XXIV Workshop on Weak Interactions and Neutrinos

WIN 2013

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Measurement of γ from $B \to DK$ decays

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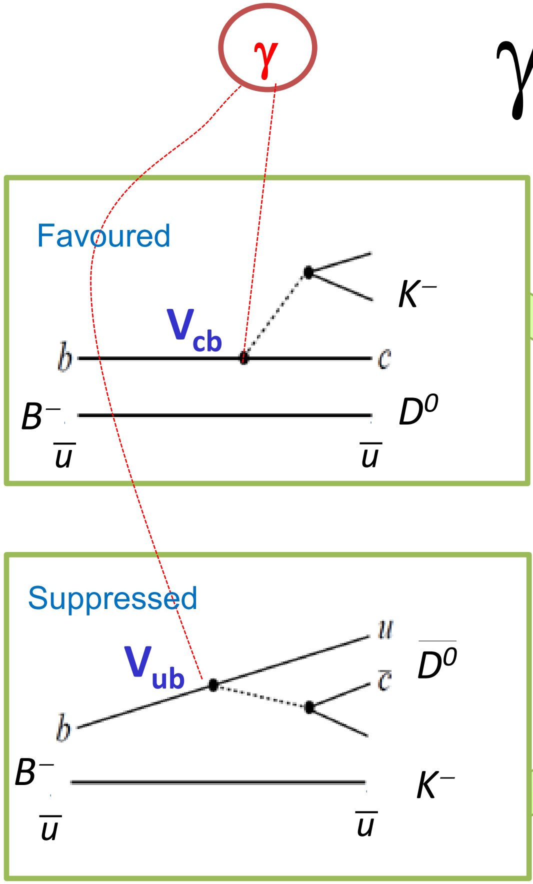
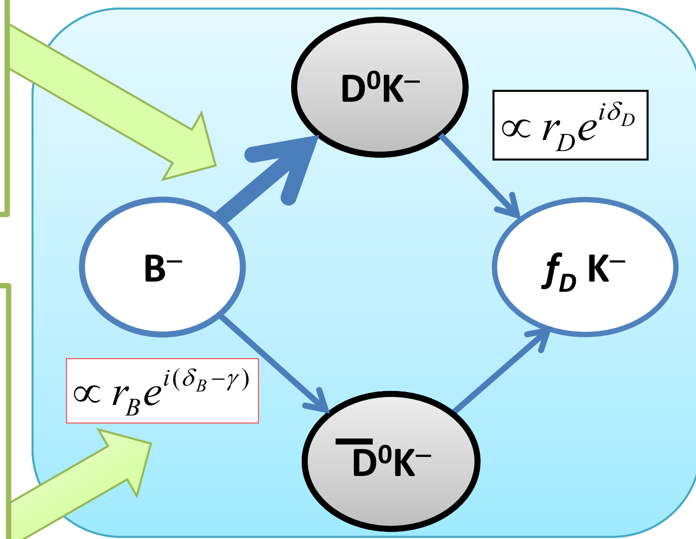
On behalf of the LHCb Collaboration

Outline

- Motivation and methods
- Results with $B^+ \to DK^+$ decays
- The LHCb γ combination
- Additional measurements from
  - $B^0 \to DK^{*0}$
  - $B^0_{(s)} \to D^0K^+\pi^-$
  - $B^0_s \to D_s^{\pm}K^{\mp}$
  - $B^0_s \to D^0\phi$ first observation

γ with $B^- \to DK^-$





$$r_B e^{i(\delta_B-\gamma)} \equiv \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)}$$

$$r_D e^{i\delta_D} \equiv \frac{A(D^0 \to f_D)}{A(\bar{D}^0 \to f_D)}$$

All unknowns from data
$\Rightarrow$ No hadronic uncertainties

Methods and D final states

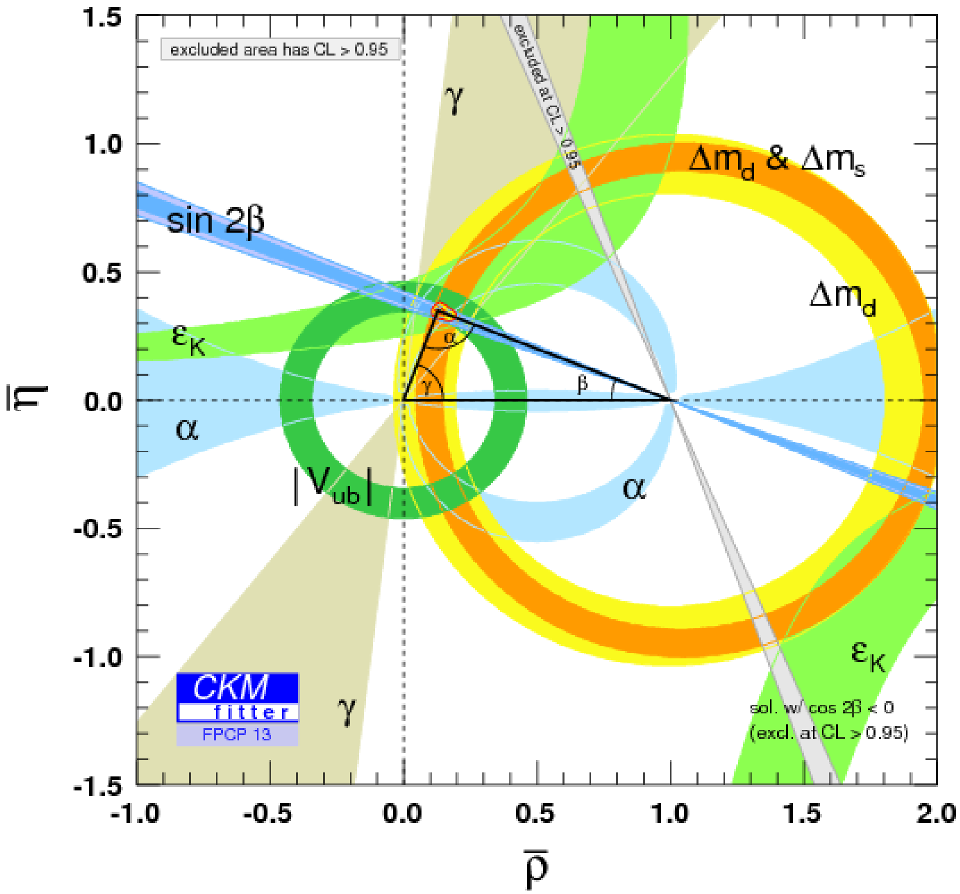
GLW : $f_D = KK, \pi\pi$ [Gronau-London-Wyler] PLB 253,483(1991), PLB 265,172 1991)

ADS : $f_D = K\pi, K\pi\pi\pi$ [Atwood-Dunietz-Soni] PRL 78,257(1997), PRD 63,036005(2001)

GGSZ : $f_D = K_S\pi\pi, K_SKK$ [Giri-Grossman-Soffer-Zupan] PRD 68,054018(2003)
Bondar,PRD 70,072003 (2004)

Same methods apply to $B^- \to D\pi^-$, but interference smaller

The compelling case for measuring γ



- Indirect path to New Physics discovery through precise CKM metrology
- γ from $B^+ \to DK^+$ free from theoretical uncertainties (tree-level decays only)
- Still large experimental uncertainty from direct measurements

CKMFITTER (post FPCP13) $\gamma = 68.0^{+8.0}_{-8.5}{}^\circ$

UTFIT (pre-Moriond13) $\gamma = 70.8 \pm 7.8^\circ$

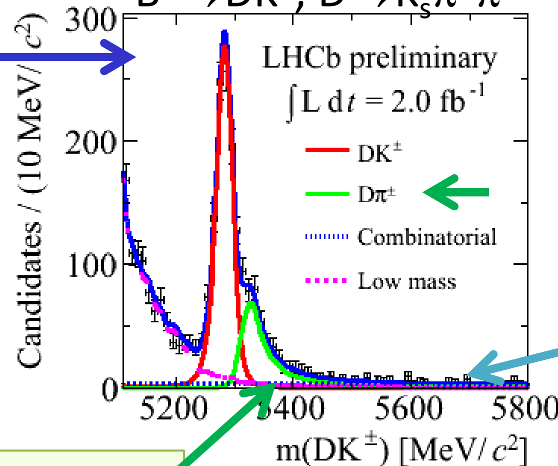
Above averages include early LHCb results

Smallest theoretical uncertainty but largest experimental error among all UT constraints!

Experimental challenges

Large data sample
⇒dedicated trigger
Efficient retention of fully hadronic B decays while limiting the overall output <5KHz

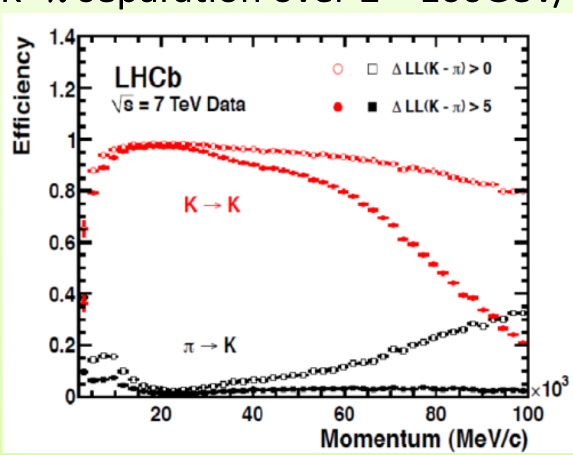
$B^+ \to DK^+$, $D \to K_s\pi^+\pi^-$

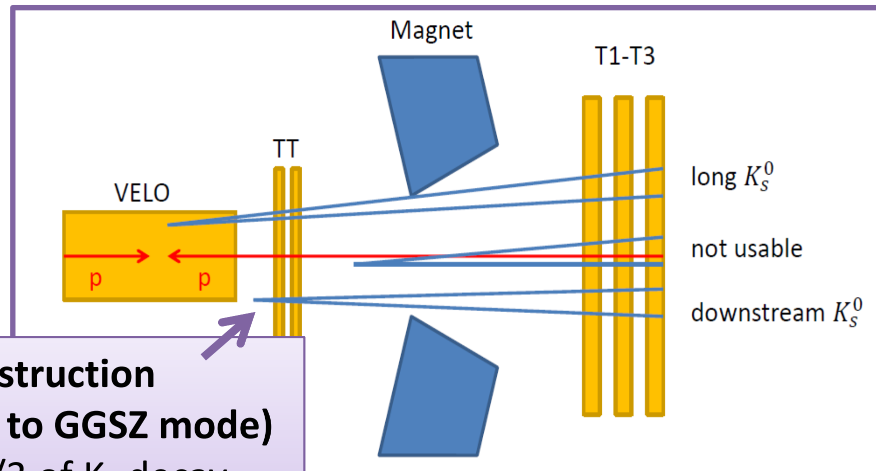


Precision @VERTEX
LHCB Vertex detector and tracking
⇒Excellent invariant mass resolution
⇒Excellent vertex resolution

Mass resolution and displaced vertices for separation from low-mass background and rejection of combinatorial background

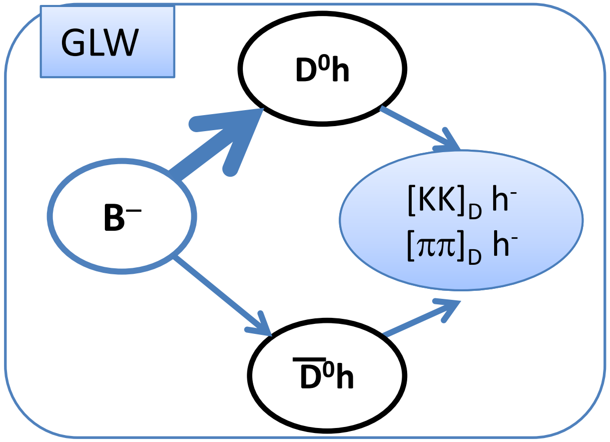
PID : 2 RICH detectors @LHCb
K–π separation over 2—100GeV/c

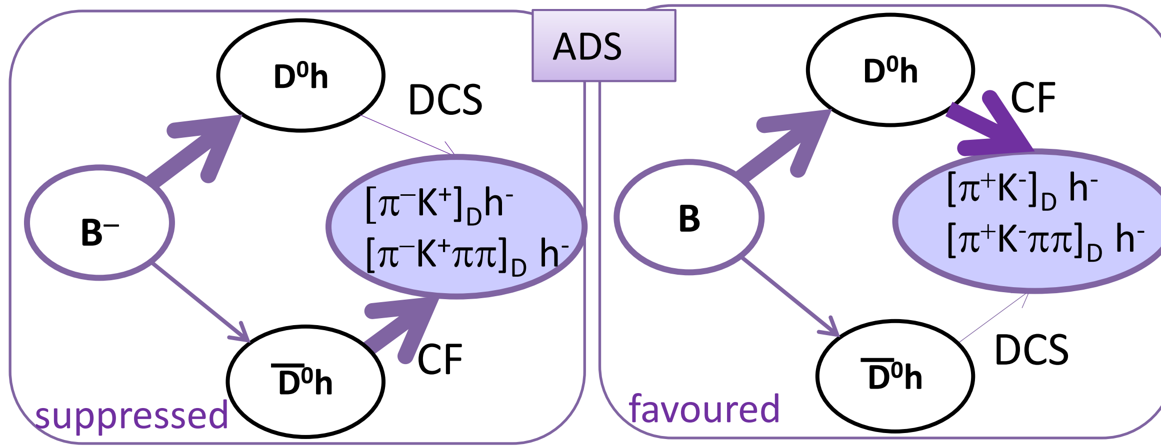




K_S reconstruction
(specific to GGSZ mode)
About 2/3 of K_S decay downstream of vertex detector

GLW and ADS observables





GLW and ADS observables built as ratios of branching fractions
(many systematic uncertainties cancel in the ratios)

ADS/GLW CP asymmetries, f_D = KK, ππ ,Kπ, Kπππ

$$A_h^f \equiv \frac{\Gamma(B^- \to f_D h^-) - \Gamma(B^+ \to f_D h^+)}{\Gamma(B^- \to f_D h^-) + \Gamma(B^+ \to f_D h^+)}$$

ADS/GLW K/π ratios, f_D = KK, ππ ,Kπ, Kπππ

$$R^f{}_{K/\pi} \equiv \frac{\Gamma(B^- \to f_D K^-) + \Gamma(B^+ \to f_D K^+)}{\Gamma(B^- \to f_D \pi^-) + \Gamma(B^+ \to f_D \pi^+)}$$

Ratio of ADS suppressed and favoured final states, f_D = Kπ, Kπππ

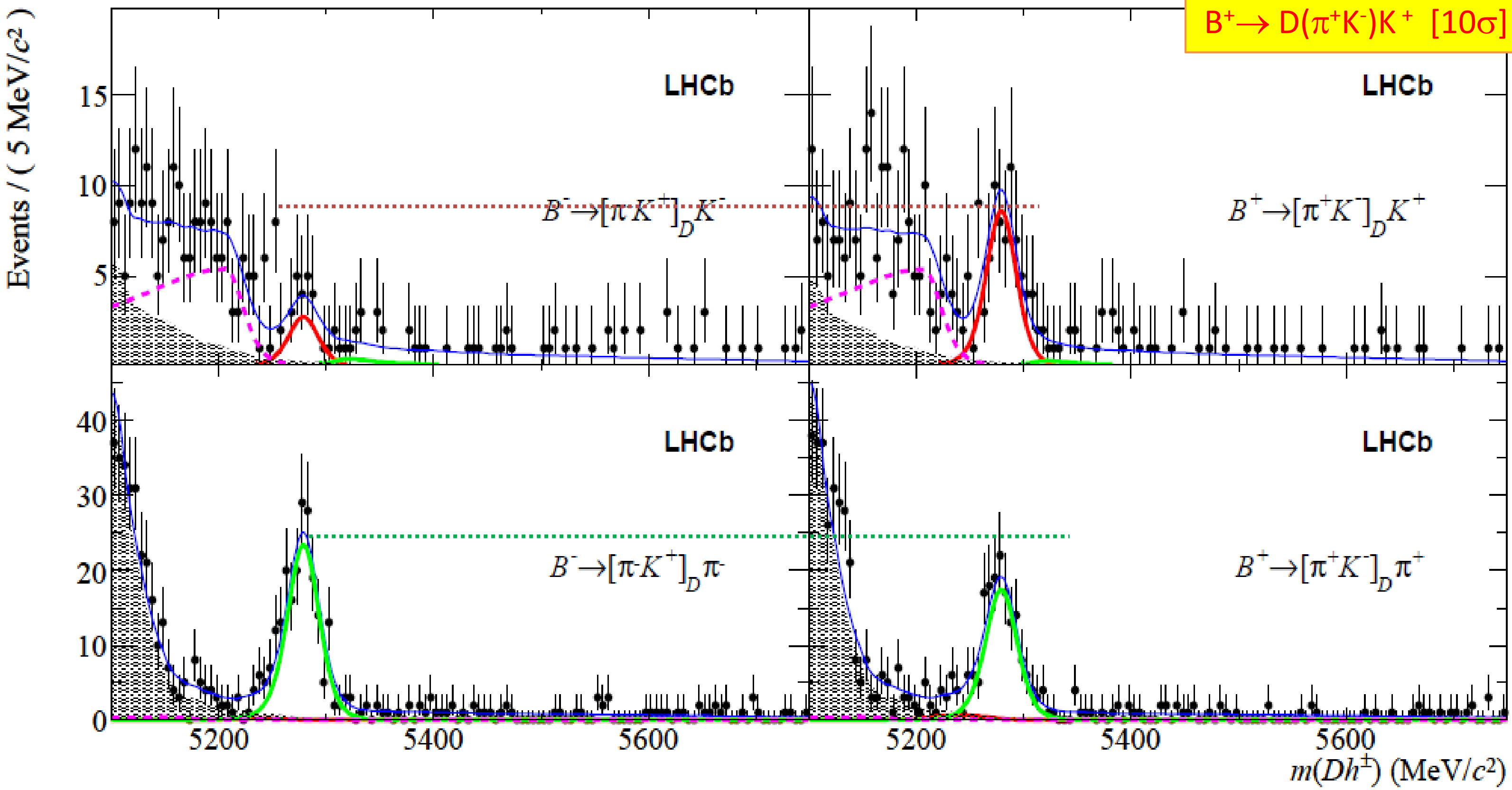
$$R_h^{f\pm} \equiv \frac{\Gamma(f_D h^\pm)^{sup}}{\Gamma(\bar{f}_D h^\pm)^{fav}}$$

[PLB 712(2012),213]

1 fb^{-1}

GLW/ADS with $B^+ \to Dh^+$, $D \to$ 2body

First observation of rare ADS
$B^+ \to D(\pi^+K^-)K^+$ [10σ]



Large asymmetry in $B \to DK$: A_{ADS} = (-52 ± 15 ± 2)% [4σ]

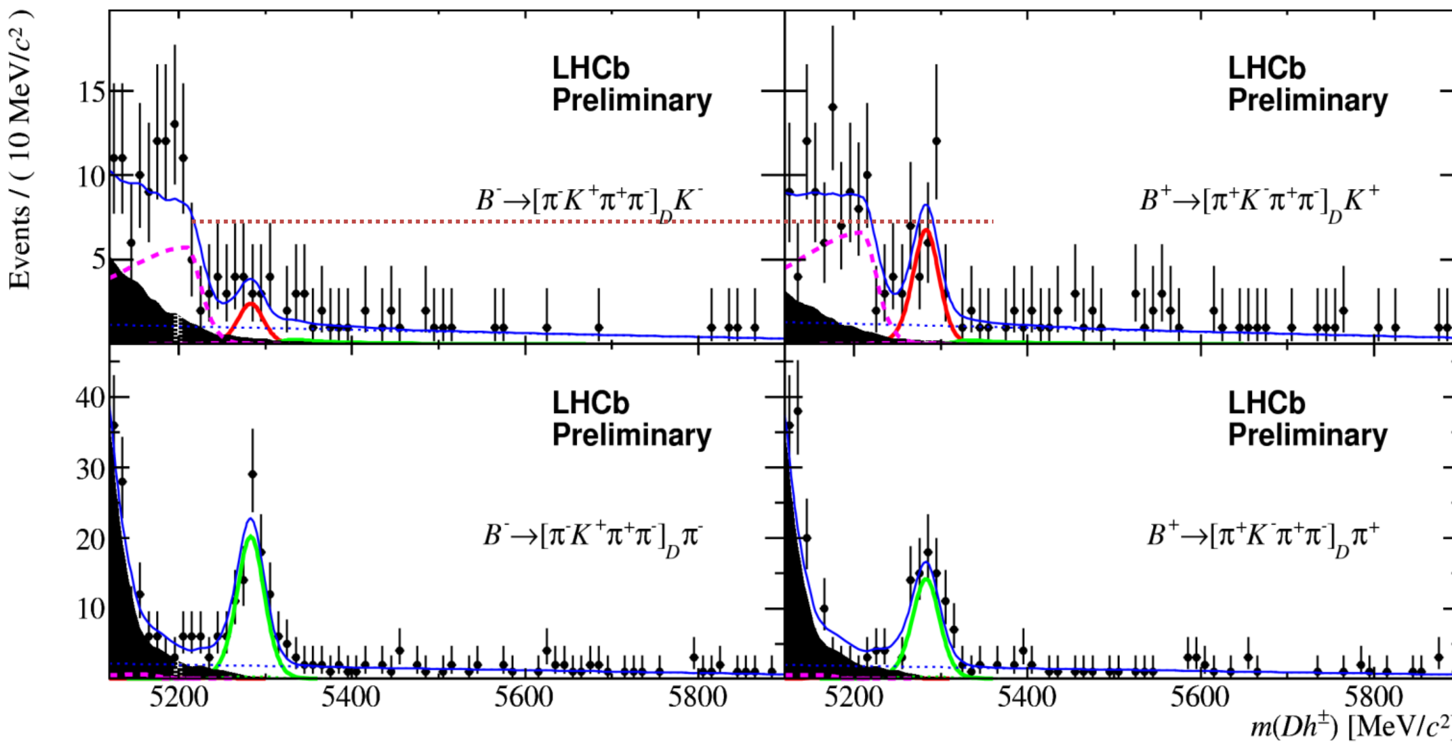
Hint of asymmetry in $B \to D\pi$: A_{ADS} = (14.3 ± 6.2 ± 1.1)% [2.4σ]

[PLB 723 (2013) 44-53]

1 fb^{-1}

ADS with $B^+ \to Dh^+$, $D \to K\pi\pi\pi$

Same r_B and δ_B, but different *D* decay parameters
Complementary information to $B \to D(K\pi)K$ not just additional statistics



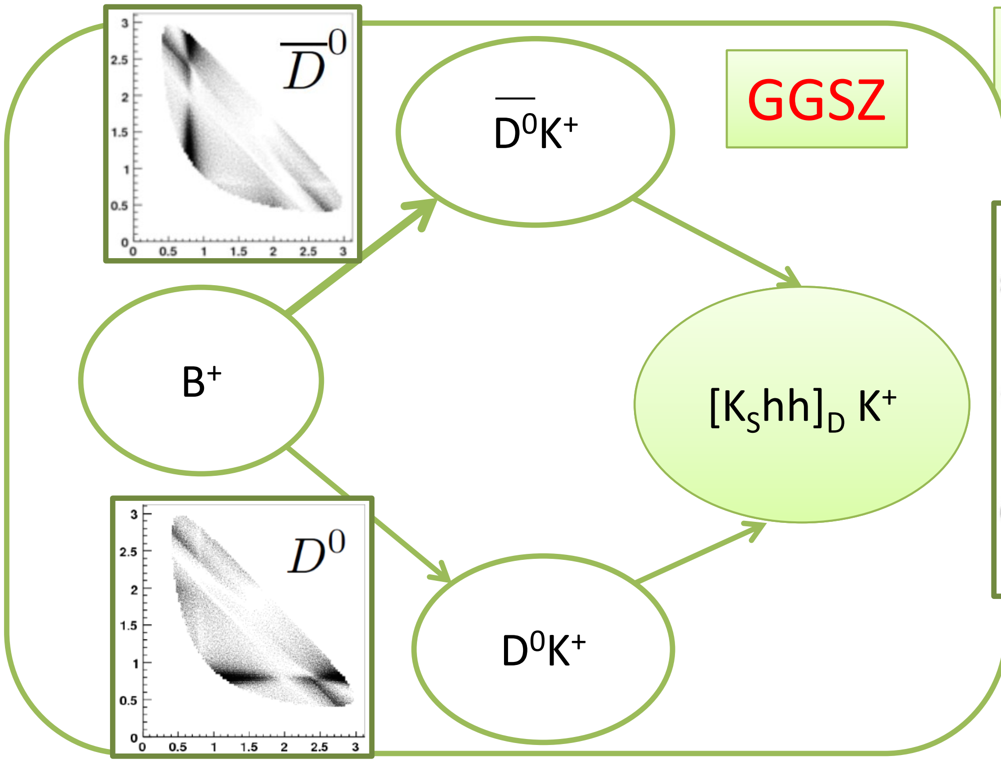
First observation of rare ADS mode in
$B \to DK$ [5.1σ]
and
$B \to D\pi$ [>10σ]

Hint of asymmetry in $B \to DK$: A_{ADS} = (-42 ± 22)%

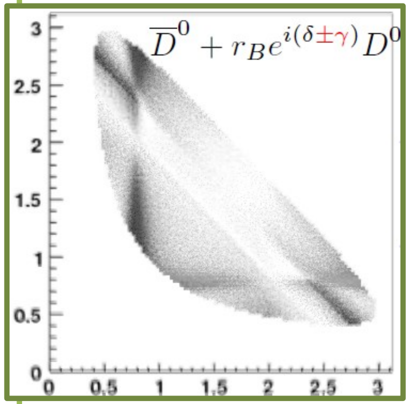
$B \to D\pi$: A_{ADS} = (13 ± 10)%

GGSZ with $B^+ \to DK^+$, $D \to K_s h^+ h^-$

Exploits interference pattern in the $D \to K_S \pi^+ \pi^-$ and $D \to K_S K^+ K^-$ Dalitz plots



Rich resonance structure ⇒ powerful method (dominates precision on γ at B-factories)



Published results using 2011 data sample (1 fb^{-1}) [PLB 718(2012) 43]

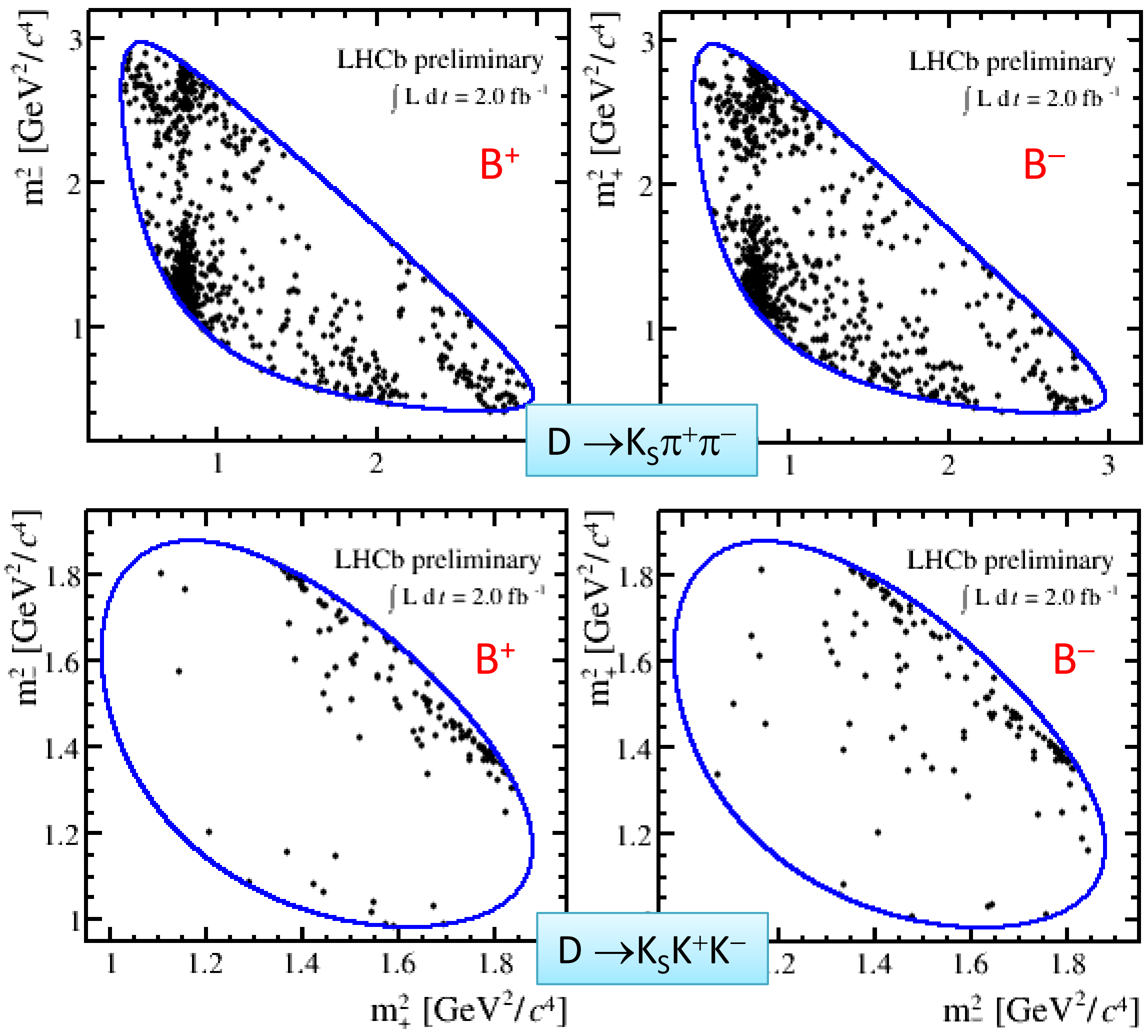
Preliminary results using 2012 data sample ($2fb^{-1}$) [LHCB-CONF-2013-004]

[LHCB-CONF-2013-004]

2 fb^{-1}

GGSZ with $B^+ \to DK^+$

Different interference structure for B^+ and B^-



$m_{\pm} = m(K_S h^{\pm})$

>85% purity

Extraction of γ requires information on the $D \to K_S hh$ decay amplitude variation over Dalitz plot:
both amplitude and phase δ_D

1. model of decay amplitude or
2. external measurements (model independent approach)

GGSZ observables: binned approach

Use discrete measurements of δ_D in Dalitz plot bins from CLEO-c: **c_i, s_i** [PRD82(2010)112006]

$$N(B^\pm)_{+i} = h_{B^\pm}\varepsilon_i[K_{\mp i} + (x_\pm^2 + y_\pm^2)K_{\pm i} + 2\sqrt{K_i K_{-i}}\{x_\pm c_i \mp y_\pm s_i\}]$$

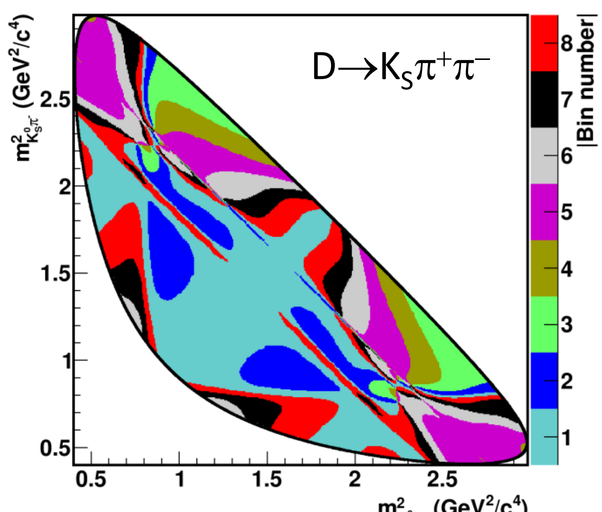
$K_i = \int_i |A_D(m_+^2, m_-^2)|^2 \, dm_+^2 dm_-^2$
from $B^- \to D\pi^-$ decays

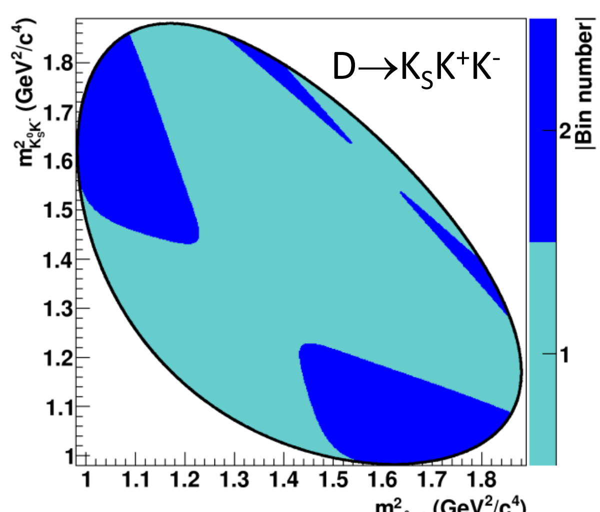
$$x_\pm = r_B \cos(\delta_B \pm \gamma)$$
$$y_\pm = r_B \sin(\delta_B \pm \gamma)$$

$$c_i = \langle \cos \delta_D \rangle_i$$

$$s_i = \langle \sin \delta_D \rangle_i$$

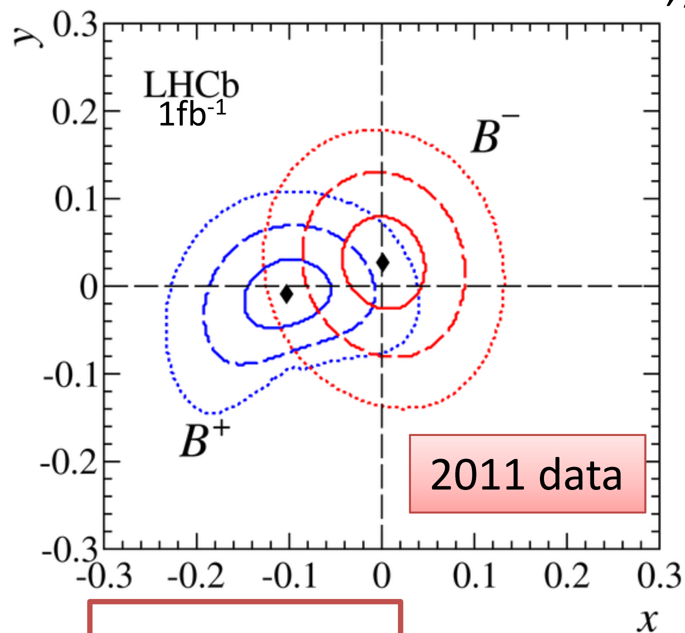
- $x_\pm$, $y_\pm$ extracted from a simultaneous fit to the signal yields in each Dalitz-plot bin
- Chosen binning optimises γ sensitivity
- $K_S KK$ sample adds 2 bins

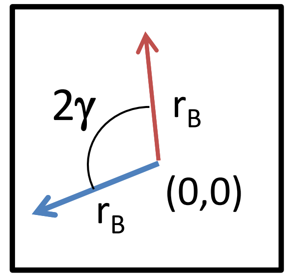


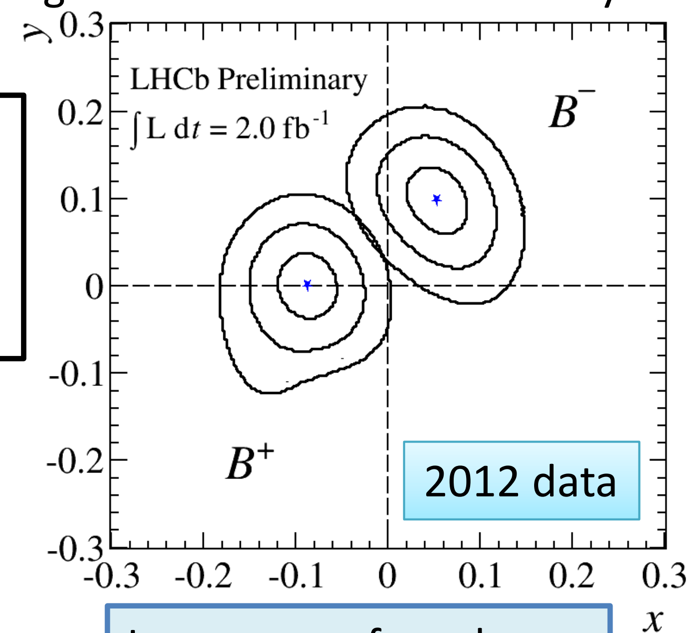


GGSZ results

Confidence intervals in the x,y plane including statistical uncertainties only







$\gamma = (44^{+43}_{-38})^{o}$

$r_B = 0.07 \pm 0.04$

2011+2012 data

$\gamma = (57 \pm 16)^{o}$

$r_B = 0.09 \pm 0.02$

Larger r_B preferred

$\Rightarrow$ larger sensitivity to γ

$$x_+ = (-8.7 \pm 3.1 \pm 1.6 \pm 0.6) \times 10^{-2}$$
$$x_- = (5.3 \pm 3.2 \pm 0.9 \pm 0.9) \times 10^{-2}$$
$$y_+ = (0.1 \pm 3.6 \pm 1.4 \pm 1.9) \times 10^{-2}$$
$$y_- = (9.9 \pm 3.6 \pm 2.2 \pm 1.6) \times 10^{-2}$$

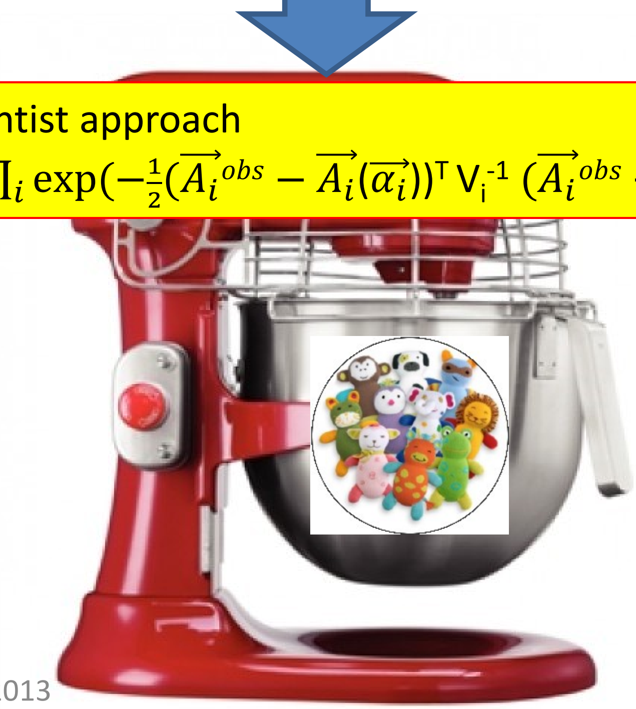
- Statistical error still dominant
- Leading source of experimental systematic uncertainty: assumption of NO CPV in $B \to D\pi$ used to determine efficiency ($\varepsilon_i K_i$)

The LHCb γ combination

Input	Observables (A_i)
$B^+ \to D(hh)h^+$	A^{KK}_h, $R^{KK}_{K/\pi}$, $A^{\pi\pi}_h$, $R^{\pi\pi}_{K/\pi}$
	$A^{K\pi}_h$, $R^{K\pi}_{K/\pi}$, $R^{\pm K\pi}_h$
$B^+ \to D(K\pi\pi\pi)h^+$	$A^{K3\pi}_h$, $R^{K3\pi}_{K/\pi}$, $R^{\pm K3\pi}_h$
$B^+ \to D(K_S hh)K^+$	$x_\pm$, $y_\pm$
Charm constraints	

Frequentist approach

$$L(\overrightarrow{\alpha})=\prod_i \exp\left(-\tfrac{1}{2}(\overrightarrow{A_i}^{obs} - \overrightarrow{A_i}(\overrightarrow{\alpha_i}))^T V_i^{-1} (\overrightarrow{A_i}^{obs} - \overrightarrow{A_i}(\overrightarrow{\alpha_i}))\right)$$



Charm hadronic parameters are determined from data but constrained by CLEO, HFAG and D-mixing studies at LHCb

Decay	Parameters (α_i)
$B^+ \to Dh^+$	γ
$B^+ \to DK^+$	r_B^K, δ_B^K
$B^+ \to D\pi^+$	r_B^π, δ_B^π
$B^+ \to DK^+ / B^+ \to D\pi^+$	R_{cab}
$D \to K\pi$	$r_{K\pi}$, $\delta_{K\pi}$, $\Gamma(D \to K\pi)$
$D \to K\pi\pi\pi$	$r_{K3\pi}$, $\delta_{K3\pi}$, $\kappa_{K3\pi}$, $\Gamma(D \to K3\pi)$
$D \to KK$	$A^{dir}_{CP}(KK)$
$D \to \pi\pi$	$A^{dir}_{CP}(\pi\pi)$
D^0-D^0bar mixing	x_D, y_D

$0 \le \kappa \le 1$ Coherence factor for D decays
=1 for $D \to$ 2-body decays

Observables and physics parameters

(including D mixing effects)

ADS GLW

CP asymmetries [f_D = KK, ππ, Kπ, Kπππ, 4x2 observables]

$$A_h^f = \frac{+2r_B^h \kappa \sin(\delta_B^h - \delta_f)\sin\gamma + M_-^h - M_+^h}{1+(r_B^h r_f)^2 + 2r_B^h r_f \kappa \cos(\delta_B^h - \delta_f)\cos\gamma + M_-^h + M_+^h}$$

K/π ratios [f_D = KK, ππ, Kπ, Kπππ, 4 observables]

$$R_{K/\pi}^f = R_{cab} \frac{1+(r_B^K r_f)^2 + 2r_B^K r_f \kappa \cos(\delta^K{}_B + \delta_f) + M_-^K + M_+^K}{1+(r_B^\pi r_f)^2 + 2r_B^\pi r_f \kappa \cos(\delta^\pi{}_B + \delta_f) + M_-^\pi + M_+^\pi}$$

Ratio of suppressed and favoured final state [f_D = Kπ, Kπππ, 2x2x2 observables]

$$R_h^{\pm f} = \frac{r_f^2 + (r_B^h)^2 + 2r_B^h r_f \kappa \cos(\delta^h{}_B + \delta_f \pm \gamma) - [M_\pm^h]_{sup}}{1+(r_B^h r_f)^2 + 2r_B^h r_f \kappa \cos(\delta^h{}_B - \delta_f \pm \gamma) + M_\pm^h}$$

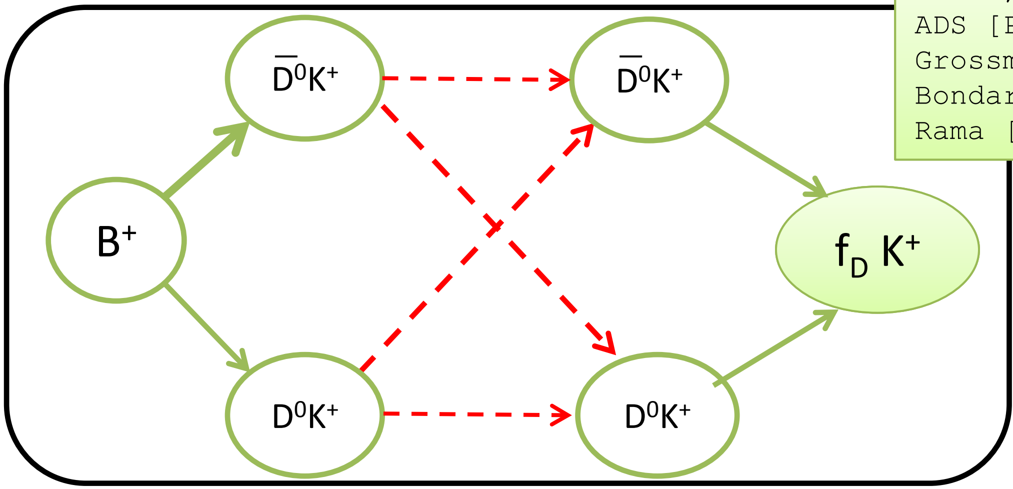
GGSZ

Cartesian coordinates [f_D = $K_S$hh 4 observables]

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

$B^+ \to DK^+$ GGSZ effects of D-mixing negligible

Effect of D^0-mixing on B decay rates



Silva, Soffer [PRD61(2000)112001]
ADS [PRD63(2001)036005]
Grossman,Soffer,Zupan[PRD 72(2005)031501]
Bondar,Poluektov,Vorobiev[PRD 82(2010)034033]
Rama [arXiv:1307.4384]

D^0 mixing terms at leading order in x_D and y_D

$$M_{\pm}^{h} = (\kappa r_f((r_B^h)^2 - 1)\sin\delta_f + r_B^h(1 - r_f^2)\sin(\delta_B{}^h \pm \gamma))a_D x_D - (\kappa r_f((r_B^h)^2 + 1)\cos\delta_f + r_B^h(1 + r_f^2)\cos(\delta_B{}^h \pm \gamma))a_D y_D$$

$$[M_{\pm}^{h}]_{\text{sup}} = (\kappa r_f((r_B^h)^2 - 1)\sin\delta_f + r_B^h(1 - r_f^2)\sin(\delta_B{}^h \pm \gamma))a_D x_D + (\kappa r_f((r_B^h)^2 + 1)\cos\delta_f + r_B^h(1 + r_f^2)\cos(\delta_B{}^h \pm \gamma))a_D y_D$$

important for $B^+ \to D\pi^+$ since $r_B{}^{\pi} \sim x_D$ *or* y_D

$\Rightarrow$ corrections comparable to leading interference term

Included in a γ measurement for the first time by LHCb

Other constraints on charm parameters

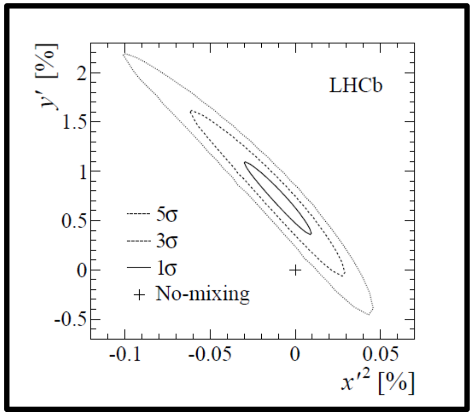
- HFAG – direct CPV in D→KK and D→ππ affects GLW measurements

$$A^{\rm dir}_{CP}(KK) = (-0.31 \pm 0.24) \times 10^{-2}$$
$$A^{\rm dir}_{CP}(\pi\pi) = (+0.36 \pm 0.25) \times 10^{-2}$$

$$A_h^{KK} \rightarrow A_h^{KK} + A_{CP}^{dir}(KK)$$
$$A_h^{\pi\pi} \rightarrow A_h^{\pi\pi} + A_{CP}^{dir}(\pi\pi)$$

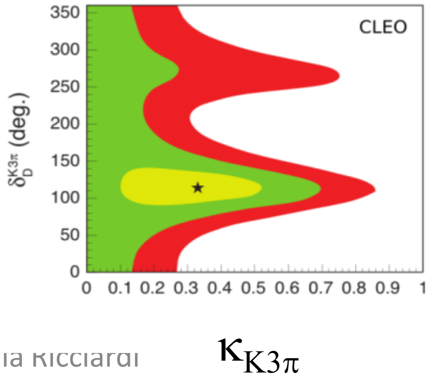
- LHCb charm-mixing results on $D^0 \rightarrow K^+\pi^-$

$$R_D = r^2_{K\pi}\,,$$
$$y'_D = x_D \sin\delta_{K\pi} - y_D \cos\delta_{K\pi}\,,$$
$$x'^2_D = (x_D \cos\delta_{K\pi} + y_D \sin\delta_{K\pi})^2$$



Correlations taken into account in the combination

- CLEO $D \rightarrow K^+\pi^-$, $D \rightarrow K^+\pi^-\pi^+\pi^-$

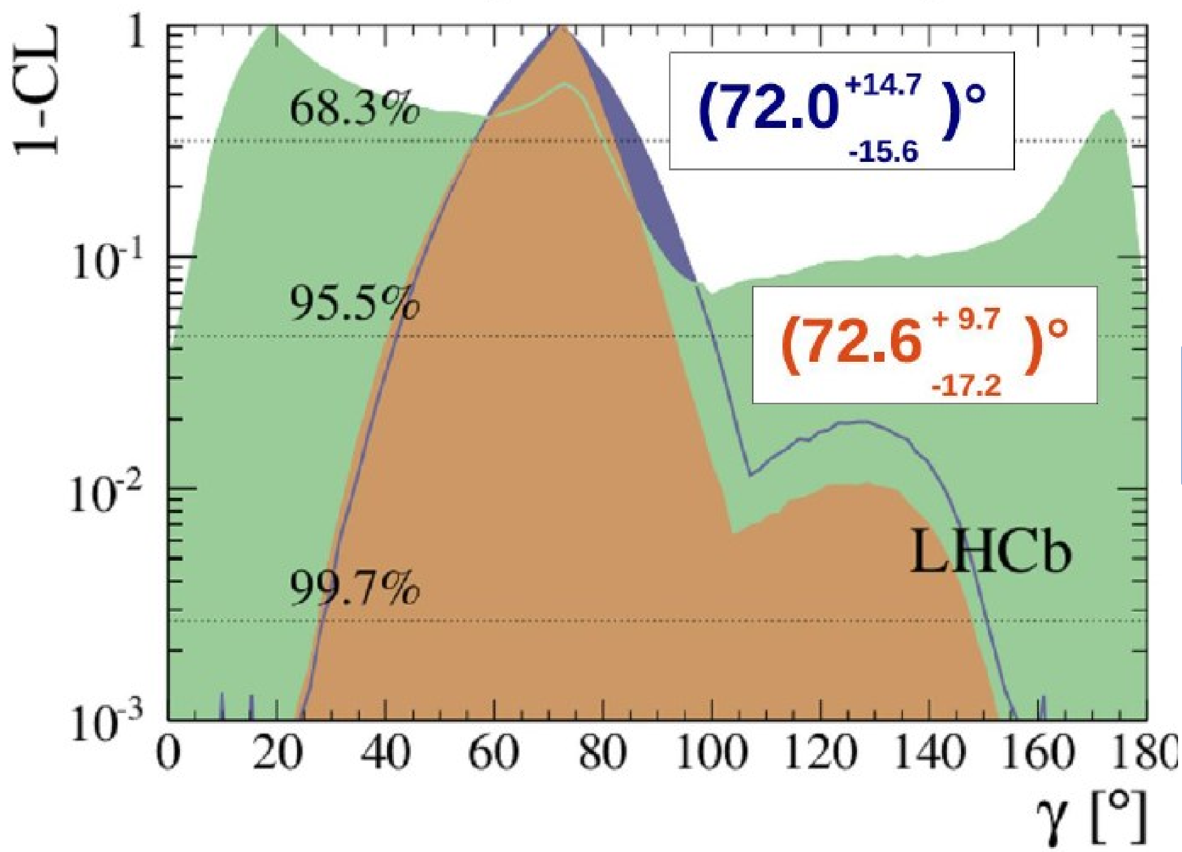


Non-Gaussian 2D likelihood between $\delta_D^{K3\pi}$ and $\kappa_{K3\pi}$ included in the combination

arXiv:1305.2050
Accepted by PLB

$B^+ \to Dh^+$ γ-combination [1 fb^{-1}]

- 2011 data only
- First combination to include $B^+ \to D\pi^+$
- Result corrected for neglected correlations between systematic uncertainties and undercoverage



$B^+ \to DK^+$ only (blue)
$B^+ \to D\pi^+$ only (green)
$B^+ \to DK^+$ + $B^+ \to D\pi^+$ (brown)

BaBar γ = $(69^{+17}_{-16})°$
Belle γ = $(68^{+15}_{-14})°$

- Excellent agreement with B-factories
- Comparable uncertainty

$B^+ \to DK^+$ γ combination with GGSZ $3fb^{-1}$ update

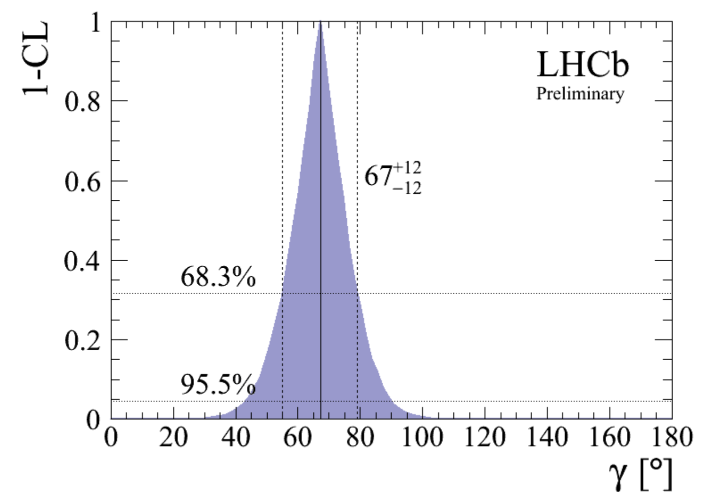
[LHCB-CONF-2013-006]

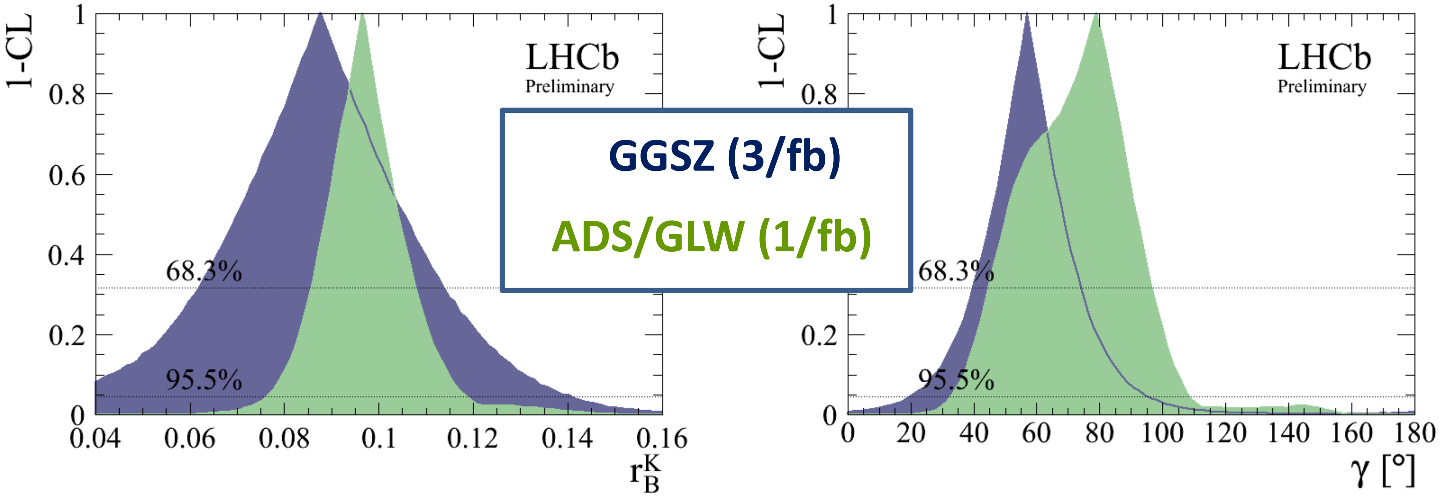
Combination includes:

- 1/fb 2011 $B^+ \to DK^+$ ADS/GLW
- 3/fb 2011+2012 $B^+ \to DK^+$ GGSZ

$\gamma = (67 \pm 12)°$ PRELIMINARY

Best γ measurement from a single experiment





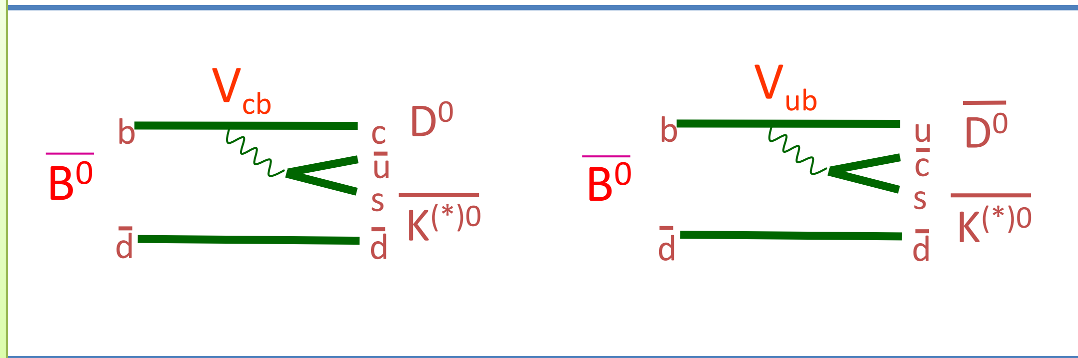
ADS/GLW update to $3fb^{-1}$ will improve precision further

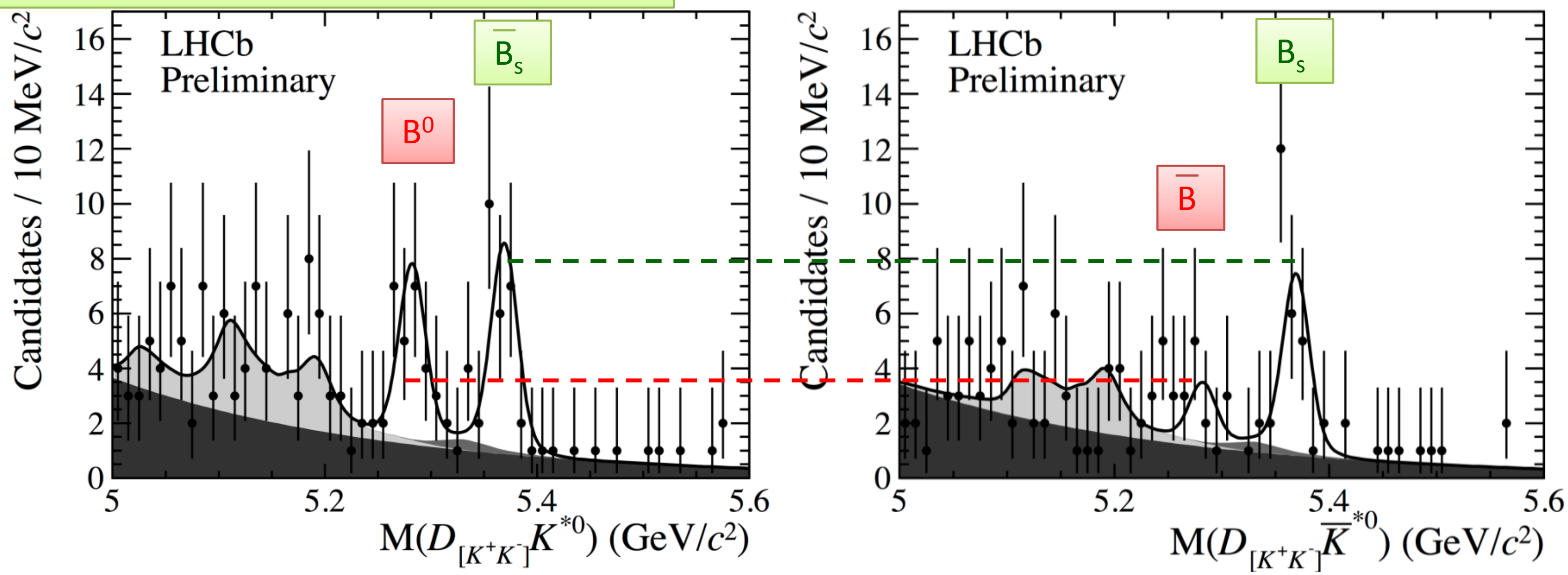
$B^0 \to D^0 K^{*0}$, $D^0 \to KK$

1 fb^{-1}

[JHEP03(2013)067]

- Self-tagged mode $\Rightarrow$ time-integrated methods similar to $B^+ \to D(hh)K^+$
- Interfering diagrams both colour suppressed:
  - Larger r_B (3x) $\Rightarrow$ larger interference
  - Low yields
- ADS+GLW will be performed with 3fb^{-1}





Hint of large asymmetry in $B^0 \to DK^{0*}$: $A^d_{CP+} = (-47 \pm 25 \pm 2)\%$

No significant asymmetry in $B_s \to DK^{*0}$: $A^s_{CP+} = (4 \pm 17 \pm 1)\%$

$B^0_{(s)} \to DK^+\pi^-$

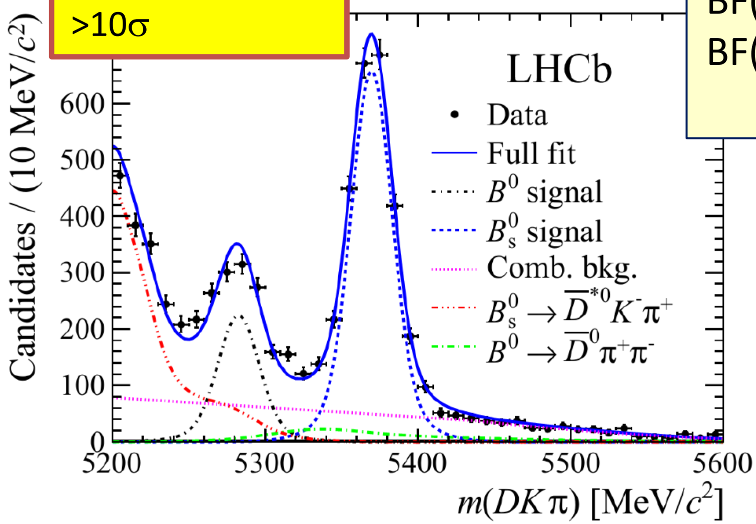
1 fb^{-1}

[PRD, 87(2013)112009]

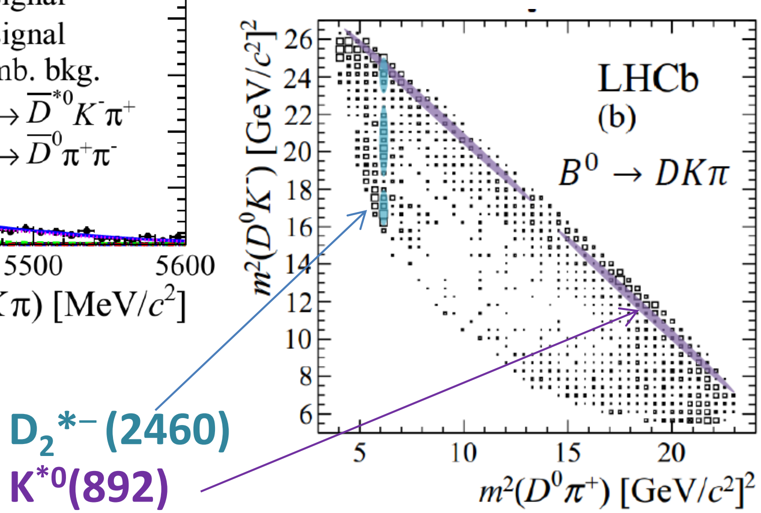
Dalitz plot analysis of $B^0 \to DK^+\pi^-$ very promising

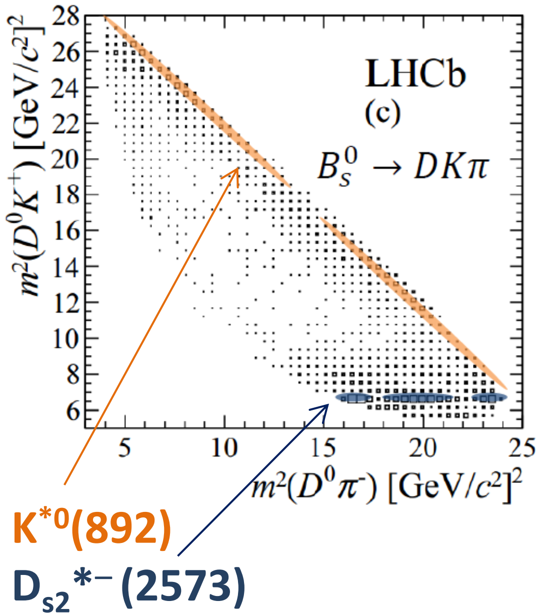
- Larger branching fraction
- Exploit fully interference structure

$B_s \to D^0K^+\pi^-$
First observation
$>10\sigma$

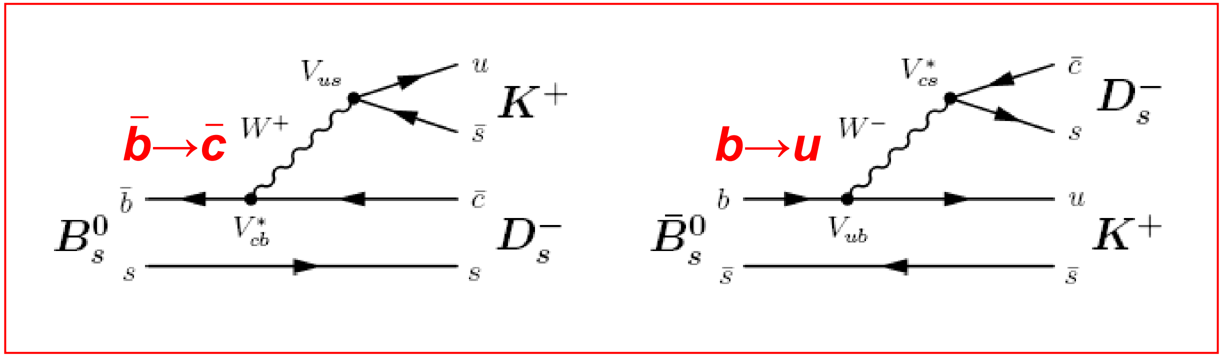


$BF(B^0_s \to D^0K^+\pi^-) = [1.00 \pm 0.04\,(stat) \pm 0.09(syst) \pm 0.10(norm)]\times10^{-3}$
$BF(B^0 \to D^0K^+\pi^-) = [9.0 \pm 0.6(stat) \pm 0.6(syst) \pm 0.9(norm)]\times10^{-5}$
World-best measurement





Time-dependent study of $B_s \to D_s^{\mp} K^{\pm}$



Two final states:

$D_s^+K^-$ and $D_s^-K^+$

Both accessible to B_s and $\overline{B}_s$

CPV in decay w & w/out mixing

⇒ sensitive to $\gamma - 2\beta_s$

Time-dependent analysis and flavour tagging required

Unique to LHCb

$$\frac{d\Gamma_{B_s\to f}(t)}{dt} \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C\cos(\Delta m_s t) - S_f \sin(\Delta m_s t)\right]$$

$$\frac{d\Gamma_{\bar{B}_s\to f}(t)}{dt} \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C\cos(\Delta m_s t) + S_f \sin(\Delta m_s t)\right]$$

+ other 2 equations for $\bar{f}$

$$D_f = \frac{2r_{DsK}\cos(\Delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}$$

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

$$S_f = \frac{2r_{DsK}\sin(\Delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}$$

5 Observables:

C

$S_f, S_{\bar{f}}$

$D_f, D_{\bar{f}}$

CP sensitivity in D thanks to $\Delta\Gamma_s \neq 0$ untagged&tagged events

r_{DsK} ~0.4

relative magnitude of the CKM-suppressed to CKM-favoured amplitudes

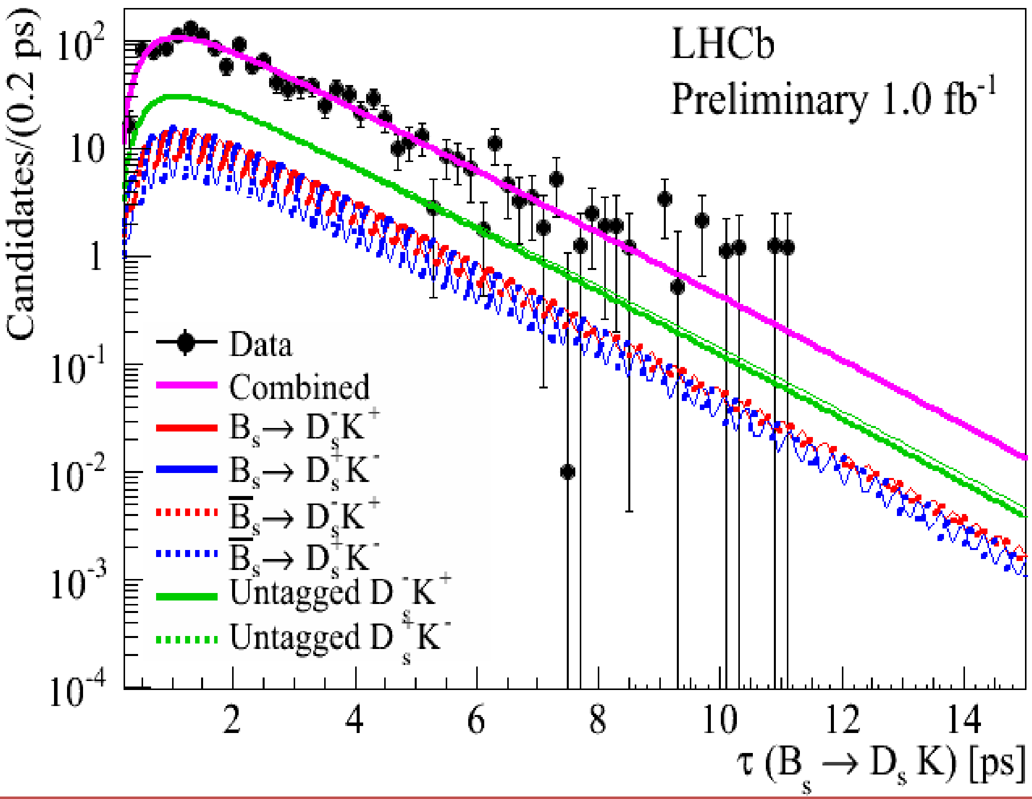
CP sensitivity in S tagged events only

1 fb^{-1}

$B_s \to D_s^{\mp} K^{\pm}$ results

[LHCB-CONF-2012-029]

First measurement of the CP parameters in $B_s \to D_s K$



$$C = 1.01 \pm 0.50 \pm 0.23$$
$$S_f = -1.25 \pm 0.56 \pm 0.24$$
$$S_{\bar{f}} = 0.08 \pm 0.68 \pm 0.28$$
$$D_f = -1.33 \pm 0.60 \pm 0.26$$
$$D_{\bar{f}} = -0.81 \pm 0.56 \pm 0.26$$

Main systematic uncertainties:
fixed parameters (Γ_s, $\Delta\Gamma_s$, Δm_s, acceptance);
tagging calibration

Includes both tagged (40%) and untagged (60%) events

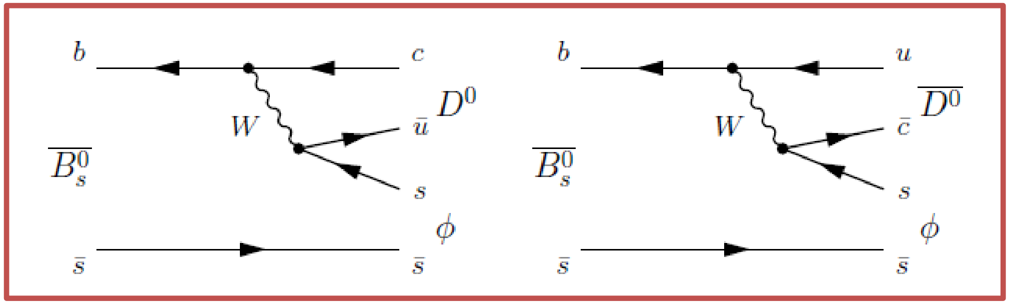
Extraction of γ sensitive to correlations:
work in progress to determine
systematic error covariance matrix

1 fb^{-1}

$B^0_s \rightarrow D^0 \phi$

[arXiv:1308.4583]

- $B_s \rightarrow D^0\phi$ TD is sensitive to γ and β_s
- Both amplitudes colour-suppressed $\Rightarrow$ small yields
- Time-integrated methods to determine γ also available, promising sensitivity at LHCb

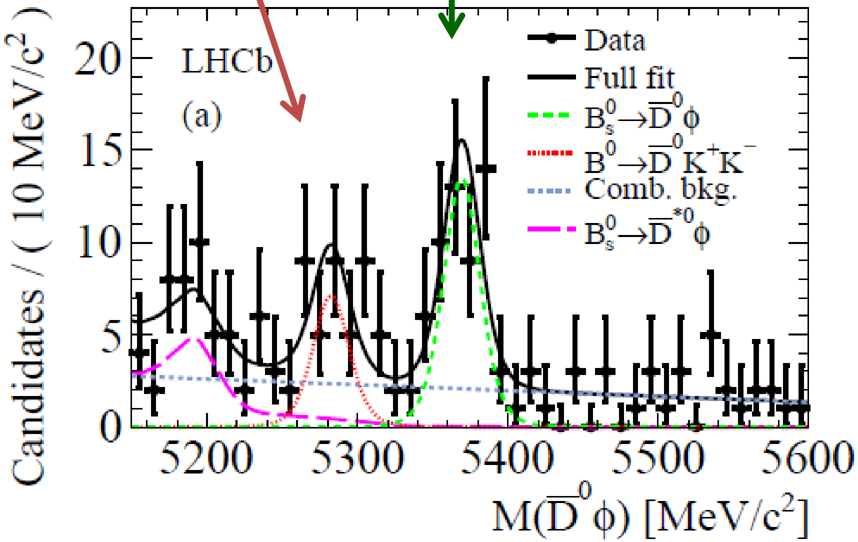


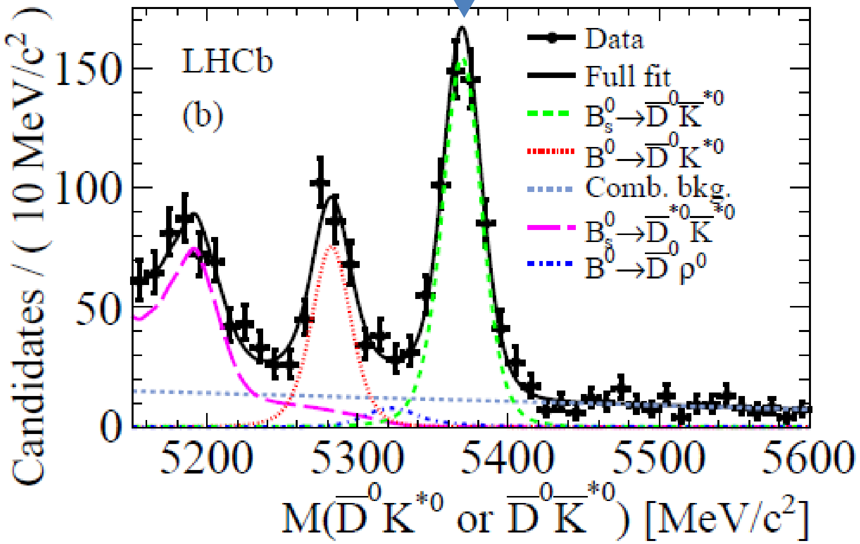
$B_d \rightarrow \overline{D^0}KK$
LHCB-PAPER-2012-018

$B_s \rightarrow D^0\phi$
First observation
$>6\sigma$

$BF(B^0_s \rightarrow D^0\phi) = [2.3 \pm 0.4\,(stat) \pm 0.2(syst) \pm 0.5(norm)]\times 10^{-5}$

First step : measurement of branching ratio wrt $B_s \rightarrow D^0K^{*0}$





Summary

- LHCb measurement of γ with first year data (1 fb^{-1})
  - First measurement to include $B^- \to D\pi^-$ and D-mixing corrections
  - Good agreement and similar sensitivity to B-factories
- Partial update of GGSZ measurement to 3fb^{-1} combined with $B^- \to DK^-$ ADS/GLW 1fb^{-1} leads to best single-experiment measurement

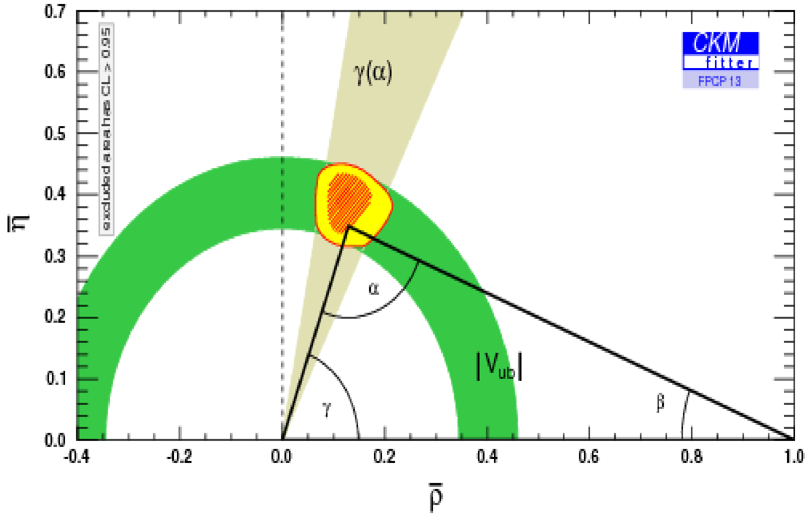
$\gamma = 67 \pm 12°$ PRELIMINARY

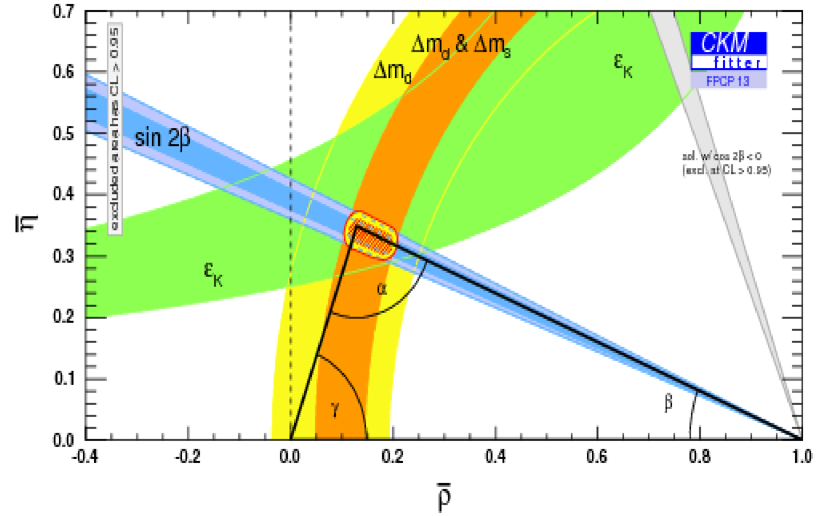
- Precision will keep improving faster than $\sqrt{L}$ with ADS/GLW 3fb^{-1} update and the addition of other channels in the combination

ADDITIONAL MATERIAL

The compelling case

New Physics (indirect) search through precise CKM metrology





- Tree-level largely insensitive to NP
  $\gamma(^\circ)$= 68.0 [+8.0 -8.5]

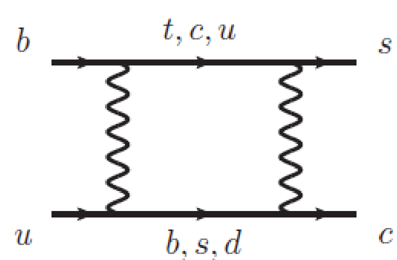
- Loop-level NP sensitive
  $\gamma(^\circ)$= 69.7 [+1.3 -2.8]

- Excellent agreement in the overall picture at the current level of precision
- γ from trees : the precise SM reference required to unravel *increasingly subtle* NP effects

Theoretically pristine

- $B \to DK$ tree-dominated amplitude

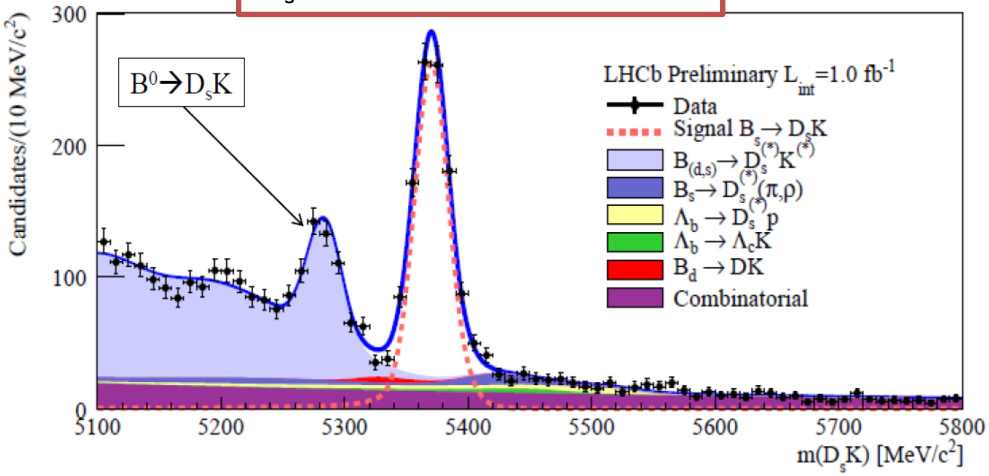
- Negligible theoretical uncertainties
  - Only irreducible ones from higher order electroweak corrections $\delta\gamma < O(10^{-7})$ [Brod & Zupan, arXiv:1308.5663]



$B_s \to D_s^{\mp} K^{\pm}$: analysis ingredients

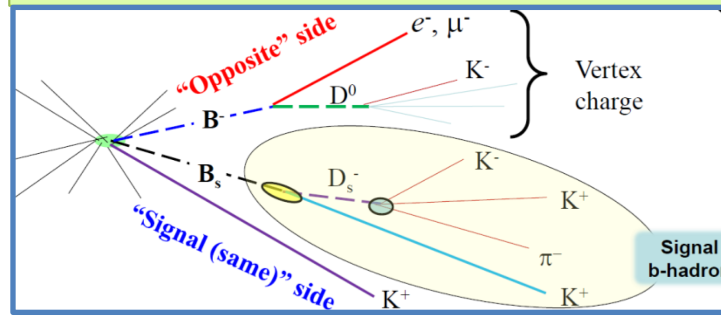
Precision tracking and PID:
for background suppression
***B* mass fit:** statistical separation
of signal from remaining background

$B_s \to D_s K$
$D_s \to KK\pi$ / $\pi\pi\pi$/$K\pi\pi$

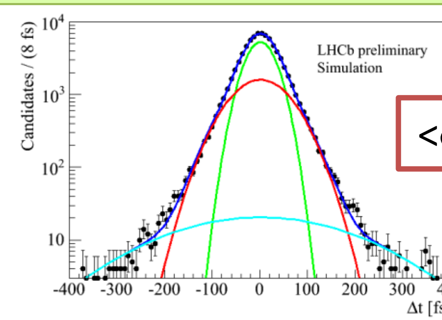


Signal yield = 1390±98

Tagging:
OS only used in this first analysis, εD^2=1.9%



Proper time resolution:
from MC corrected for data/MC differences



$<\sigma_t>$~50 fs

Proper time acceptance:
a,b,n,β from fit to $B_s \to D_s\pi$ data

$$a(t) = \left(1 - \frac{1}{(1+(at)^n - b}\right)(1-\beta t) \qquad t > 0.2\,ps$$