Measurements of γ from LHCb

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On behalf of the LHCb Collaboration

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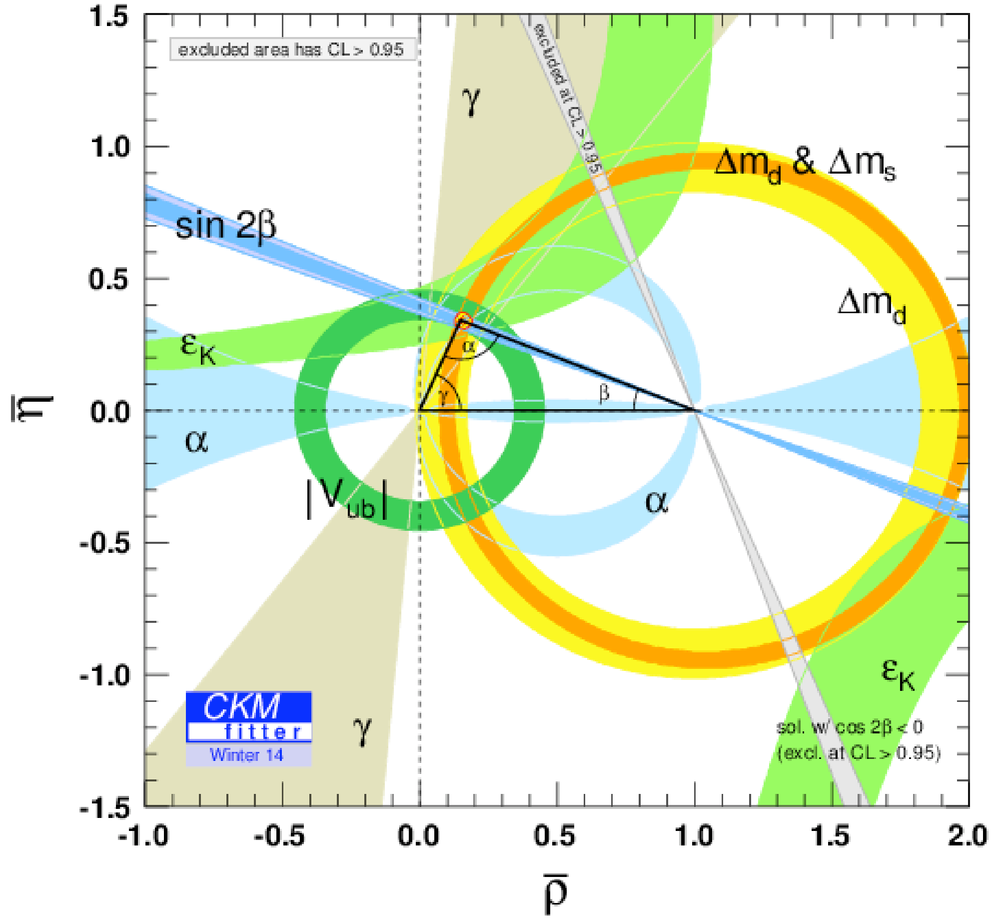
The CKM angle γ



CKM matrix parameterises quark couplings

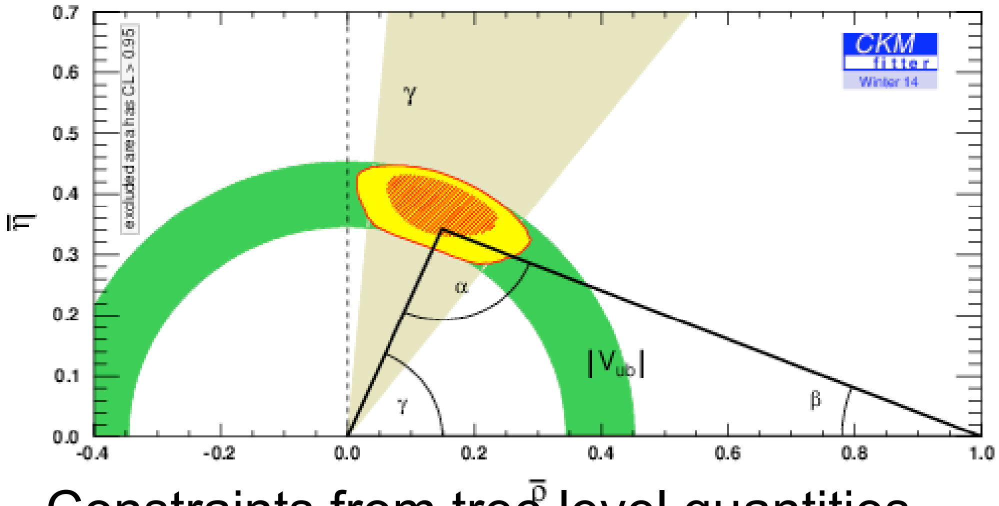
The matrix has one complex phase that results in CPV

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



Constraints from tree level quantities

γ is the only angle directly accessible in tree decays

"Standard Model" measurement possible

Direct measurements (all results combined):

$$70.0^{+7.7\circ}_{-9.9}$$

Indirect precision from global CKM fit: $66.5^{+1.3\circ}_{-2.5}$

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

Goal : Improve the direct precision

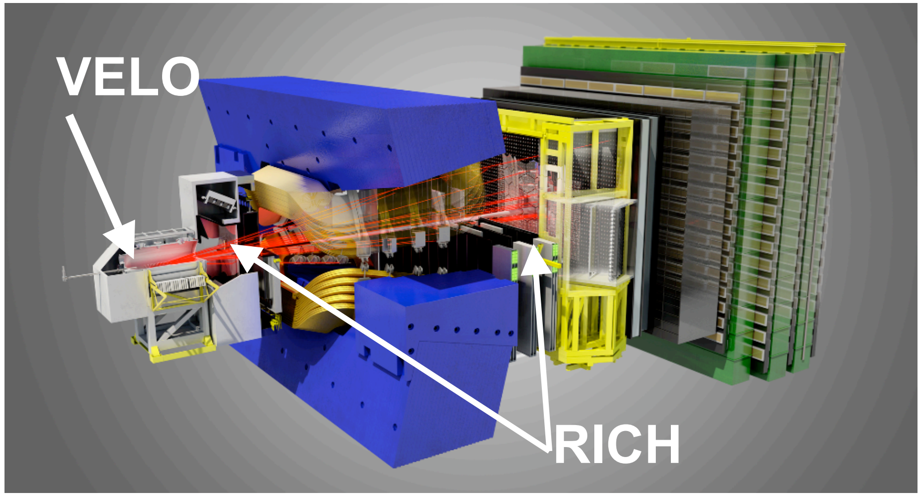
This talk

4 new exciting recent results from LHCb

- Model Independent B➔DK, D➔$K_S$hh 3 fb^{-1} NEW
- Model dependent B➔DK, D➔$K_s\pi\pi$ 1 fb^{-1}
- B^0➔DK^{0*} , D➔hh
- B_s➔D_sK

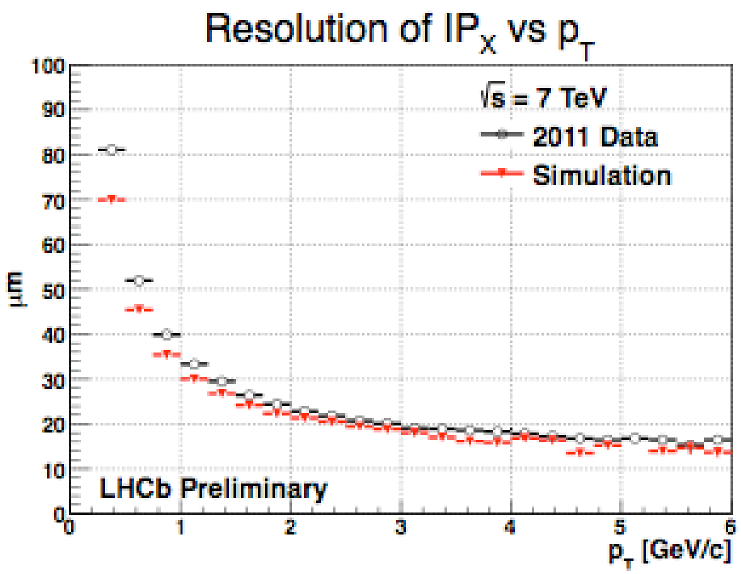
All papers to be submitted to journals soon

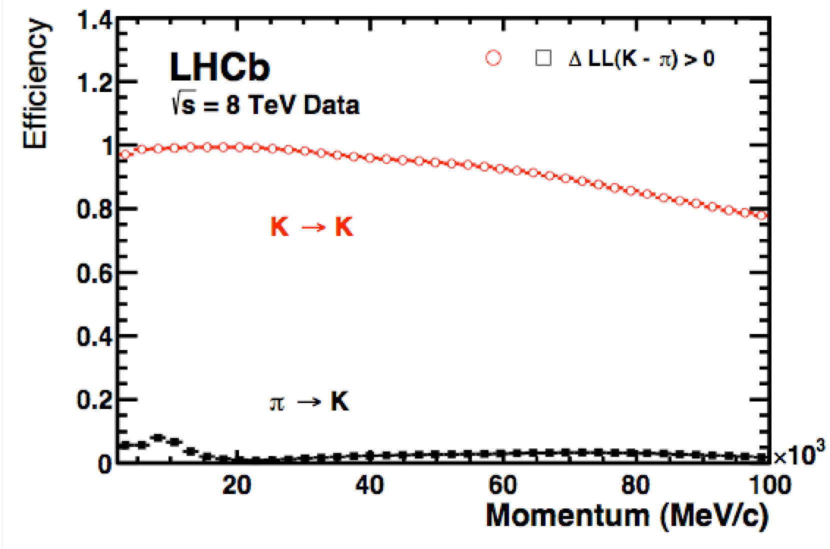
The LHCb detector



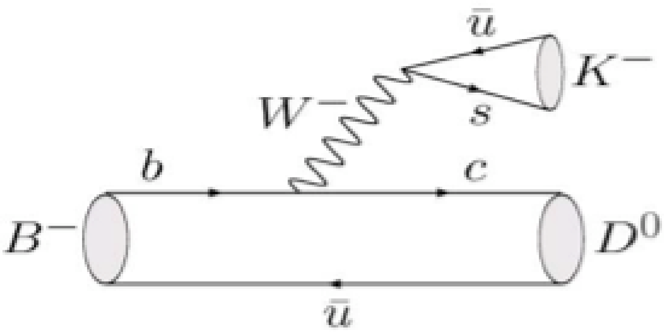
All measurements profit from the VELO for displaced vertices and the RICH for particle identification

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



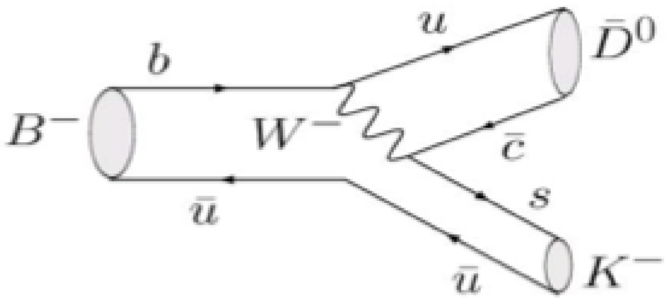


B→DK, D→$K_s$hh - the golden mode



b → c (favoured)

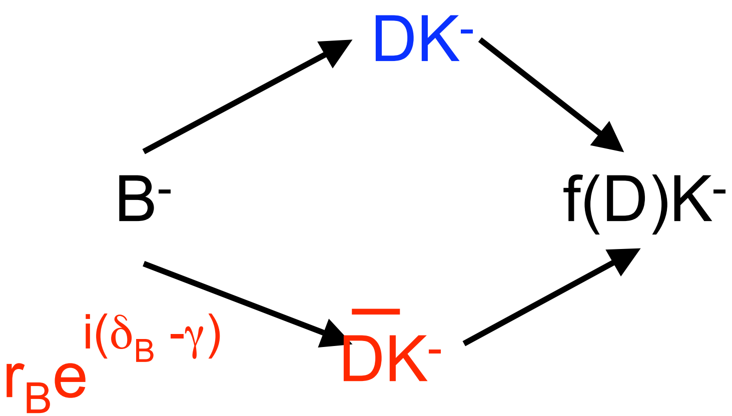
b → u (suppressed)



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

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

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



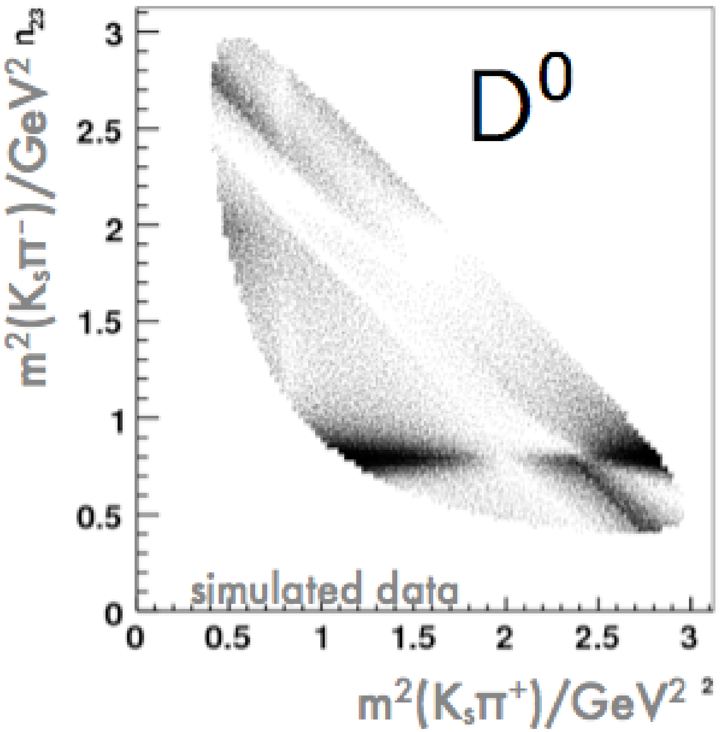
Self-conjugate three body final states are particularly sensitive "GGSZ"

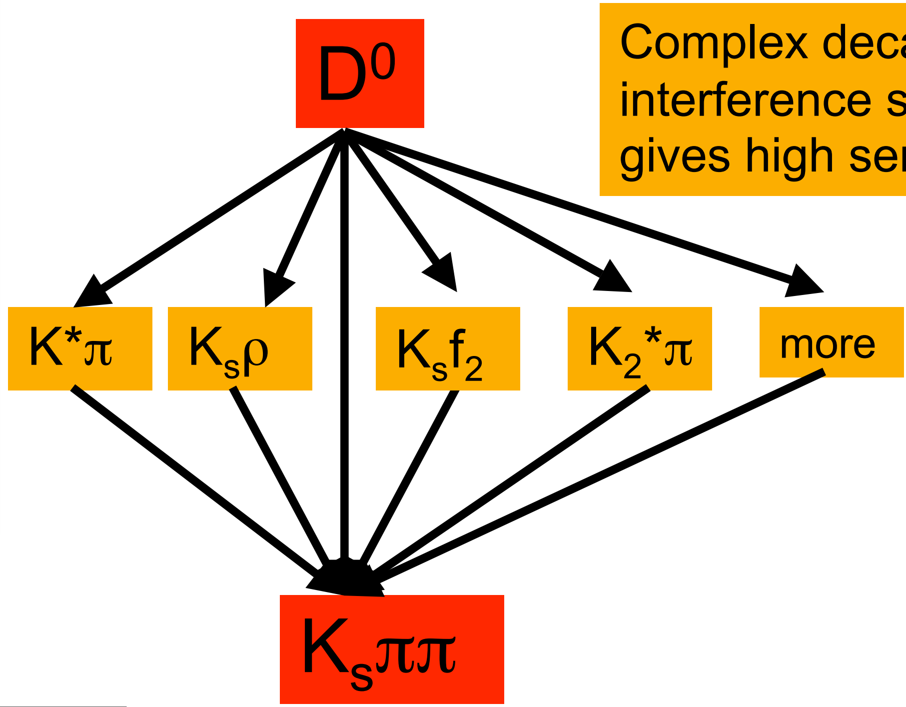
D→$K_s\pi\pi$

D→K_sKK

$r_B \sim 0.1$

D→$K_s\pi\pi$: accessible from both D flavours

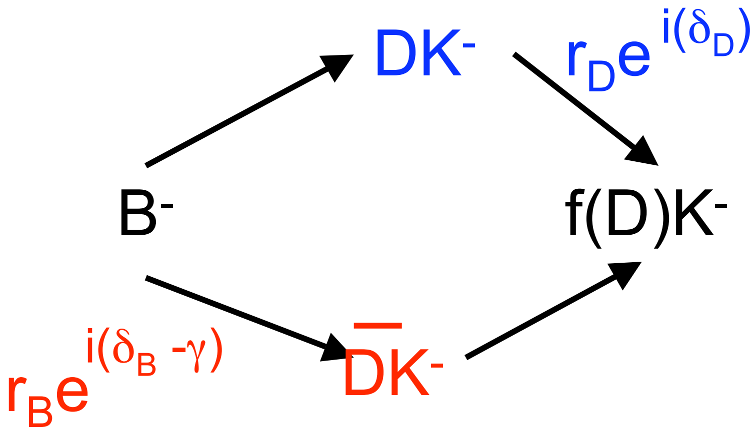




Complex decay. Rich interference structure gives high sensitivity to γ.

Compare the Dalitz plots of B^+ and B^- decays. Difference driven by r_B, δ_B, γ

Accounting for the D strong phase difference



Complication:

D strong phase variation on Dalitz plot

2 methods of dealing with that

both pursued at LHCb

Model-independent: Count and compare signal yields in Dalitz plot regions

Counting is (relatively) easy

Necessary strong phase information available from dedicated analysis of CLEO-c data.

Well understood systematic uncertainties

Loss of statistical precision (ok if minimal)

Model-dependent: Fit the Dalitz plot

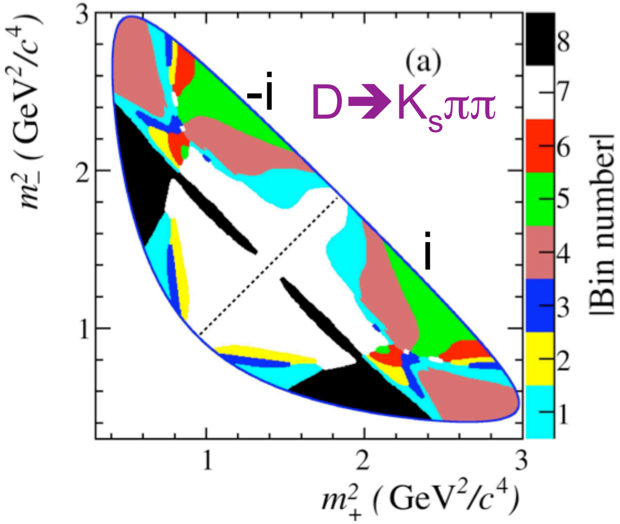
Maximises statistical power

D strong phase variation given by a model

Systematic uncertainties due to this are hard to quantify.

Problematic in the precision era.

Model-independent method

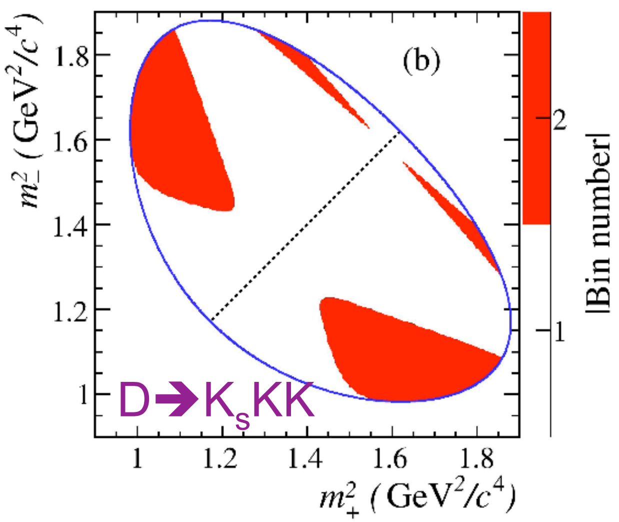


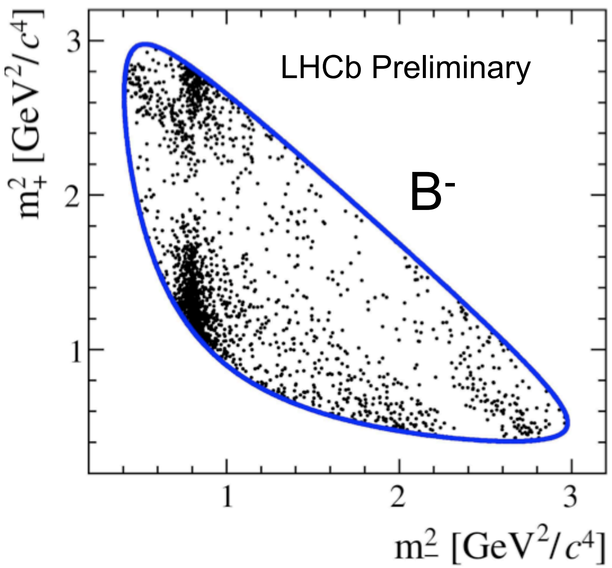
Binning shapes optimised for statistical sensitivity.

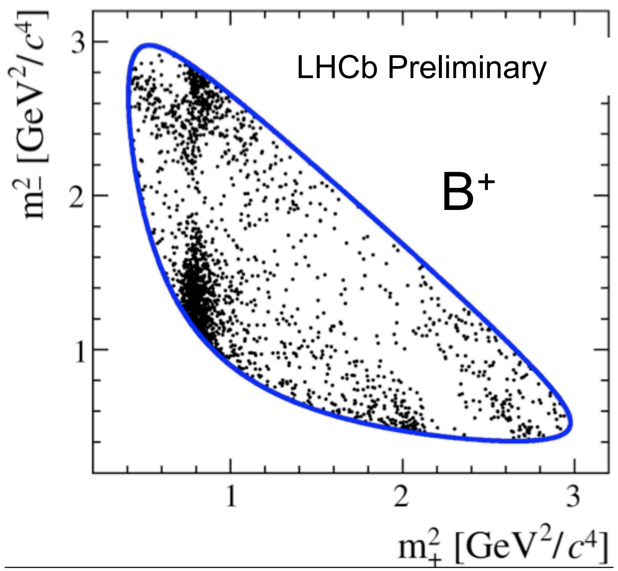
Symmetry of Dalitz plot defines positive and negative bins.

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

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







Overall 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

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

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

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

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

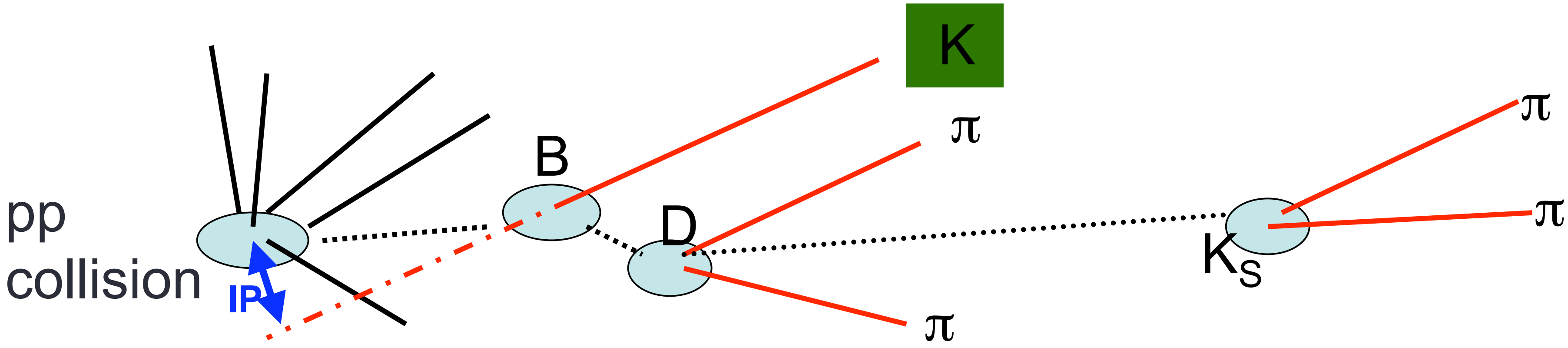
Charge of the π tags the D^0 flavour.

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

Combined measurement of 3 fb^{-1} data

Supersedes the previous 1 fb^{-1} measurement or the (1+2)fb^{-1} preliminary result

Selecting events based on topology



Separate the topology of interest from random combinations

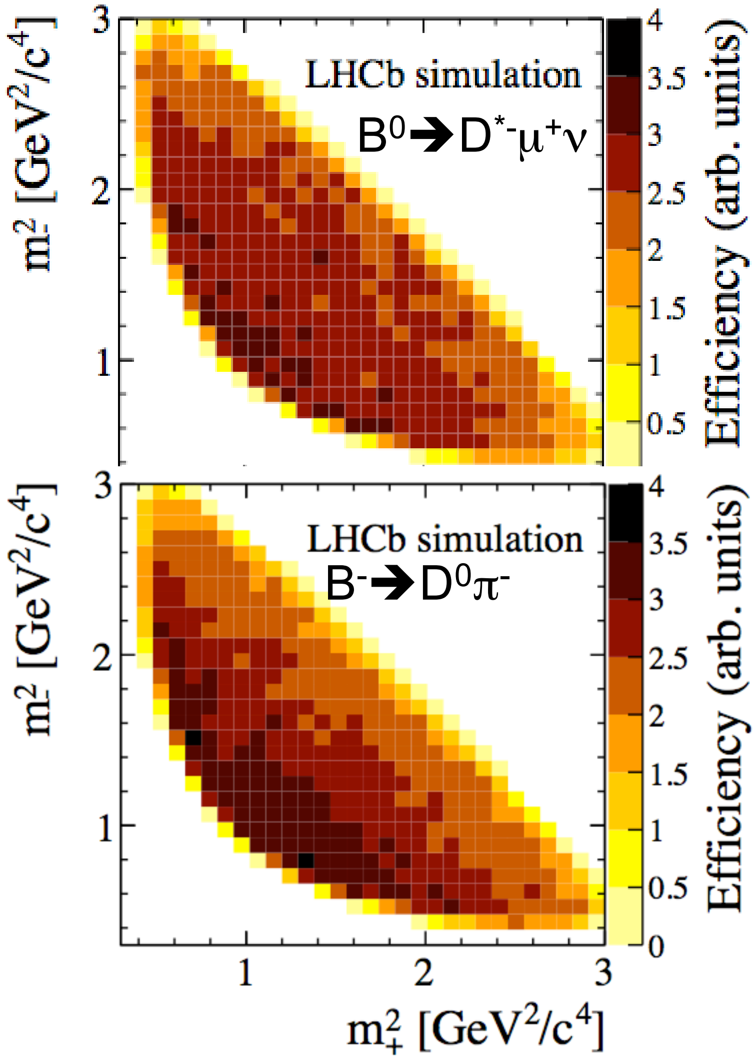
Useful variables include:

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

Specific vetos against particular backgrounds

All analyses shown here employ similar strategies

Accounting for the efficiency



B→D*μν best choice for control mode to determine K_i

D decay is flavour tagged. Similar efficiency profile to the signal channel. High purity

Small differences between B→Dh and B→D*μν efficiencies observed in MC

Previously used B→Dπ, but CPV exists in this decay→large systematic uncertainties

To determine correct K_i

Determine bin yields of B→D*μν

Modify them with correction factor derived from MC

Invariant mass distribution

$D \rightarrow K_s\pi\pi$, where the K_s decays outside of the VELO

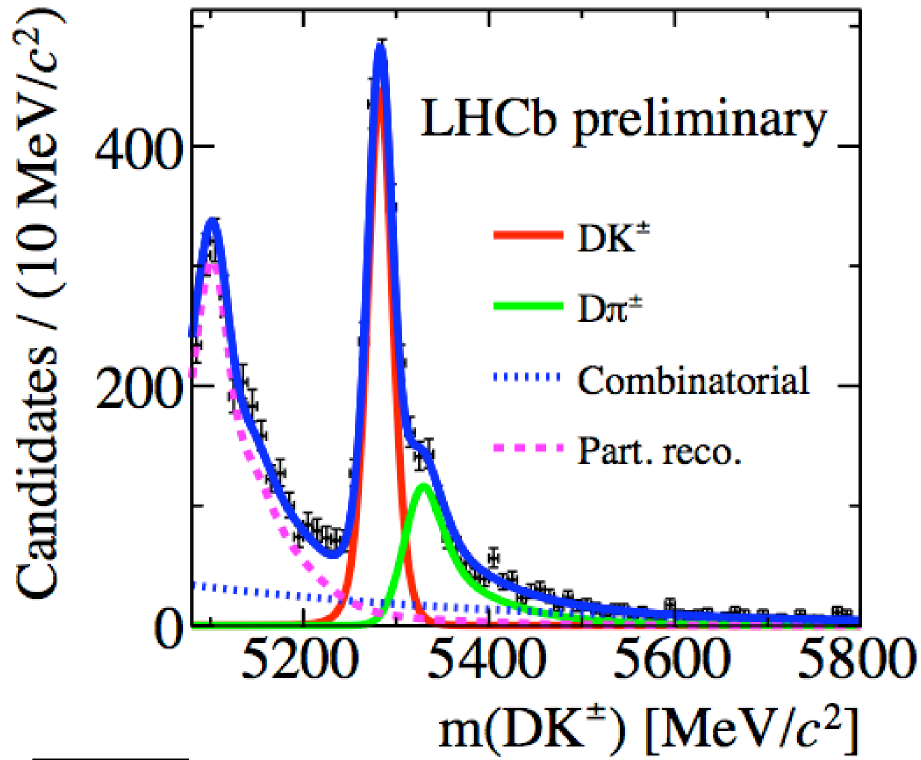
First fit mass distribution combining all Dalitz Plot bins

Split data by D decay channel and K_s decay position

In total across all categories ~2600 signal candidates

Purity ~ 75% in signal region

Second fit uses fixed mass model PDFs to determine yields in each bin simultaneously and determine best x, y values



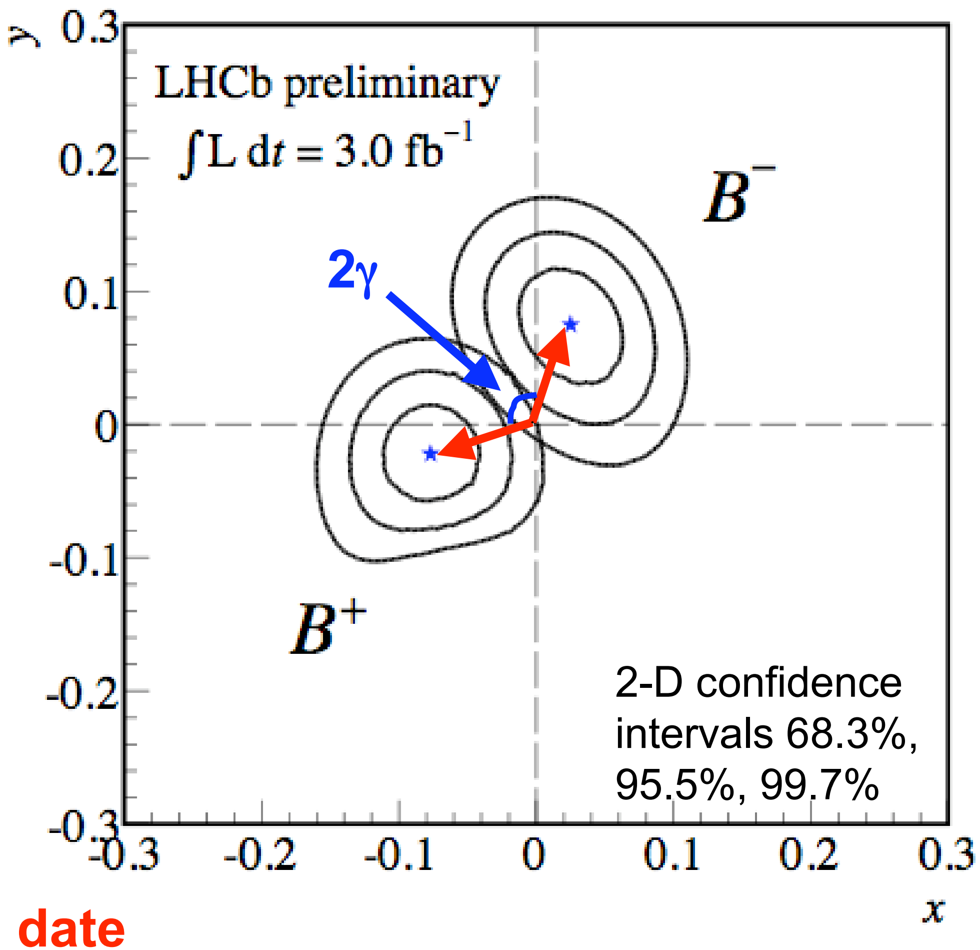
$$N^{+}_{+i} = n_{B^+}[K_{-i} + (x_+^2 + y_+^2)K_{+i} + 2\sqrt{K_{+i}K_{-i}}(x_+c_{+i} - y_+s_{+i})]$$

$$x_\pm = r_B\cos(\delta_B \pm \gamma), y_\pm = r_B\sin(\delta_B \pm \gamma)$$

Results on CP parameters

Preliminary

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



Corrections for D mixing, K_s CPV ignored - negligible effect

Most precise measurement of x,y to date

Comparing to 1 fb^{-1} result

Statistical uncertainties reduce due to increased data sample

	x_+	x_-	y_+	y_-
2011	0.045	0.043	0.037	0.052
2013	0.024	0.025	0.025	0.029

Experimental systematic uncertainty reduced due to change in control mode. MC efficiency correction dominates.

	x_+	x_-	y_+	y_-
2011	0.018	0.015	0.008	0.008
2013	0.010	0.010	0.004	0.005

Strong phase systematic reduces due to increased sample size

	x_+	x_-	y_+	y_-
2011	0.014	0.006	0.030	0.023
2013	0.004	0.005	0.010	0.014

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

Most precise measurement of x,y to date

Physics parameters of interest

Determine (stat+syst) confidence intervals for γ, r_B, δ_B

Two-fold ambiguity

$1fb^{-1}$ result: $\gamma = 44^{+43}_{-38}{}^{\circ}$

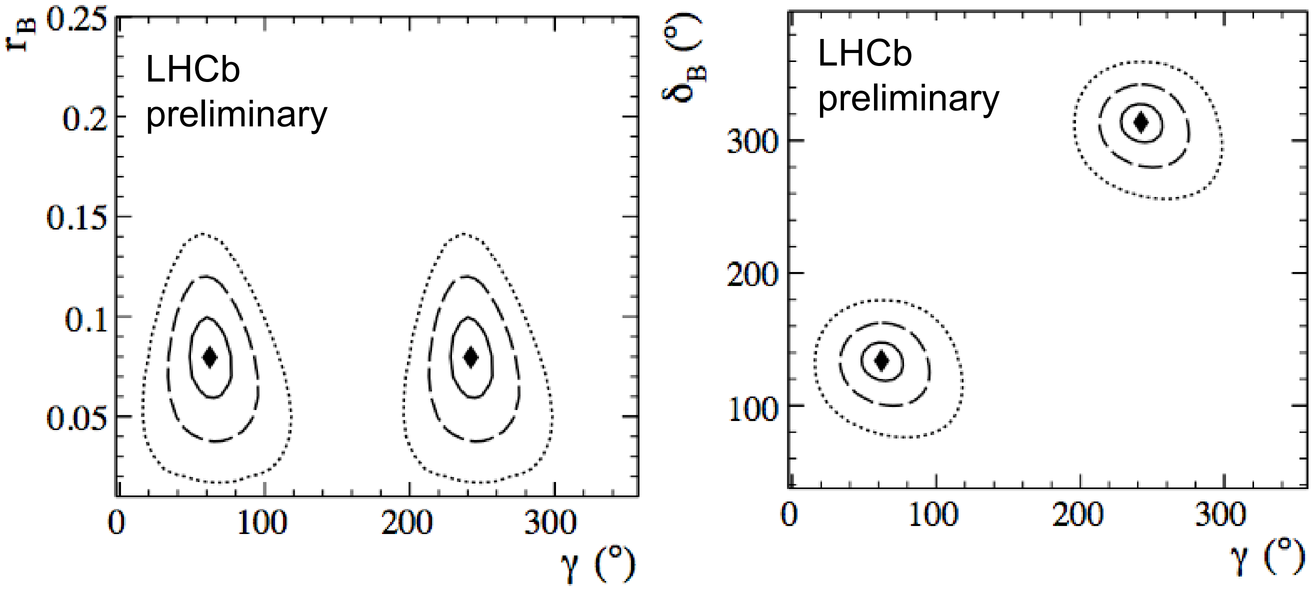
Improvement threefold - more data, lower systematic uncertainties and higher central r_B value

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

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

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

Precision matches that of either B factory γ combinations



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

Preliminary

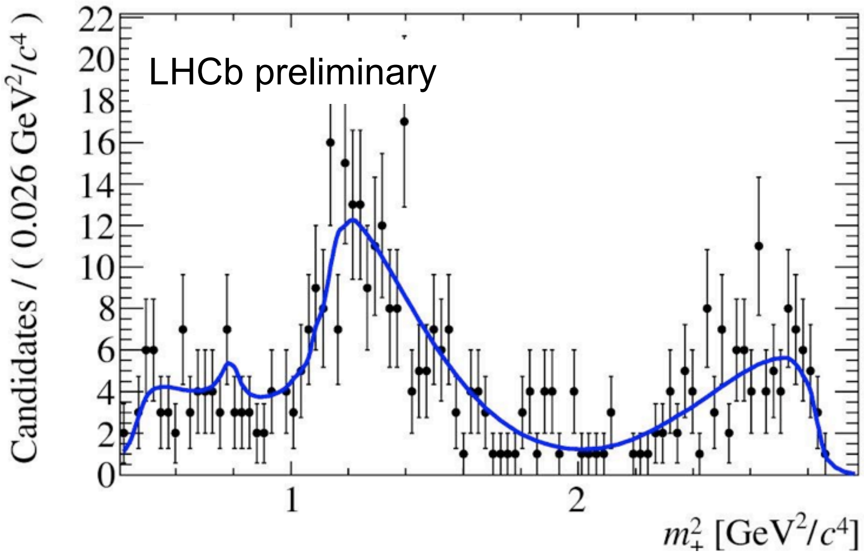
Model-dependent method

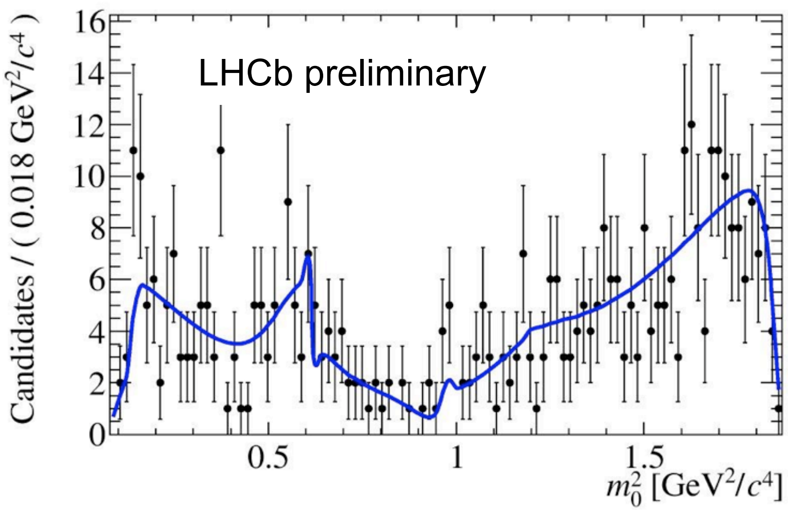
D strong phase differences accounted for by using an amplitude model

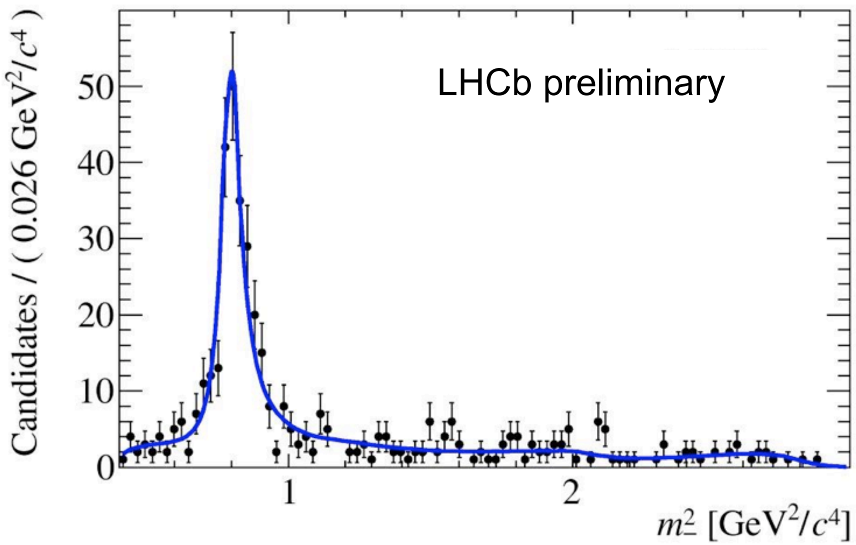
The latest BaBar amplitude model is chosen.

Only consider the $K_S\pi\pi$ decay (1 fb^{-1})

Efficiency on the Dalitz Plot determined from B➔Dπ assuming no CPV







Model-dependent results

Preliminary

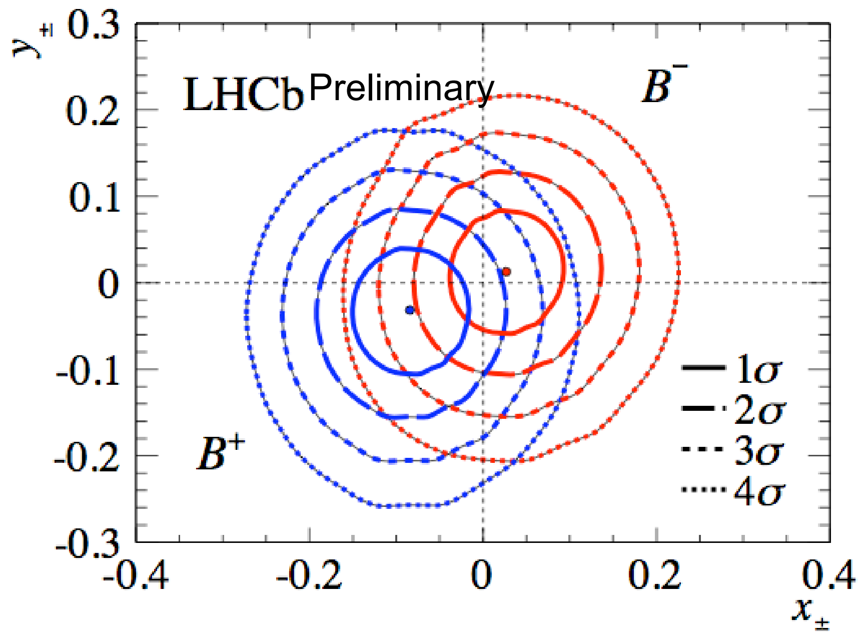
$$x_- = +0.027 \pm 0.044^{+0.010}_{-0.008} \pm 0.001,$$
$$y_- = +0.013 \pm 0.048^{+0.009}_{-0.007} \pm 0.003,$$
$$x_+ = -0.084 \pm 0.045 \pm 0.009 \pm 0.005,$$
$$y_+ = -0.032 \pm 0.048^{+0.010}_{-0.009} \pm 0.008,$$

Final uncertainty is due to model. Determined by using alternate models.

Leading experimental contributions are efficiency and background distribution uncertainties.

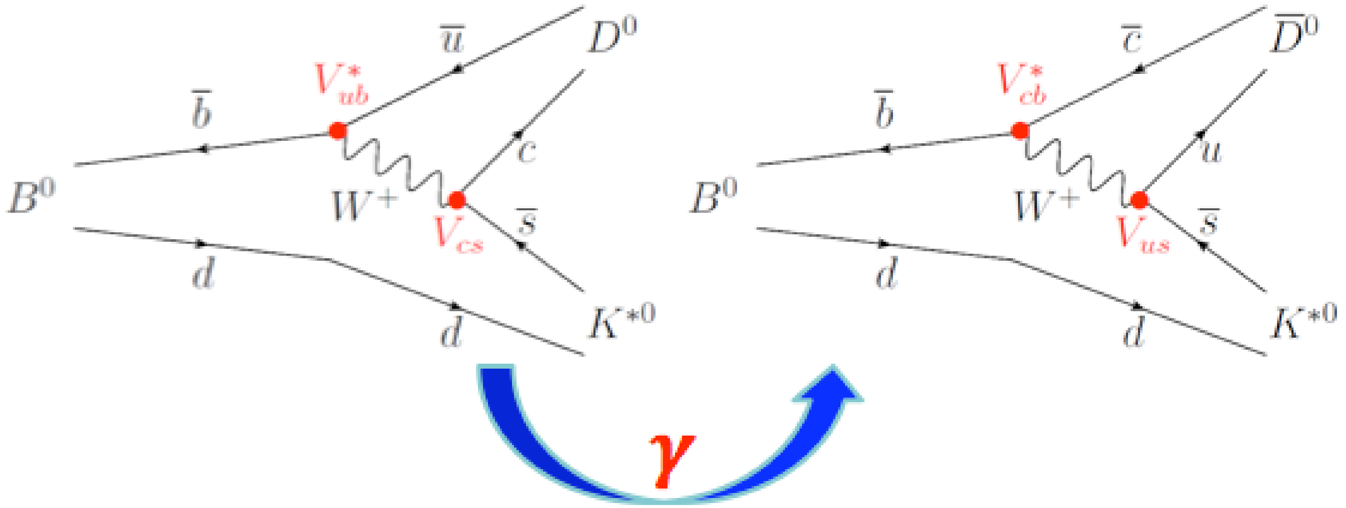
x, y measurement consistent with the $1fb^{-1}$ MI result

$$\gamma = 84^{+49}_{-42}{}^{\circ}$$



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

$B^0 \rightarrow DK^{0*}$



Both diagrams colour suppressed ➔ large r_B (large interference)

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

(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

$B^0 \rightarrow DK^{0*}$ observables

Can construct a number of observables that have sensitivity to γ

Asymmetries in D➔ CP eigenstates (KK , ππ easily accessible at LHCb)

$$\mathcal{A}_d^{hh} \equiv \frac{\Gamma(\overline{B}^0 \to D(h^+h^-)\overline{K}^{*0}) - \Gamma(B^0 \to D(h^+h^-)K^{*0})}{\Gamma(\overline{B}^0 \to D(h^+h^-)\overline{K}^{*0}) + \Gamma(B^0 \to D(h^+h^-)K^{*0})} = \frac{2r_B\kappa\sin\delta_B\sin\gamma}{1 + r_B^2 + 2r_B\kappa\cos\delta_B\cos\gamma}.$$

Can also consider the CF decay $D^0 \rightarrow K^-\pi^+$ and the DCS decay $D^0 \rightarrow K^+\pi^-$

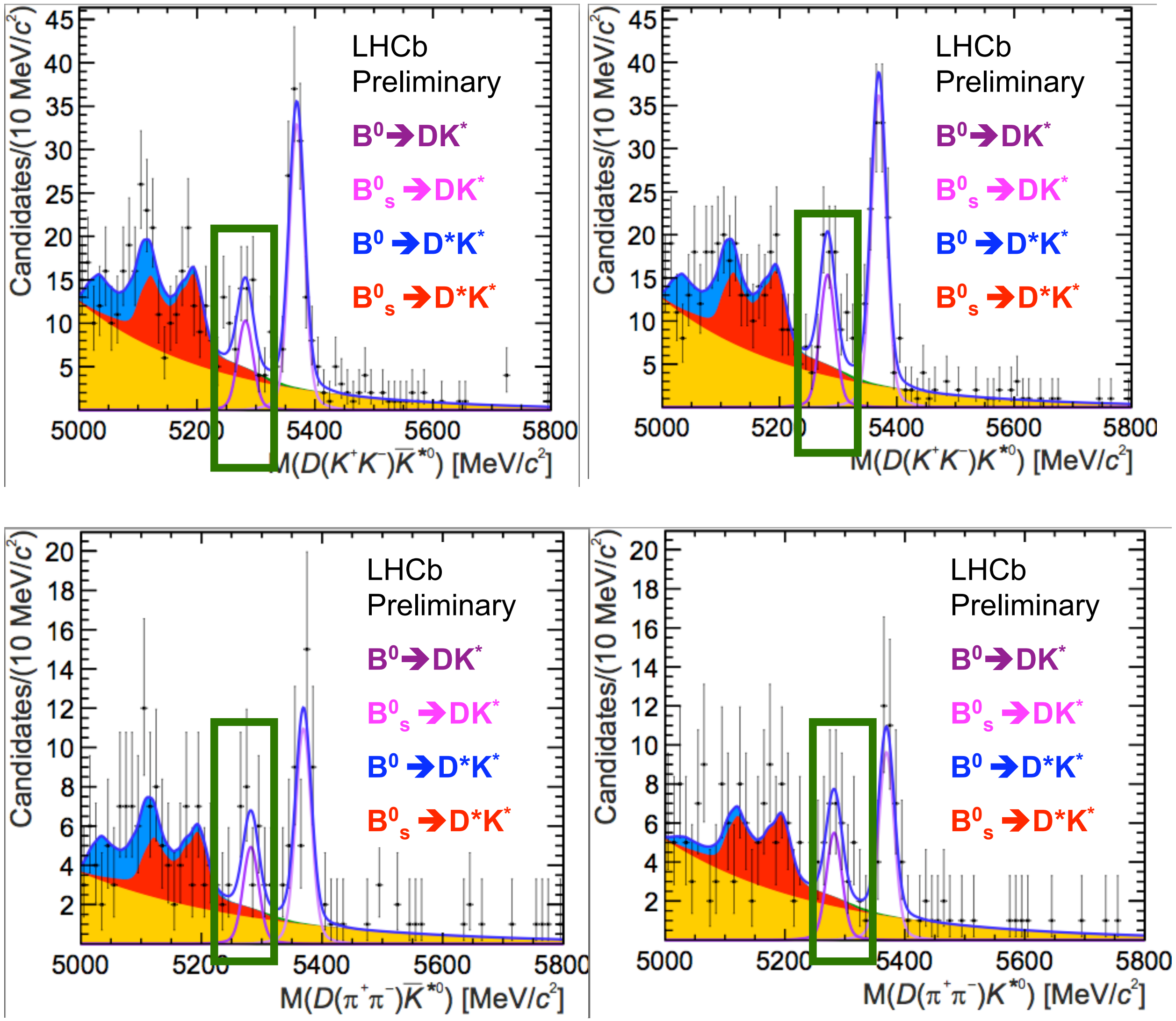
$$\mathcal{R}_d^+ \equiv \frac{\Gamma(B^0 \to D(\pi^+K^-)K^{*0})}{\Gamma(B^0 \to D(K^+\pi^-)K^{*0})} = \frac{r_B^2 + r_D^2 + 2r_Br_D\kappa\cos(\delta_B + \delta_D + \gamma)}{1 + r_B^2r_D^2 + 2r_Br_D\kappa\cos(\delta_B - \delta_D + \gamma)},$$

$$\mathcal{R}_d^- \equiv \frac{\Gamma(\overline{B}^0 \to D(\pi^-K^+)\overline{K}^{*0})}{\Gamma(\overline{B}^0 \to D(K^-\pi^+)\overline{K}^{*0})} = \frac{r_B^2 + r_D^2 + 2r_Br_D\kappa\cos(\delta_B + \delta_D - \gamma)}{1 + r_B^2r_D^2 + 2r_Br_D\kappa\cos(\delta_B - \delta_D - \gamma)}.$$

Other observables include asymmetry in $\overline{B}^0$ and B^0 in the CF decay, and ratio of CP even to the CF decay.

Relations involve κ, the coherence factor to take into account non-resonant yield in the K^{0*} region

$B^0 \rightarrow DK^{0*}$ $D \rightarrow KK, \pi\pi$



KK - significance of signal: 8.6σ

ππ - significance of signal: 5.8σ

Corrections applied for production and selection efficiencies.

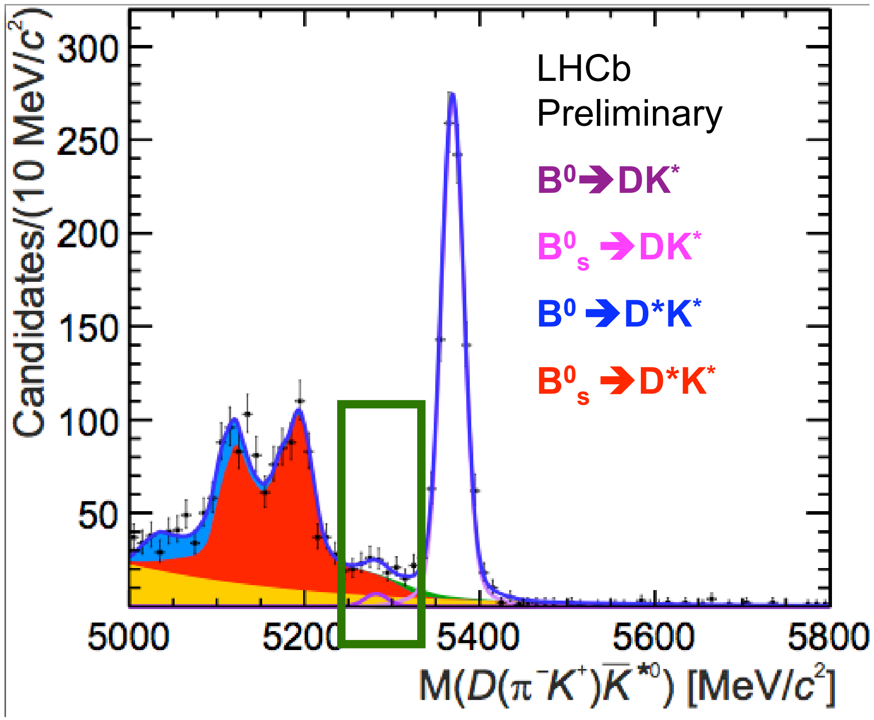
Leading systematic uncertainties from charge detection asymmetry in the K from K^{0*}

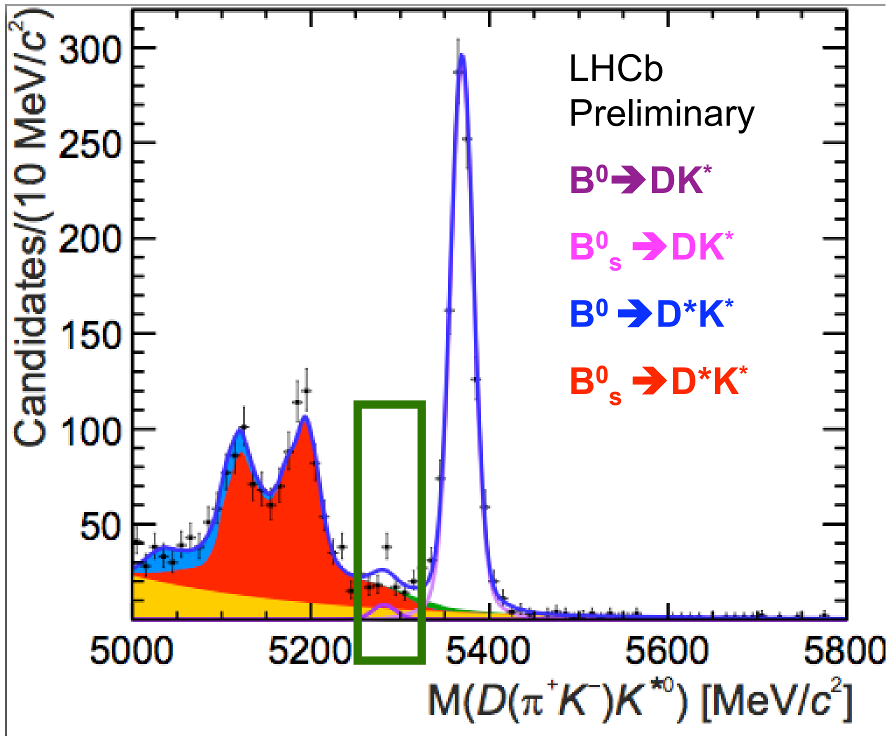
$$A_d^{KK} = -0.198^{+0.144+0.019}_{-0.145-0.020}$$

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

Preliminary

$B^0 \rightarrow DK^{0*}$, $D \rightarrow \pi K$





Combined signal significance is 2.9σ.

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

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

Preliminary

Constraints on physics parameters

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

$\kappa = 0.95 \pm 0.03$

Measurements of all observables combined to determine r_B, δ_B γ

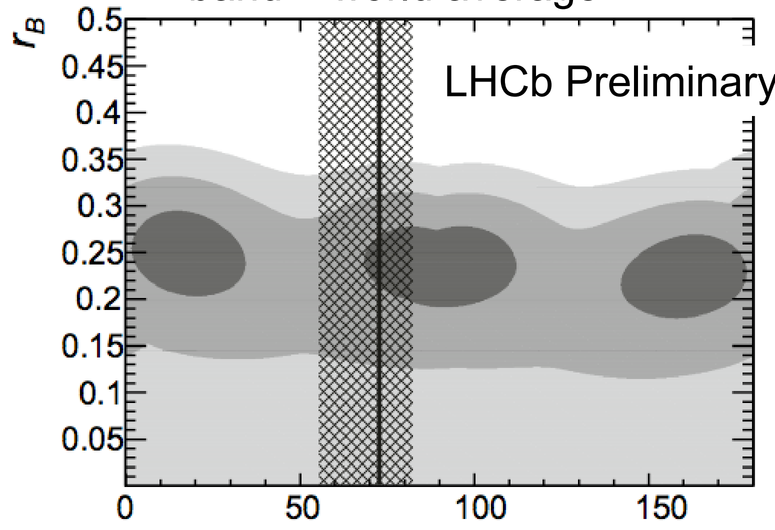
Ambiguities from the trigonometric relations

Some constraints can be set at the 68.3% CL

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

Promising decay to study further

band = world average

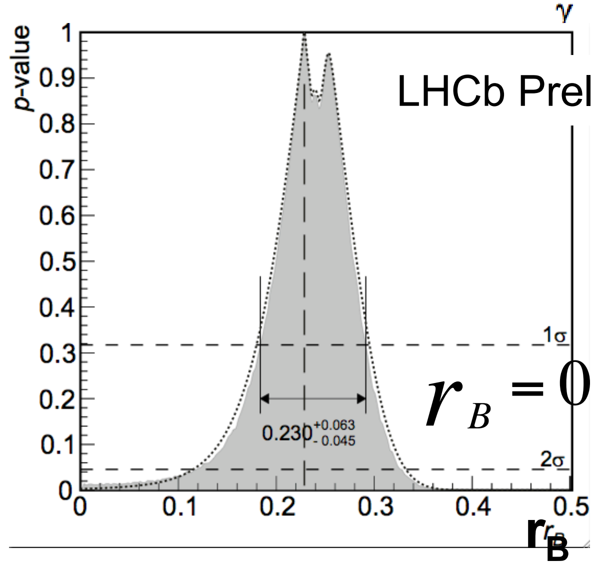


Projection of contours onto 1-D gives

68.3%

95.5%

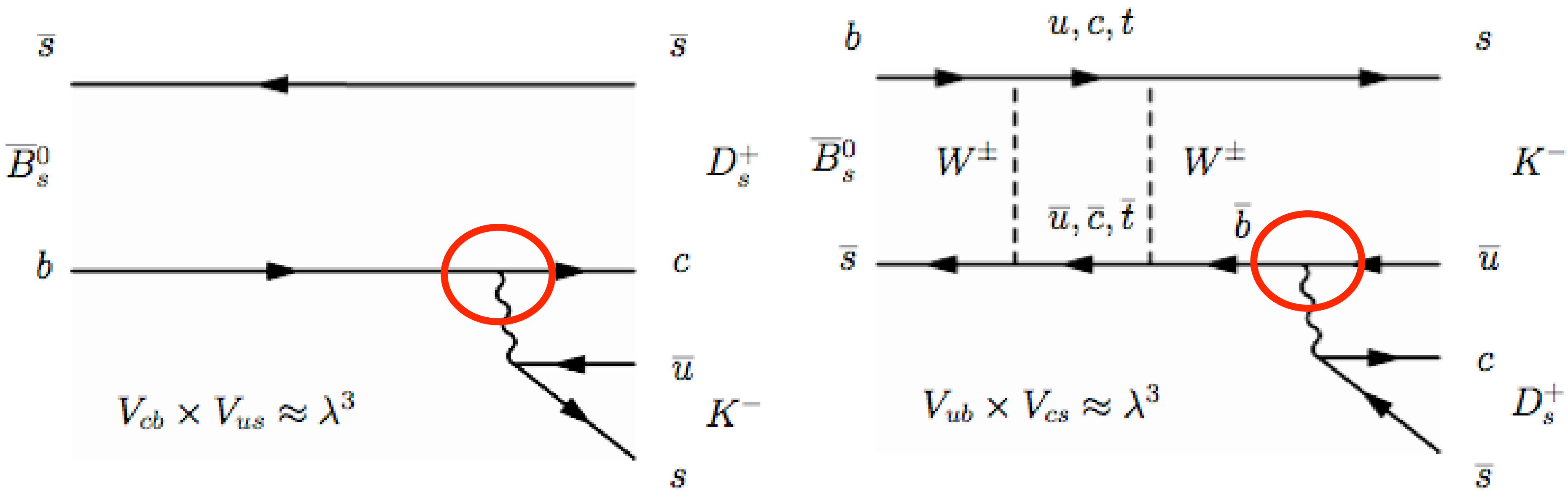
99.7%



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

$B_s \rightarrow D_s K$

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

CP Observables

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

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

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

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

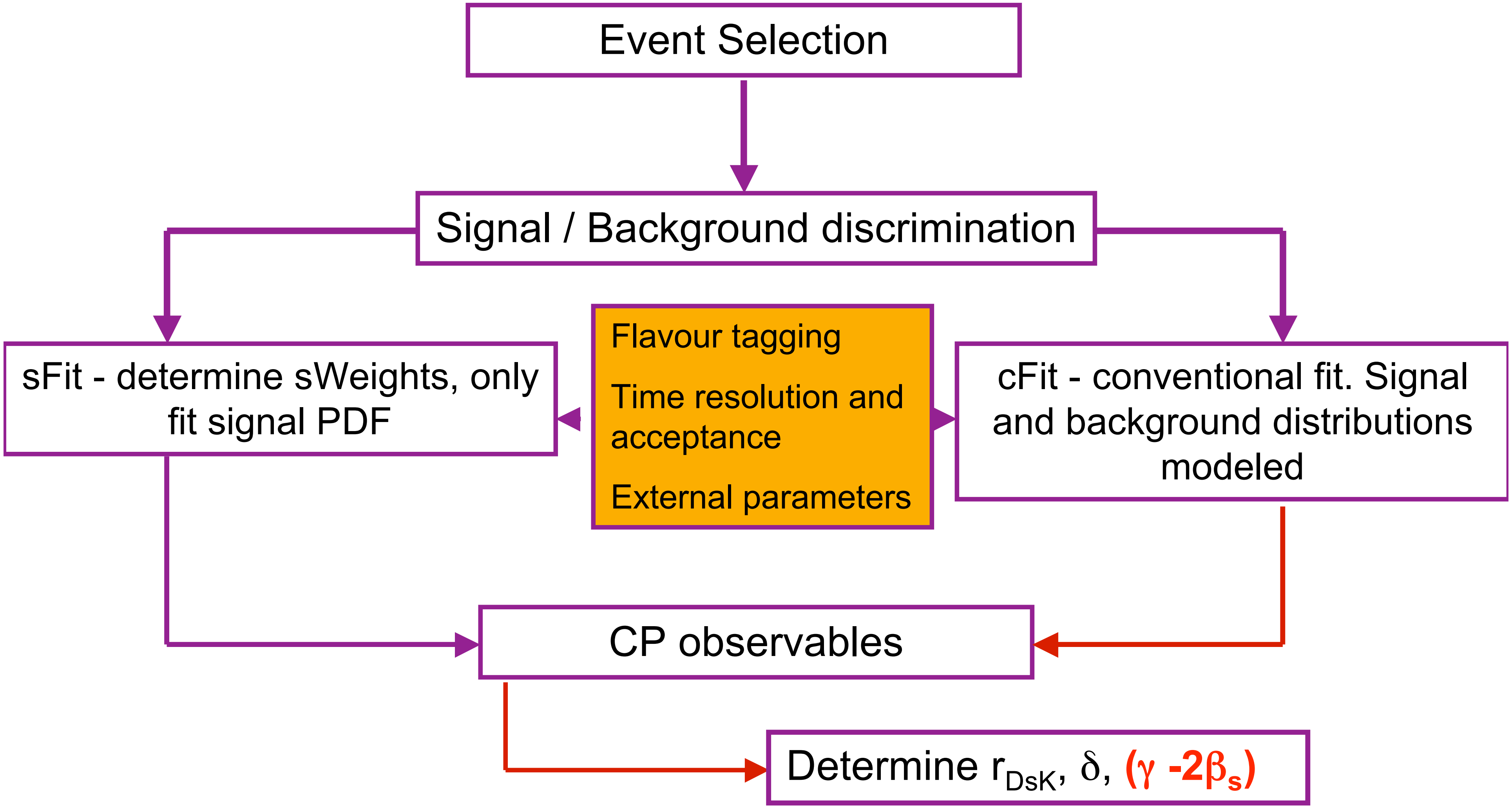
$$C_f = \frac{1-r_{D_sK}^2}{1+r_{D_sK}^2},$$

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

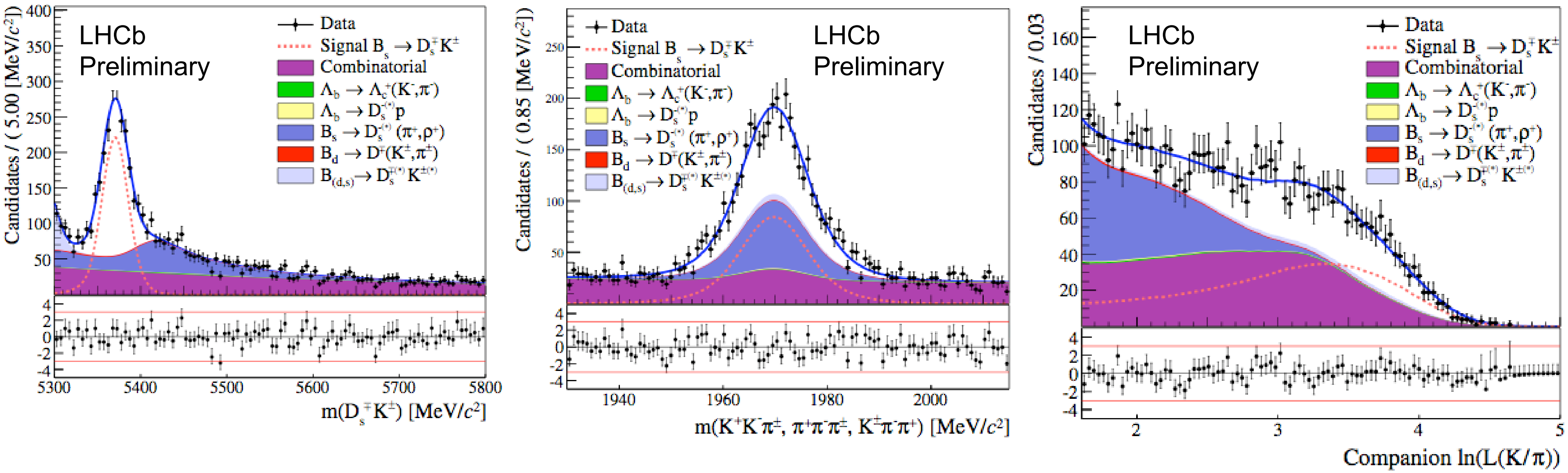
$$S_f = \frac{2r_{D_sK}\sin(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}, \quad S_{\bar{f}} = \frac{-2r_{D_sK}\sin(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2},$$

β_s - mixing phase

Analysis Strategy



Signal/Background discrimination



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

Other Inputs

Flavour tagging:

Combination of SS and OS taggers

Efficiency of tagging an event = 67.5%

Effective tagging power = 5.07%

Decay time acceptance:

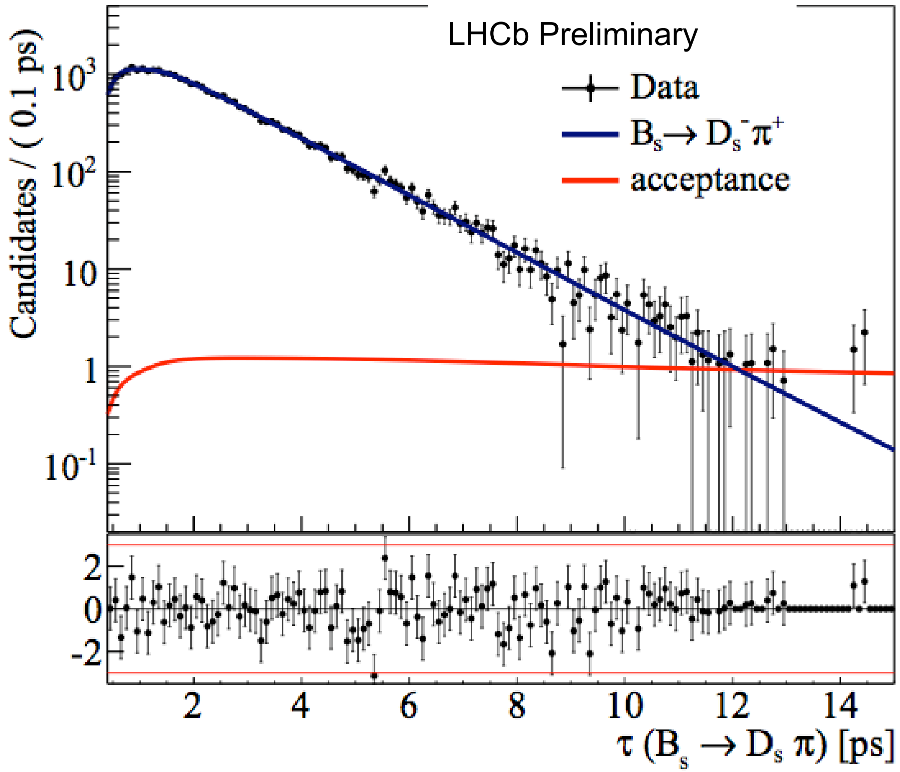
$B_s \rightarrow D_s\pi$ with additional corrections from simulation

Decay time resolution:

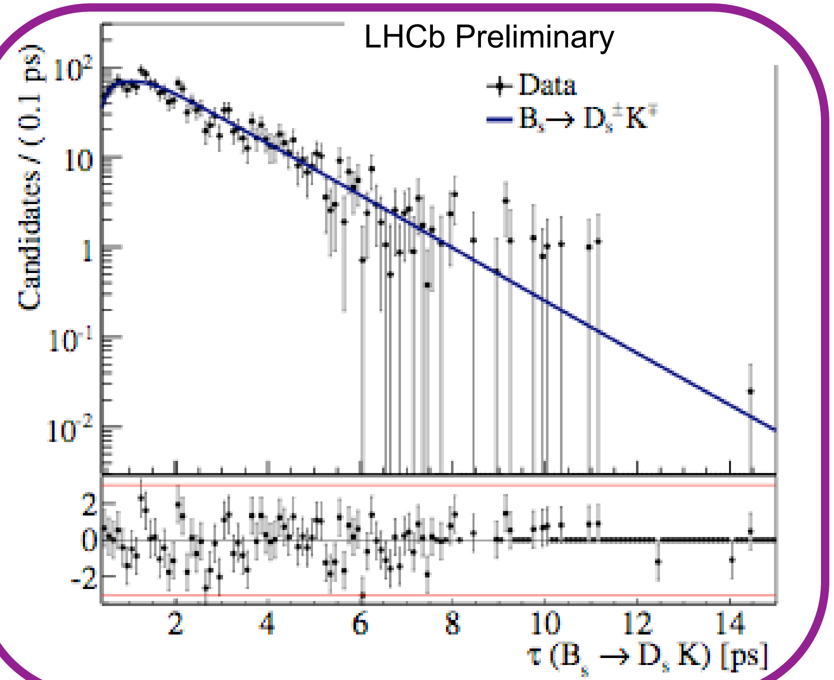
Use the per-event error. Average resolution is 47 fs

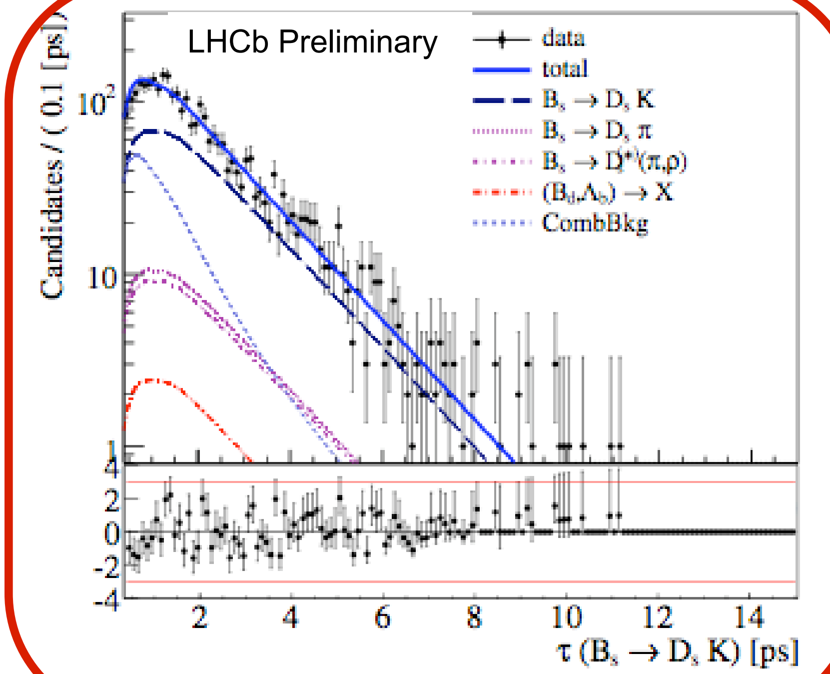
External Inputs:

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



Decay time fit





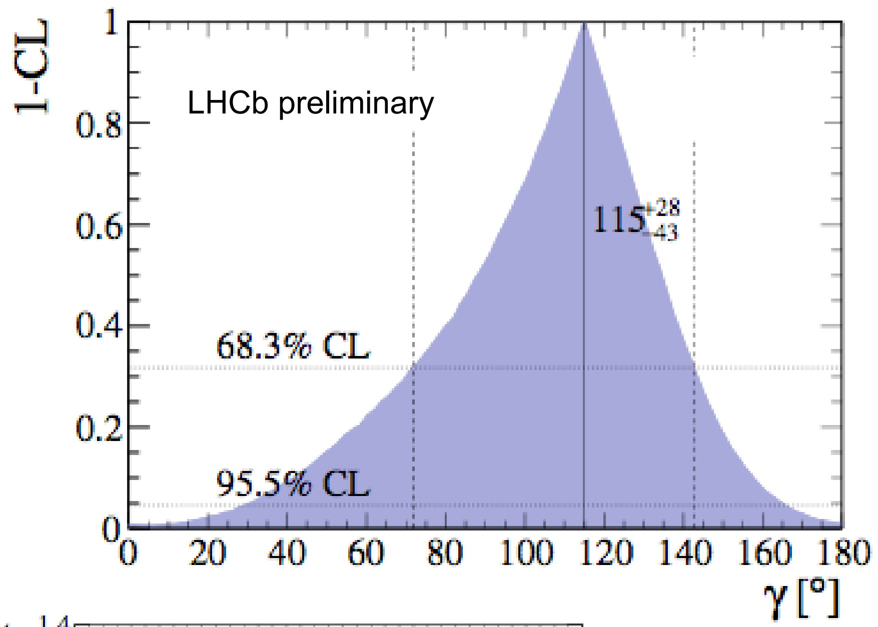
Parameter	*sFit* fitted value	*cFit* fitted value
C_f	$0.52 \pm 0.25 \pm 0.04$	$0.53 \pm 0.25 \pm 0.04$
$A_f^{\Delta\Gamma}$	$0.29 \pm 0.42 \pm 0.17$	$0.37 \pm 0.42 \pm 0.20$
$A_{\bar{f}}^{\Delta\Gamma}$	$0.14 \pm 0.41 \pm 0.18$	$0.20 \pm 0.41 \pm 0.20$
S_f	$-0.90 \pm 0.31 \pm 0.06$	$-1.09 \pm 0.33 \pm 0.08$
$S_{\bar{f}}$	$-0.36 \pm 0.34 \pm 0.06$	$-0.36 \pm 0.34 \pm 0.08$

Good agreement

sFit is a nice cross check to cFit

Measurement of angle γ

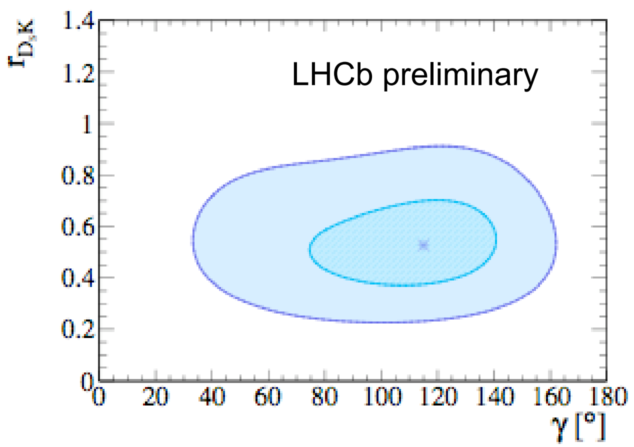
- γ determination based on cFit results
- Statistical and systematic uncertainties + correlations taken into account
- First measurement from $B_s \rightarrow D_s K$
- Only 1fb^{-1} - more available



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

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

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



Projection of contours onto 1-D gives
68.3%
95.5%

Preliminary

Summary and outlook

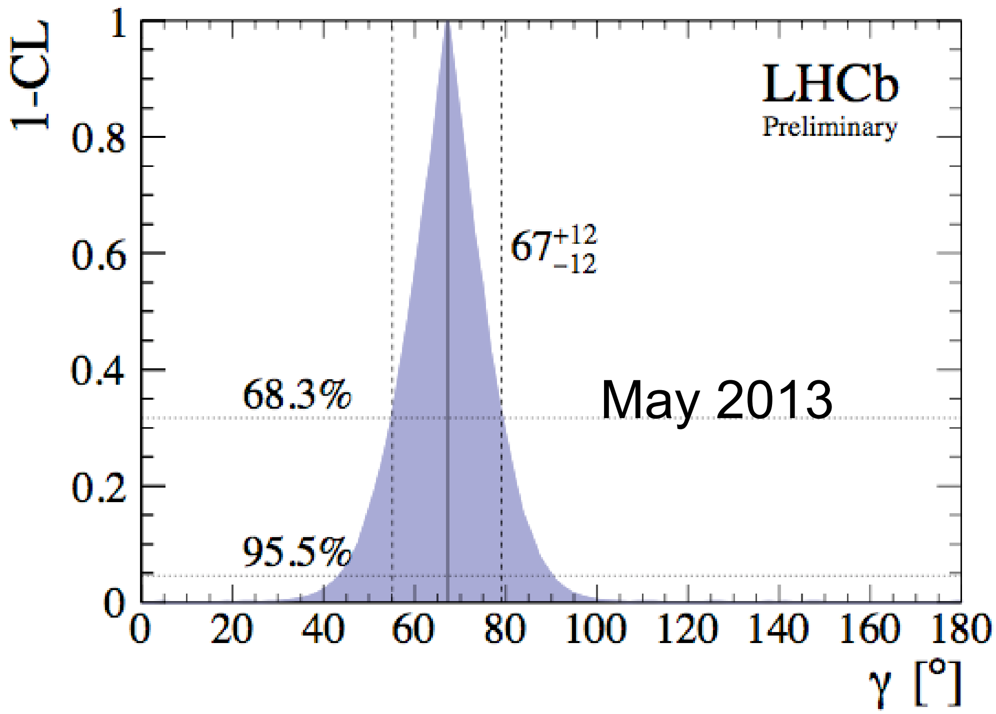
Many tree level γ measurements being pursued

Demonstrated that the complex analyses like $B_s \rightarrow D_s K$ and GGSZ can be done at LHCb

$B^0 \rightarrow DK^{0*}$, and $B_s \rightarrow D_s K$ will add to the combination and continue to drive the direct uncertainty down

Updated 3fb^{-1} GGSZ measurement has better overall precision than (1+2) fb^{-1} already included in the combination and will also continue to improve precision.

Other B→DK, B→DX analyses also pursued, either updating 1fb^{-1}→3fb^{-1} or new D decays.



Precision on direct γ measurements from LHCb will continue to reduce