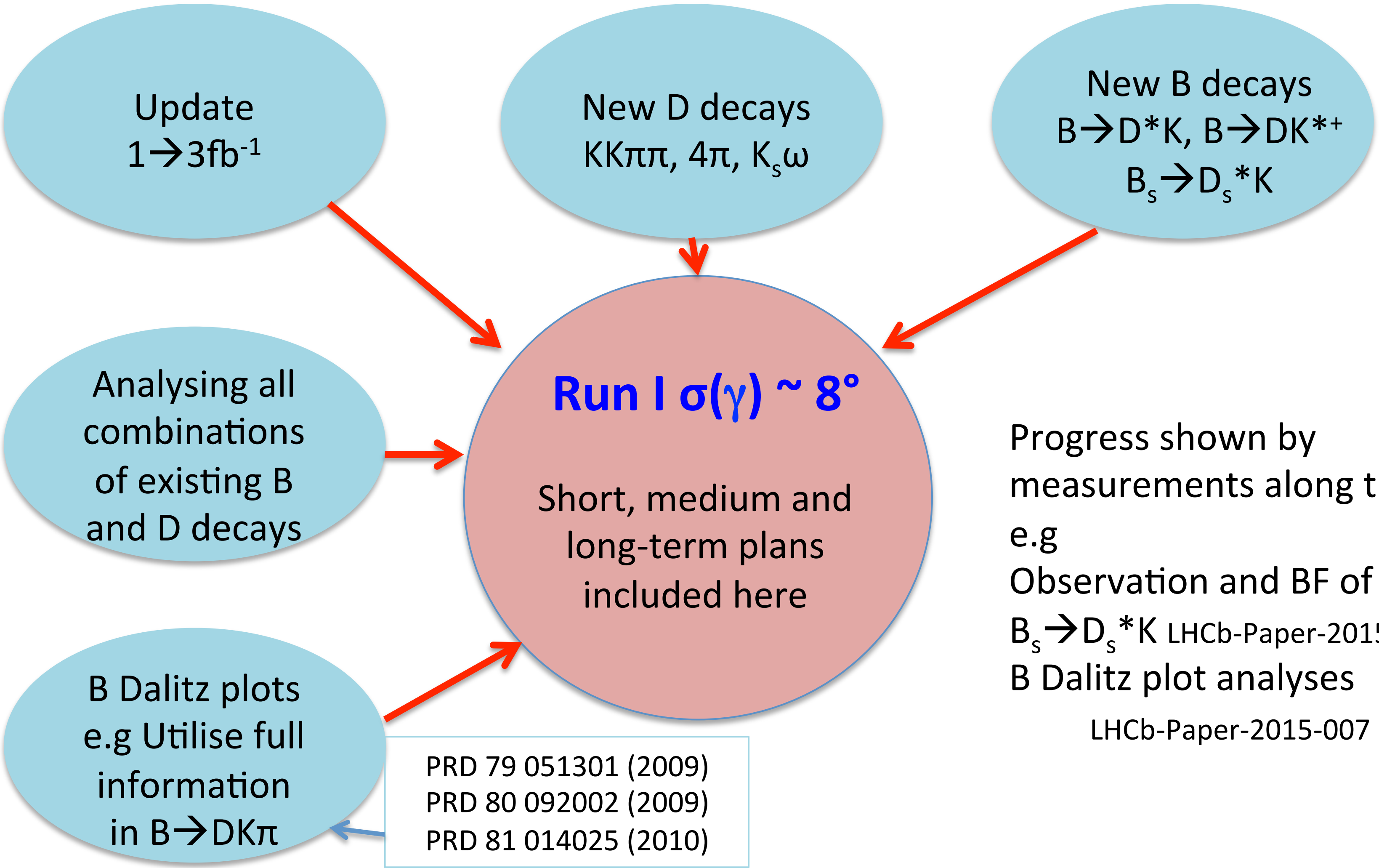
Run 1 final say



Update
$1 \to 3fb^{-1}$

New D decays
KKππ, 4π, $K_s\omega$

New B decays
B→D*K, $B \to DK^{*+}$
$B_s \to D_s^* K$

Analysing all combinations of existing B and D decays

B Dalitz plots e.g Utilise full information in B→DKπ

PRD 79 051301 (2009)
PRD 80 092002 (2009)
PRD 81 014025 (2010)

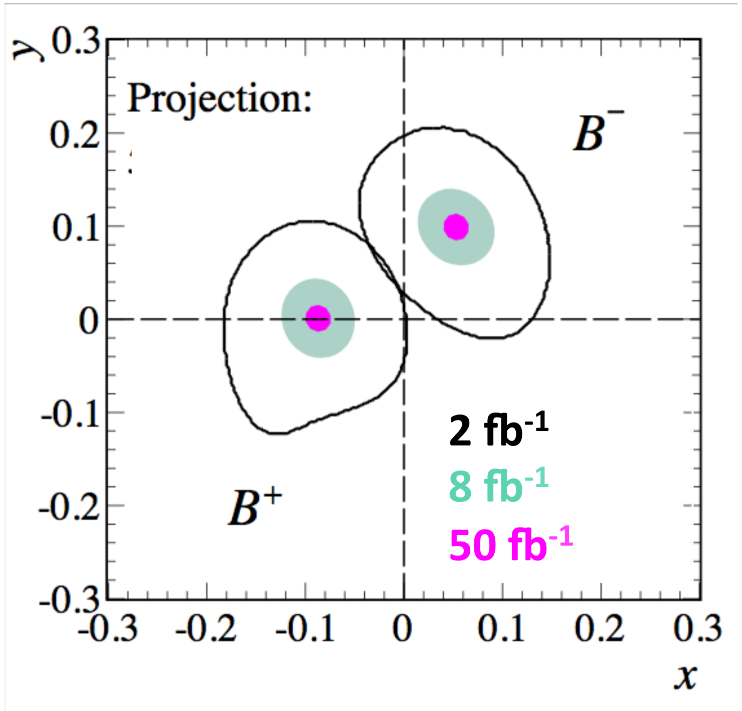
Run I σ(γ) ~ 8°

Short, medium and long-term plans included here

Progress shown by measurements along the way- e.g
Observation and BF of
$B_s \to D_s^* K$ LHCb-Paper-2015-008
B Dalitz plot analyses
LHCb-Paper-2015-007

Prospects beyond Run I

Projections for the GGSZ contours as more data is gathered



Expect to quadruple our dataset in Run II (2015 -2017)

Current γ sensitivity at end of Run I ~ 8°
Expected Run II sensitivity 4°
LHCb upgrade will take considerably more data from 2018

Final combined sensitivity ~1°

Currently statistically limited

Controlling systematic uncertainties is the key

Systematic uncertainties

External inputs

Updated charm inputs from BES-III required

- Large suite of results from CLEO-c all could use improvement in precision

c_i, s_i - Limiting uncertainty of 2°

- Current update when finished would bring uncertainty down to ~ 1°
- There are smarter things to be done
  - Optimal binning based on experiment background model
  - Take experimental efficiency model into account
  - Finer binning
- These would improve the statistical reach of a given dataset, and remove other smaller systematic uncertainties

Higher order physics effects that can be controlled

D mixing, K_s^0 mixing, CPV and regeneration

Understanding the CPV in backgrounds that start to become significant.

Experimental uncertainties

-How much to trust MC simulation for e.g Dalitz plot efficiencies.

-Controlling the level of detection and production asymmetries.

Summary

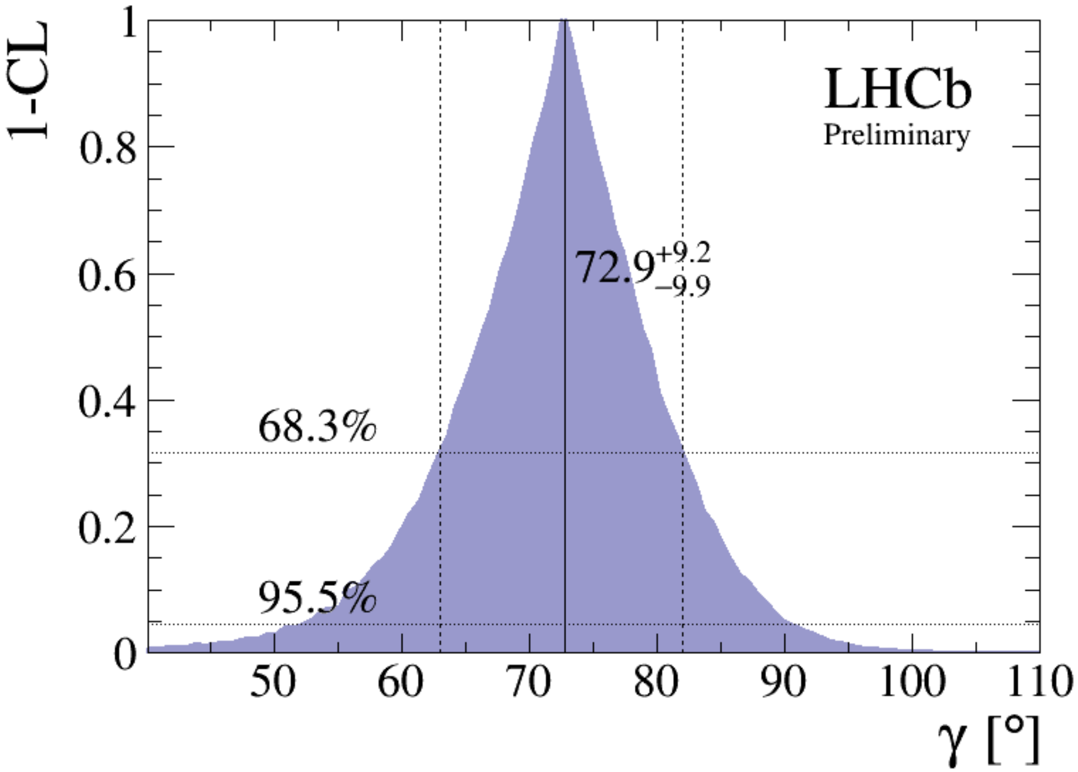
LHCb benefits from high statistics with high purity. Exploring new B decays

Success of analysis with π^0

LHCb can also target unique B_s decay modes

Expected sensitivity by year end γ ~ 8°

On target to meet Run II projected sensitivity



September 2014

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