Measurement of the CP violating phase γ at LHCb

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(Nikhef)

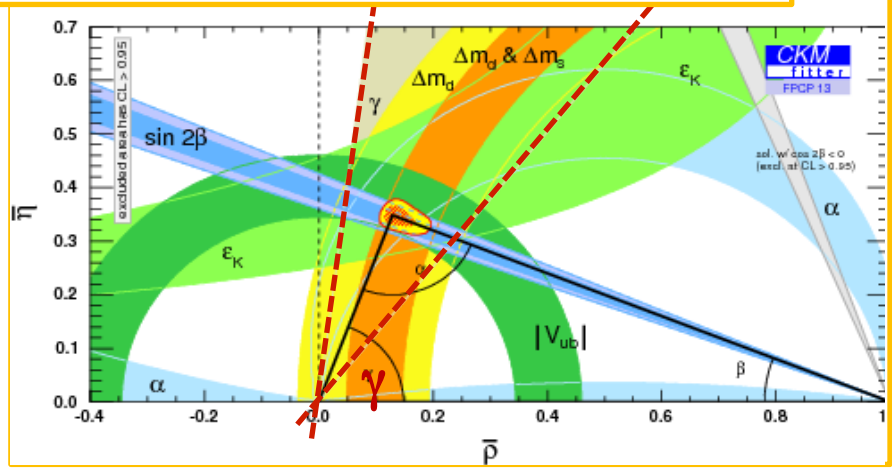
on behalf of the LHCb Collaboration

CP violation

- Mass eigenstates: u, d - well defined mass/lifetime
- Weak interaction between flavour eigenstates: u', d'

CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|\, e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|\, e^{-i\beta} & -|V_{ts}|\, e^{i\beta_s} & |V_{tb}| \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



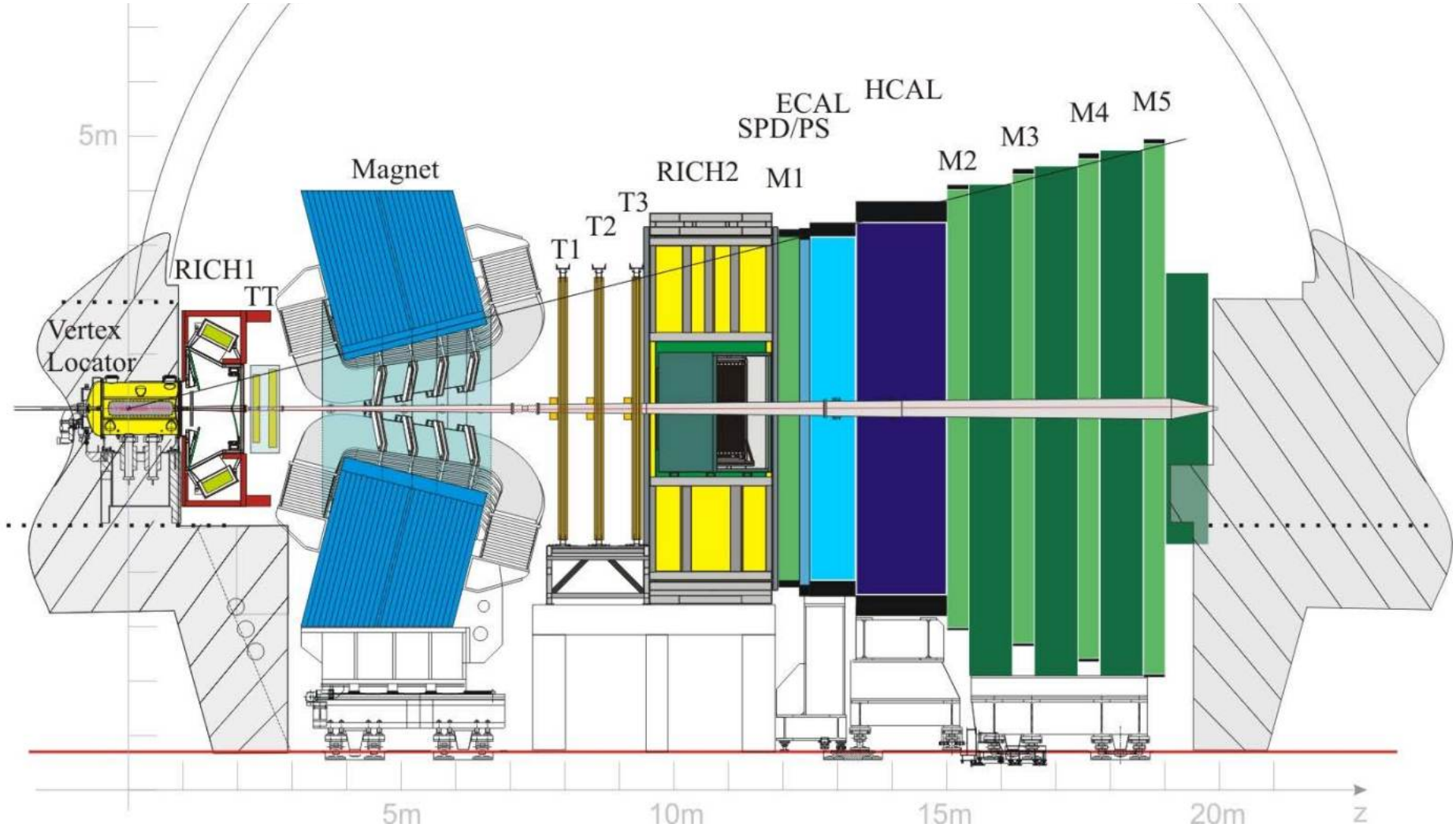
Why?

- γ is the least well known angle
- Test standard model
- Tree decays: no sensitivity new physics

How?

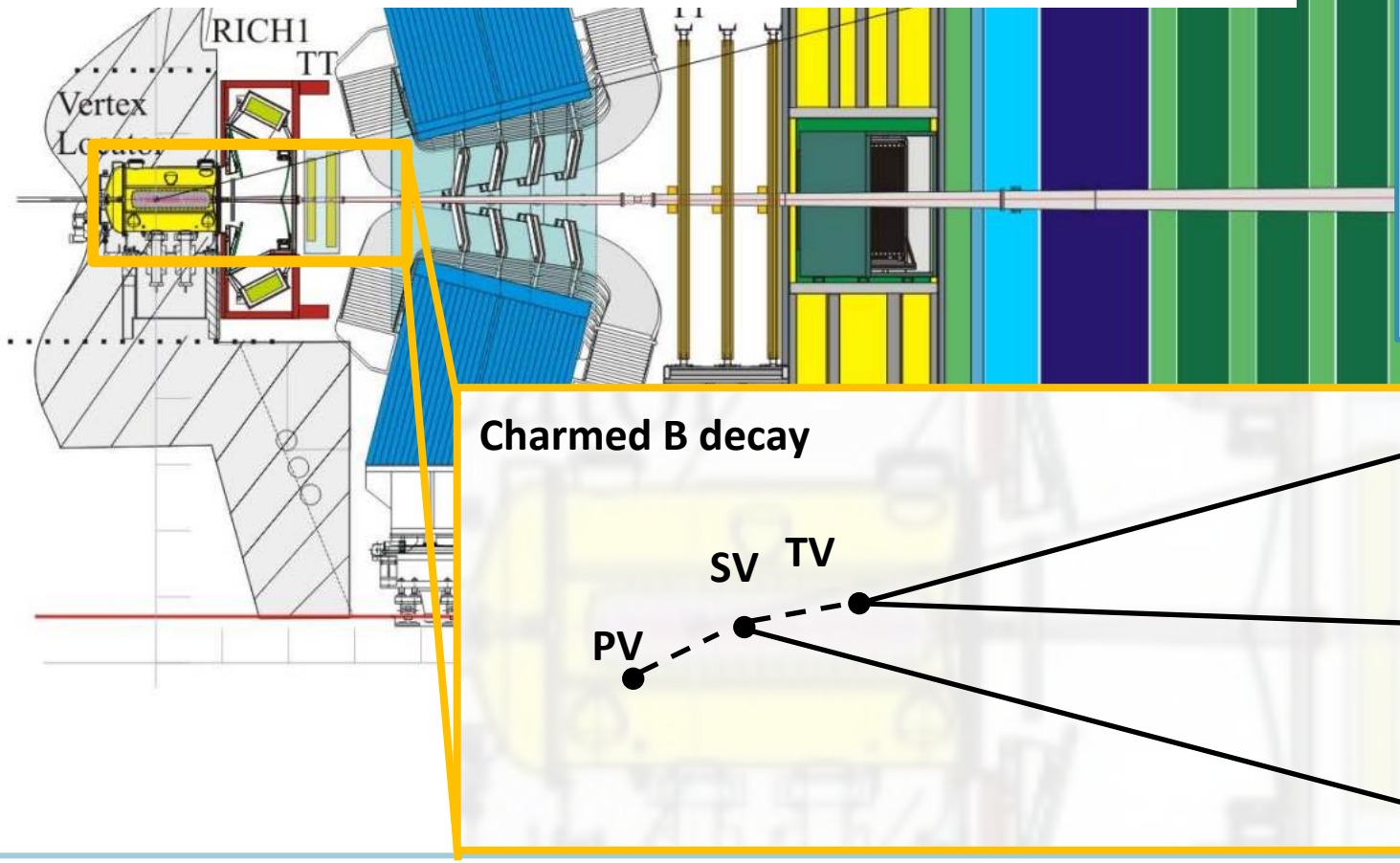
- *Interference* between b → u and b → c transitions
- $A_{ub}/A_{cb} = r_B \approx 1$
- B meson decays

LHCb


5m
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
M1
ECAL
SPD/PS
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z

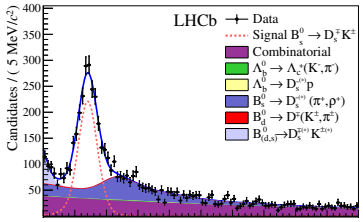
Selection of beauty decays

- Separation between primary and secondary vertex
- PID cuts on tracks
  RICH – pion, kaon identification
- Multivariate analysis, like boosted decision trees



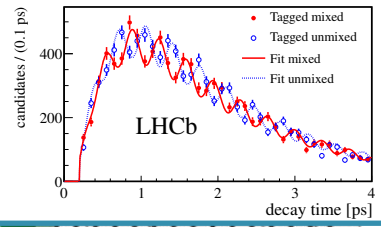
Charmed B decay

Mass resolution
18-25 MeV



[Arxiv:1407.6127]

Time resolution
~45 fs

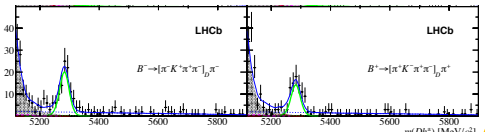


[arXiv:1304.4741]

[LHCb-CONF-2014-004]

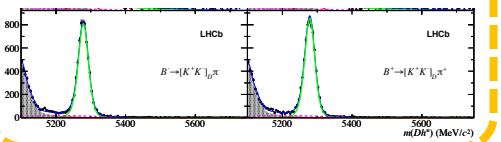
$B^+ \to Dh^+, D \to K\pi\pi\pi$

ADS, 1fb^{-1}



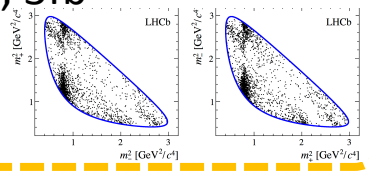
$B^+ \to Dh^+, D \to hh$

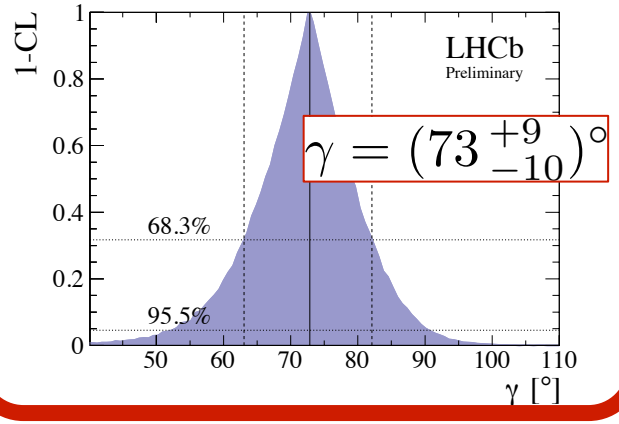
GLW/ADS, 1fb^{-1}



$B^+ \to DK^+, D \to K^0_S hh$

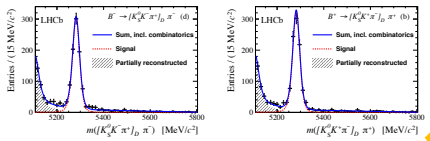
GGSZ, 3fb^{-1}





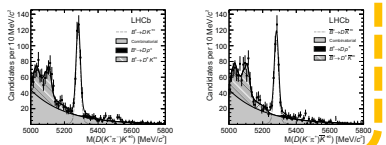
$B^+ \to DK^+, D \to K^0_S K\pi$

GLS, 3fb^{-1}



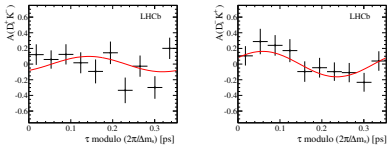
$B^0 \to DK^{*0}, D \to hh$

GLW/ADS, 3fb^{-1}



$B^0_s \to D^\pm_s K^\mp$

Time dependent, 1fb^{-1}

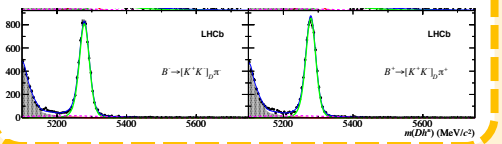


Time – integrated

[LHCb-CONF-2014-004]

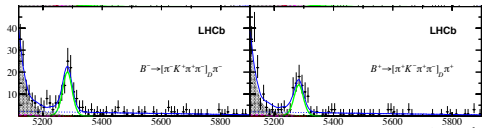
$B^+ \to Dh^+,\ D \to hh$

GLW/ADS, 1fb^{-1}



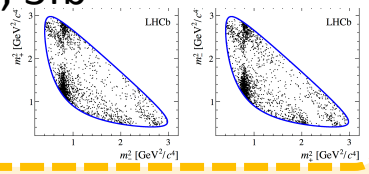
$B^+ \to Dh^+,\ D \to K\pi\pi\pi$

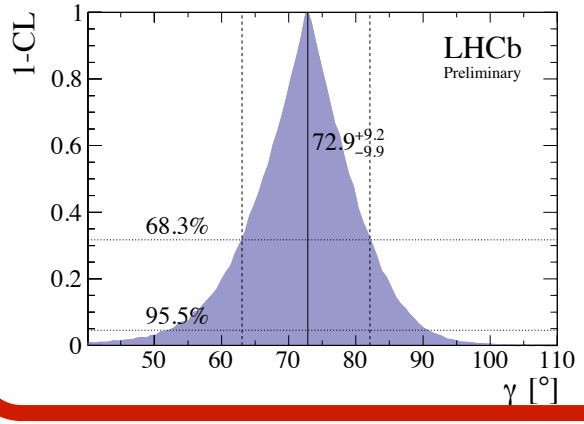
ADS, 1fb^{-1}



$B^+ \to DK^+,\ D \to K^0_S hh$

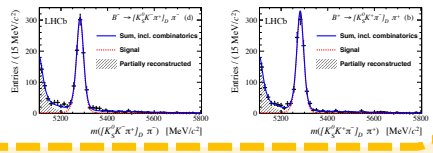
GGSZ, 3fb^{-1}





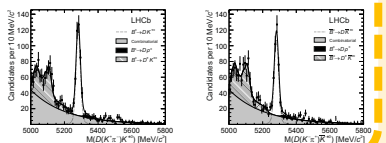
$B^+ \to DK^+,\ D \to K^0_S K\pi$

GLS, 3fb^{-1}



$B^0 \to DK^{*0},\ D \to hh$

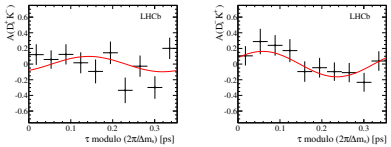
GLW/ADS, 3fb^{-1}



Time – dependent

$B^0_s \to D^\pm_s K^\mp$

Time dependent, 1fb^{-1}

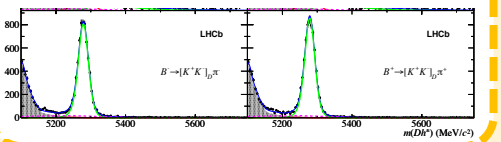


Time – integrated

[LHCb-CONF-2014-004]

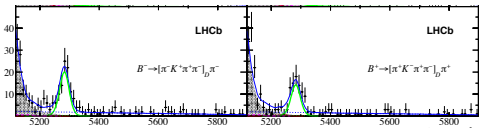
$B^+ \to Dh^+, D \to hh$

GLW/ADS, 1fb^{-1}



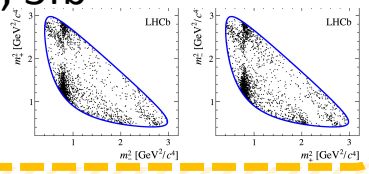
$B^+ \to Dh^+, D \to K\pi\pi\pi$

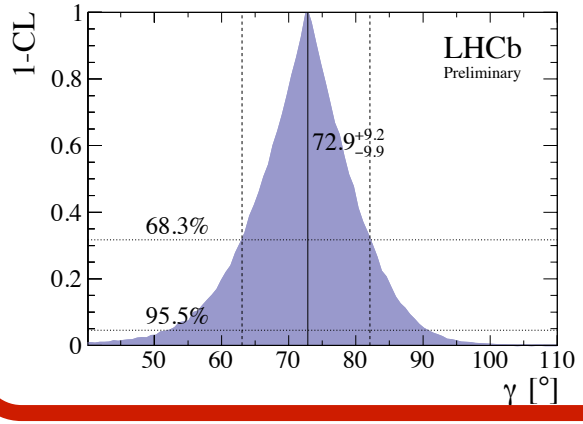
ADS, 1fb^{-1}



$B^+ \to DK^+, D \to K^0_S hh$

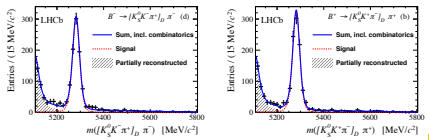
GGSZ, 3fb^{-1}





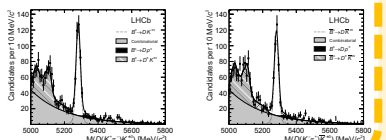
$B^+ \to DK^+, D \to K^0_S K\pi$

GLS, 3fb^{-1}



$B^0 \to DK^{*0}, D \to hh$

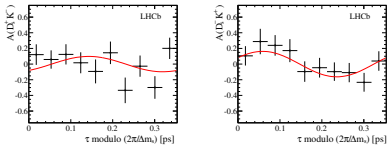
GLW/ADS, 3fb^{-1}



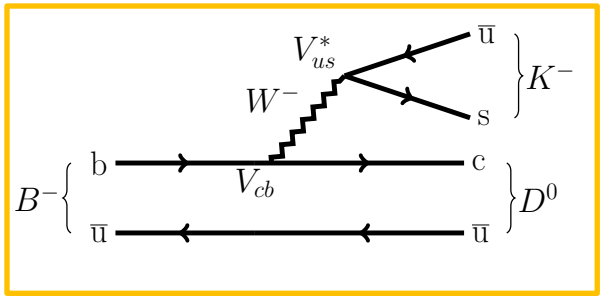
Time – dependent

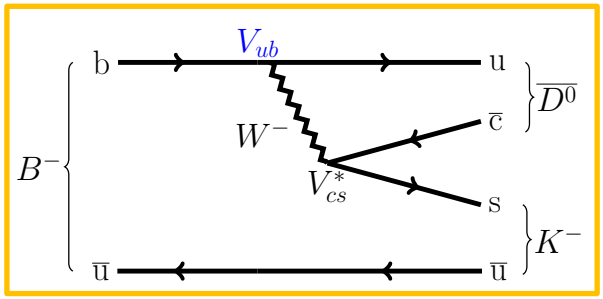
$B^0_s \to D^\pm_s K^\mp$

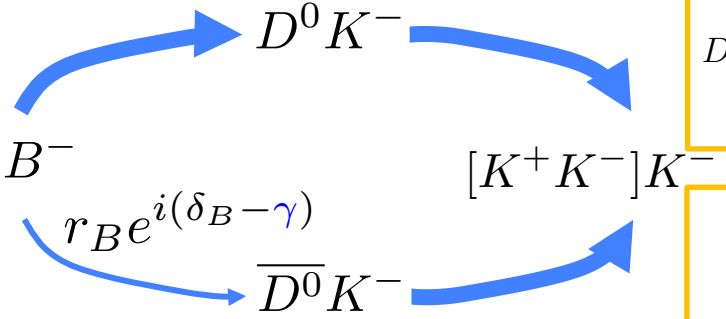
Time dependent, 1fb^{-1}

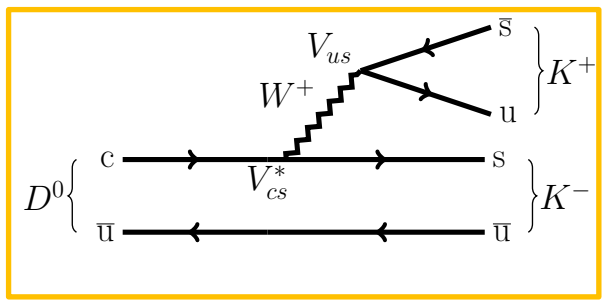


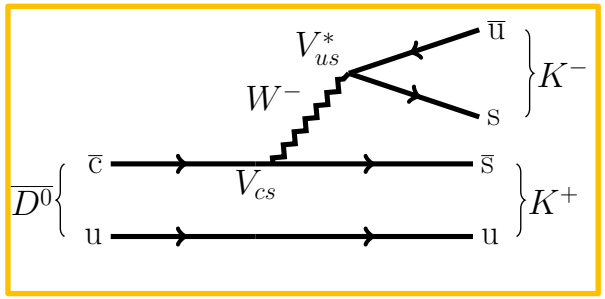
$B^{\pm} \longrightarrow D^0 h^{\pm}$







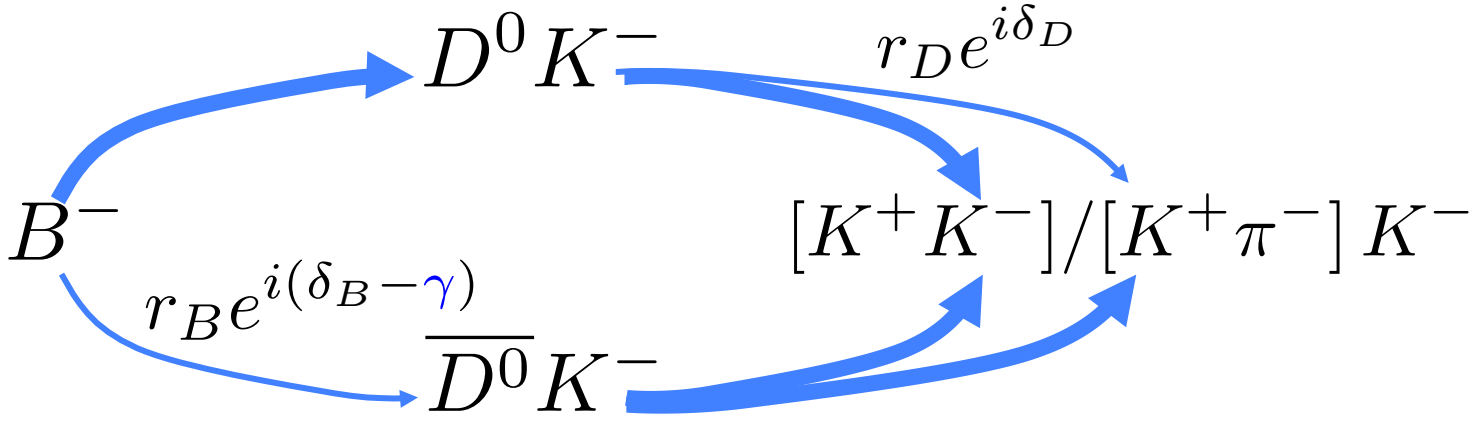




$$A^{DK,f} = \frac{\Gamma(B^- \to [D[\to f]K^-) - \Gamma(B^+ \to [D[\to \bar{f}]K^+)}{\Gamma(B^- \to [D[\to f]K^-) + \Gamma(B^+ \to [D[\to \bar{f}]K^+)}$$

$$R^f_{K/\pi} = \frac{\Gamma(B^- \to [D[\to f]K^-) + \Gamma(B^+ \to [D[\to \bar{f}]K^+)}{\Gamma(B^- \to [D[\to f]\pi^-) + \Gamma(B^+ \to [D[\to \bar{f}]\pi^+)}$$

$B^{\pm} \longrightarrow D^0 h^{\pm}$



$$A^{DK,f} = \frac{\Gamma(B^- \to [D[\to f]K^-) - \Gamma(B^+ \to [D[\to \bar{f}]K^+)}{\Gamma(B^- \to [D[\to f]K^-) + \Gamma(B^+ \to [D[\to \bar{f}]K^+)}$$

$$R^f_{K/\pi} = \frac{\Gamma(B^- \to [D[\to f]K^-) + \Gamma(B^+ \to [D[\to \bar{f}]K^+)}{\Gamma(B^- \to [D[\to f]\pi^-) + \Gamma(B^+ \to [D[\to \bar{f}]\pi^+)}$$

$$R^{DK,f}_{\pm} = \frac{\Gamma(B^{\pm} \to D[\to f_{\rm sup}]K^{\pm})}{\Gamma(B^{\pm} \to D[\to f_{\rm fav}]K^{\pm})}$$

GLW
CP eigenstate: f = KK, ππ
3 eqns, 5 parameters:
$r_B, \delta_B, r_B^\pi, \delta_B^\pi, \gamma$

ADS
common final state: f = Kπ, πK, πKππ
5 eqns, 7 parameters:
$r_B, \delta_B, r_B^\pi, \delta_B^\pi, r_D, \delta_D, \gamma$

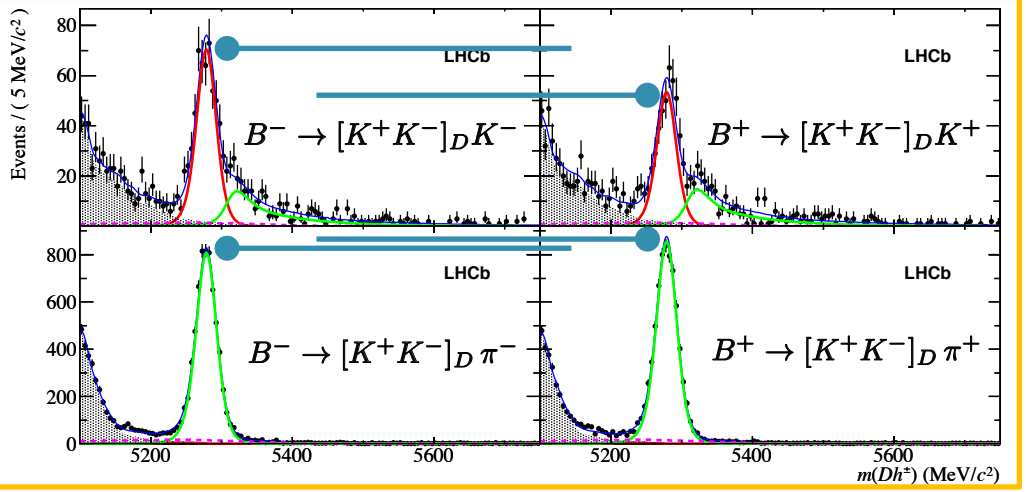
$B^{\pm} \longrightarrow D^0 h^{\pm}$

[PLB 712 (2012) 203-212]

[PLB 723 (2013) 44]

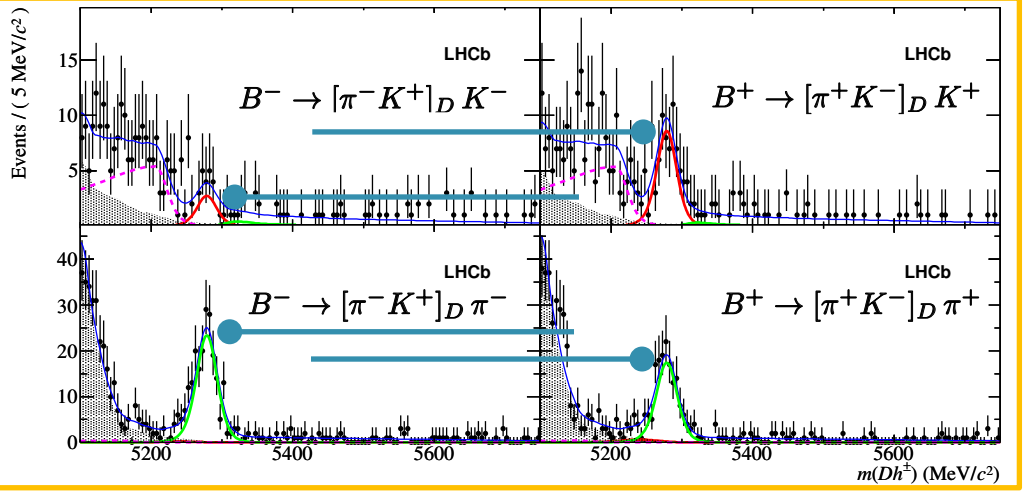
GLW

- f is CP eigenstate: K^+K^-, $\pi^+\pi^-$
- Large event rate, small interference



ADS

- common final state: $K^+\pi^-$, $K^-\pi^+$, $K^{\pm}\pi^{\mp}\pi^+\pi^-$
- Lower event rate, larger interference



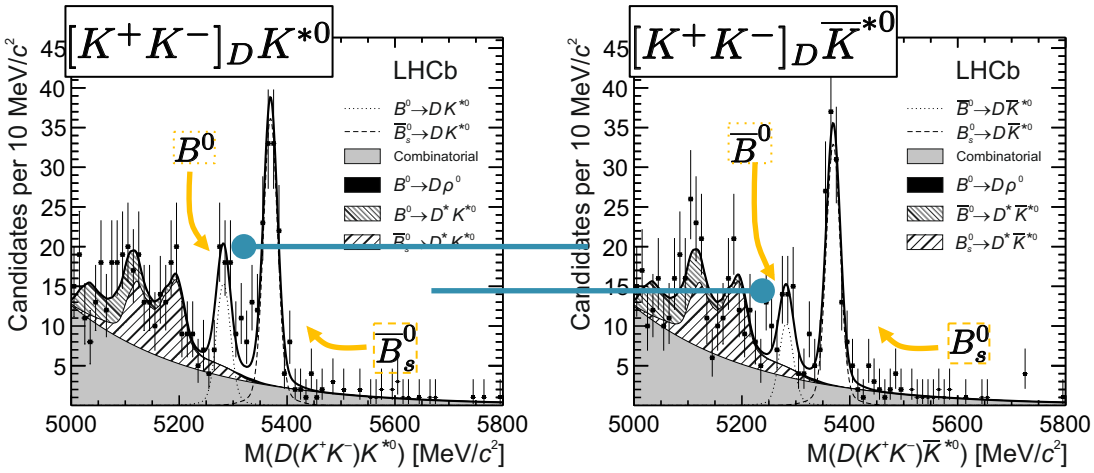
$B^0 \longrightarrow D^0K^{*0}$

[PRD 90 (2014) 112002]

Both $B^0 \longrightarrow DK^{*0}$ decay paths colour suppressed!
Self tagging decay: $K^{*0} \longrightarrow K^+\pi^-$

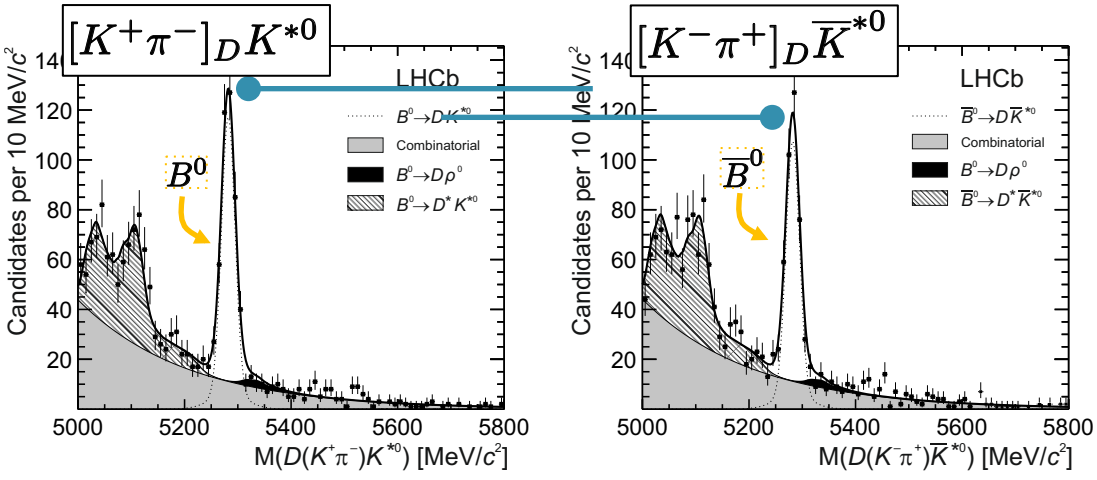
GLW

- *f* is CP eigenstate: K^+K^-, $\pi^+\pi^-$
- *Small* event rate, *large* interference



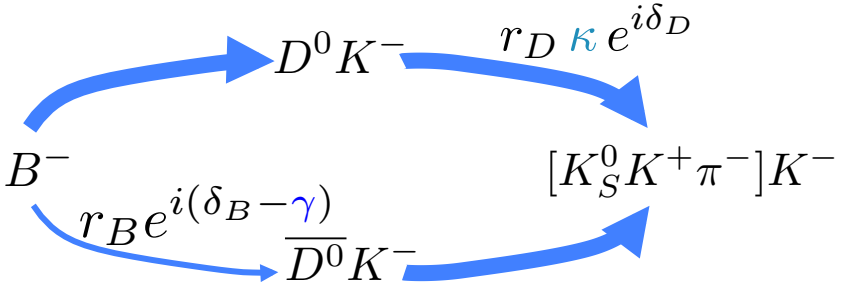
ADS

- common final state: $K^+\pi^-$, $K^-\pi^+$
- *Large* event rate, *small* interference



$B^{\pm} \longrightarrow D^0 h^{\pm}$

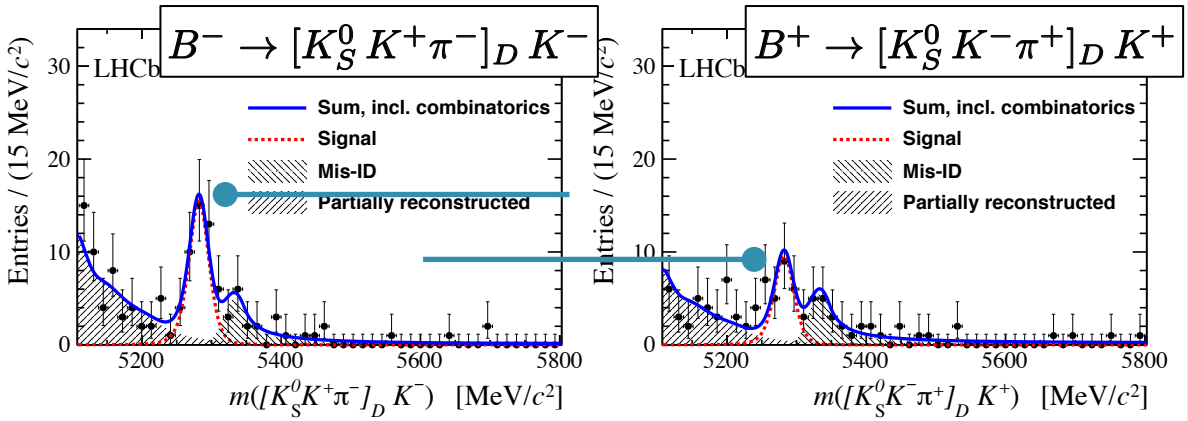
[PLB 733 (2014) 36]



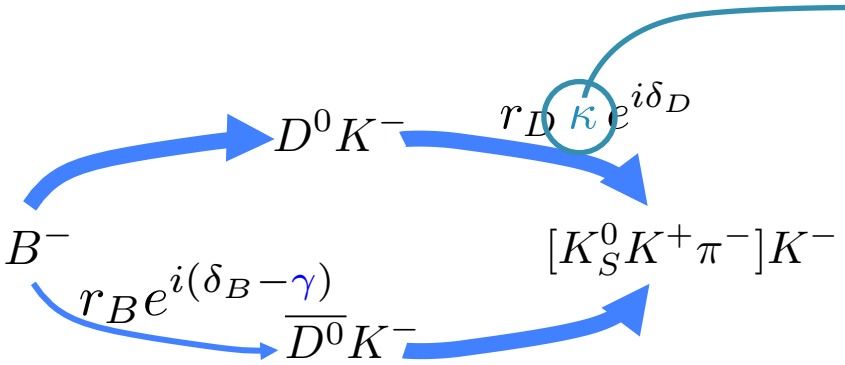
$$R^{D\pi}_{fav/sup} = \frac{\Gamma(B^- \to D[\to f_{\rm fav}]\pi^-) + \Gamma(B^+ \to D[\to f_{\rm fav}]\pi^+)}{\Gamma(B^- \to D[\to f_{\rm sup}]\pi^-) + \Gamma(B^+ \to D[\to f_{\rm sup}]\pi^+)}$$

GLS

- common final state: $K_S{}^0 K^+\pi^-$
- Single cabibbo suppressed D decay
- Large interference

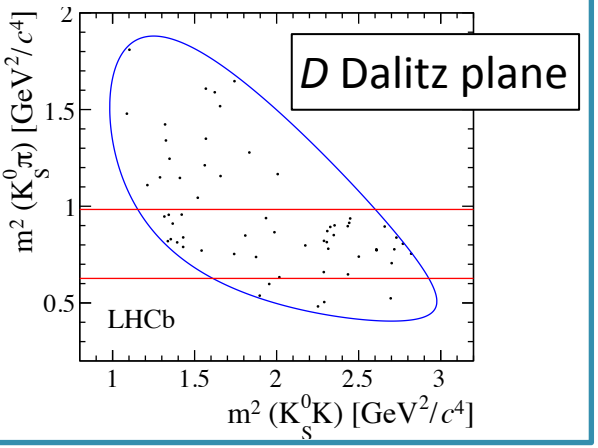


$B^{\pm} \longrightarrow D^0 h^{\pm}$



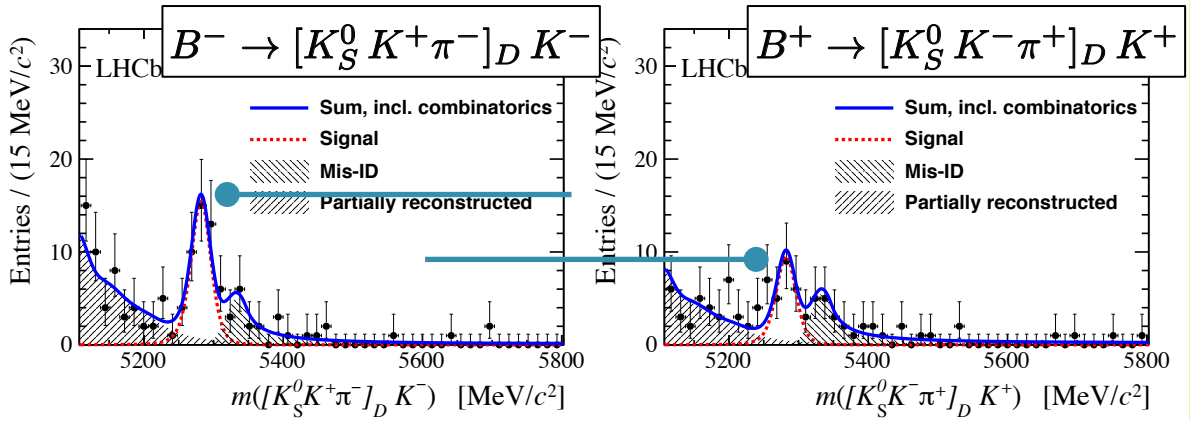
[PLB 733 (2014) 36]

Coherence factor κ takes care of variations of the strong phase in the Dalitz plane due to resonances



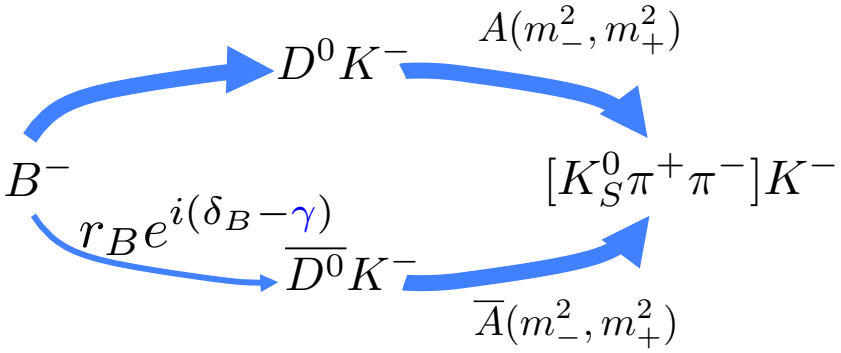
GLS

- common final state: $K_S{}^0K^+\pi^-$
- Single cabibbo suppressed D decay
- Large interference

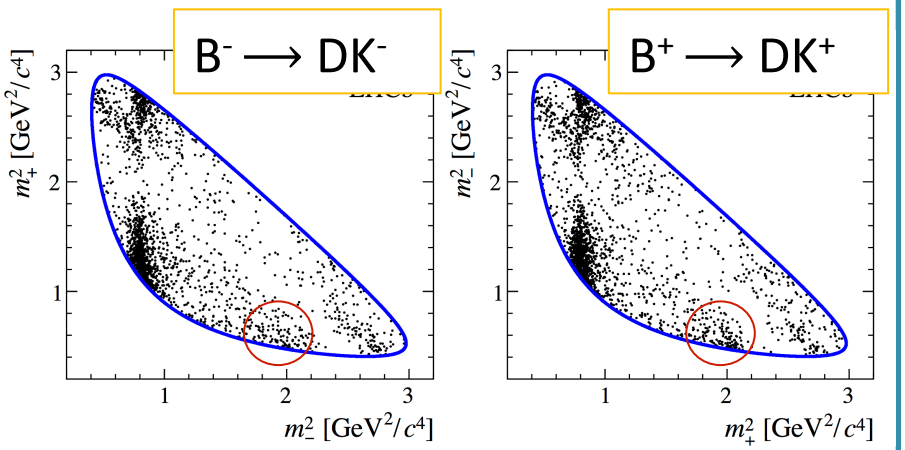


$B^{\pm} \longrightarrow D^0 h^{\pm}$

[JHEP 10 (2014) 097]



D Dalitz plane, $D \to K_S^0 \pi^+ \pi^-$



GGSZ

- common final state: $K_s^0\pi^+\pi^-$, $K_s^0 K^+ K^-$
- Decay amplitude in bins of *Dalitz plane*

$$N_{\pm i}^- = h_{B^-}\left[F_{\pm i} + r_B F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i})\right]$$
$$N_{\pm i}^+ = h_{B^+}\left[F_{\mp i} + r_B F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})\right]$$

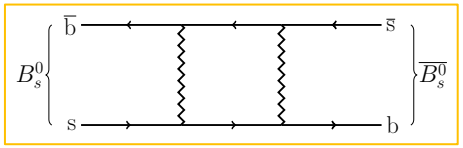
$$x_\pm \equiv r_B \cos(\delta_B \pm \gamma)$$
$$y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$$

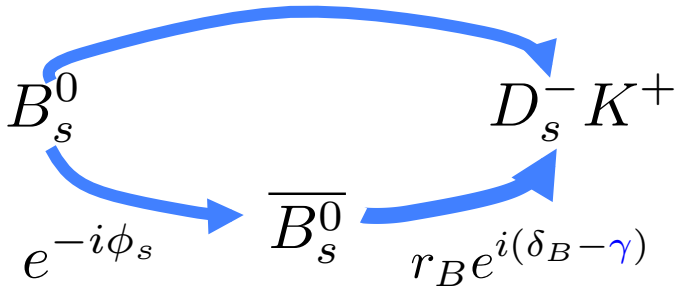
- c, s: average strong phase (CLEO), F: fraction of D decays ($B^0 \to D^{*+}\mu^-\nu X$)

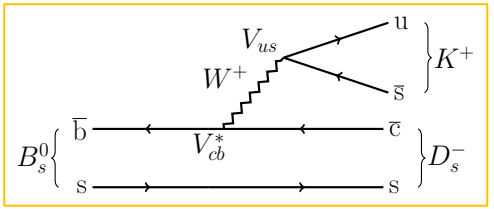
$B_s^0 \longrightarrow D_s K$

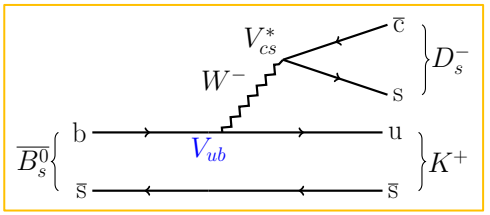
[JHEP 11 (2014) 060]

Interference between mixing and decay





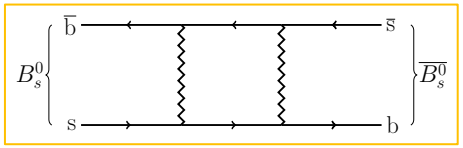




$B_s^0 \longrightarrow D_s K$

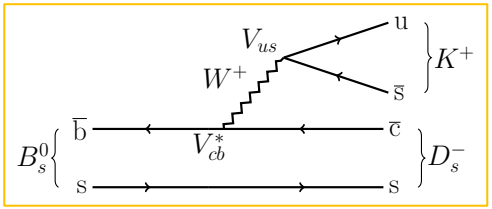
[JHEP 11 (2014) 060]

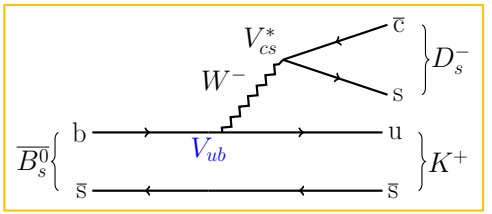
Interference between mixing and decay



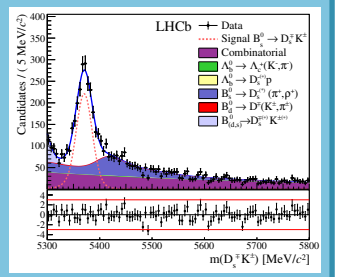
$$B_s^0 \longrightarrow D_s^- K^+$$

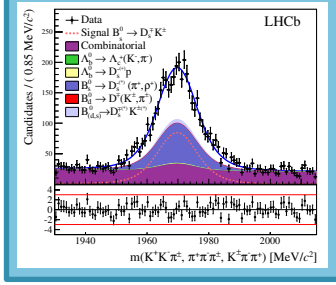
$$e^{-i\phi_s} \qquad \overline{B_s^0} \qquad r_B e^{i(\delta_B - \gamma)}$$

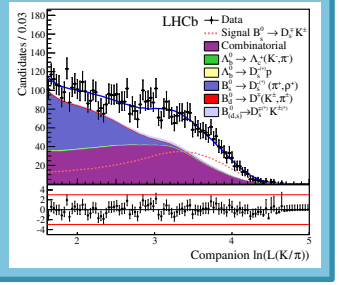




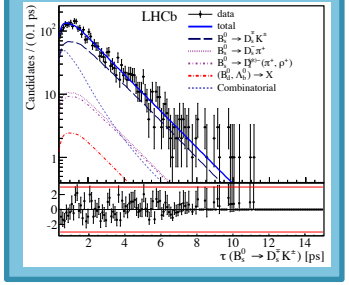
Multivariate mass fit





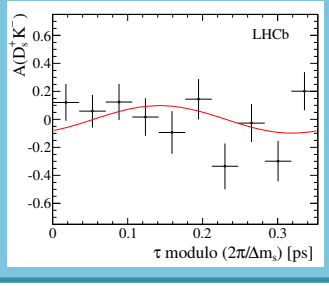


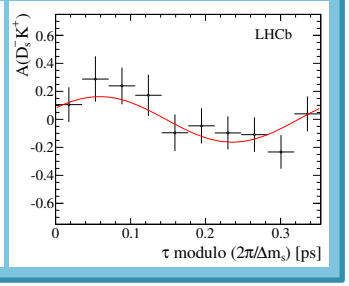
Decay time fit



$$\Gamma_f(t) \simeq e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t)\right]$$

Extract γ from CP vars





Combination

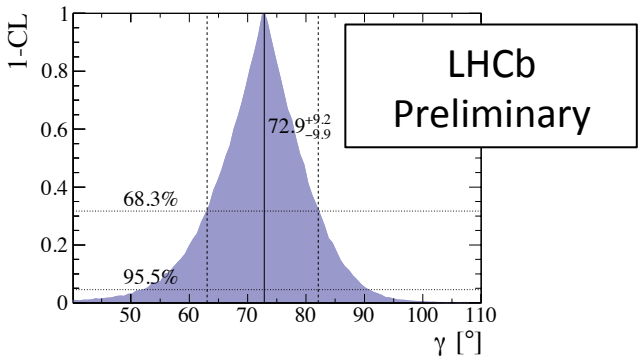
$B^+ \to Dh^+,\ D \to K\pi\pi\pi$

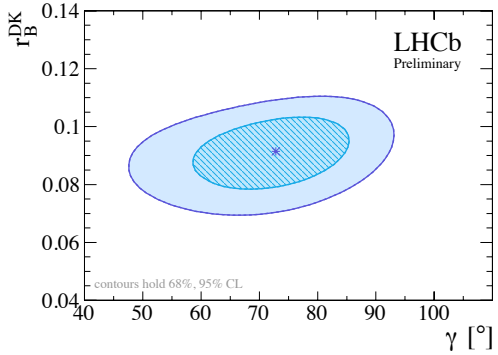
[LHCb-CONF-2014-004]

Robust combination

- Uses only decays with bachelor kaon

$$\gamma = (73\,^{+9}_{-10})^\circ$$

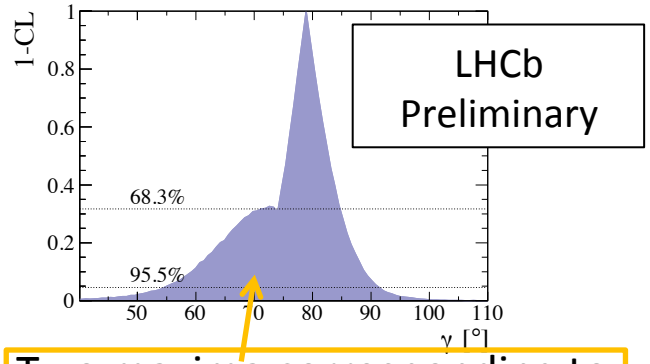




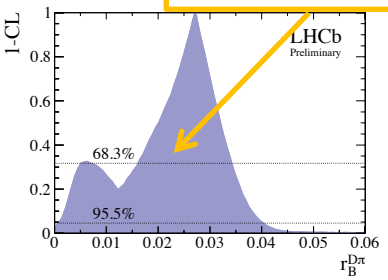
Full combination

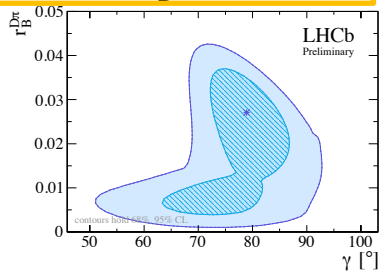
- Uses also $B^- \longrightarrow D\pi^-$

$$\gamma = (79\,^{+6}_{-7})^\circ$$



Two maxima corresponding to the two maxima in r_B^{π}





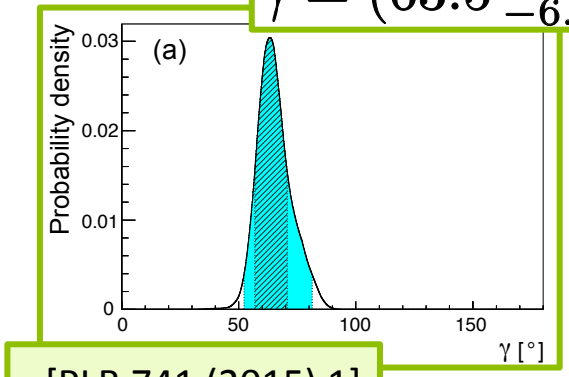
Conclusion

- Most precise measurement of γ using tree decays:
  - 30% improvement compared to pre-LHCb!

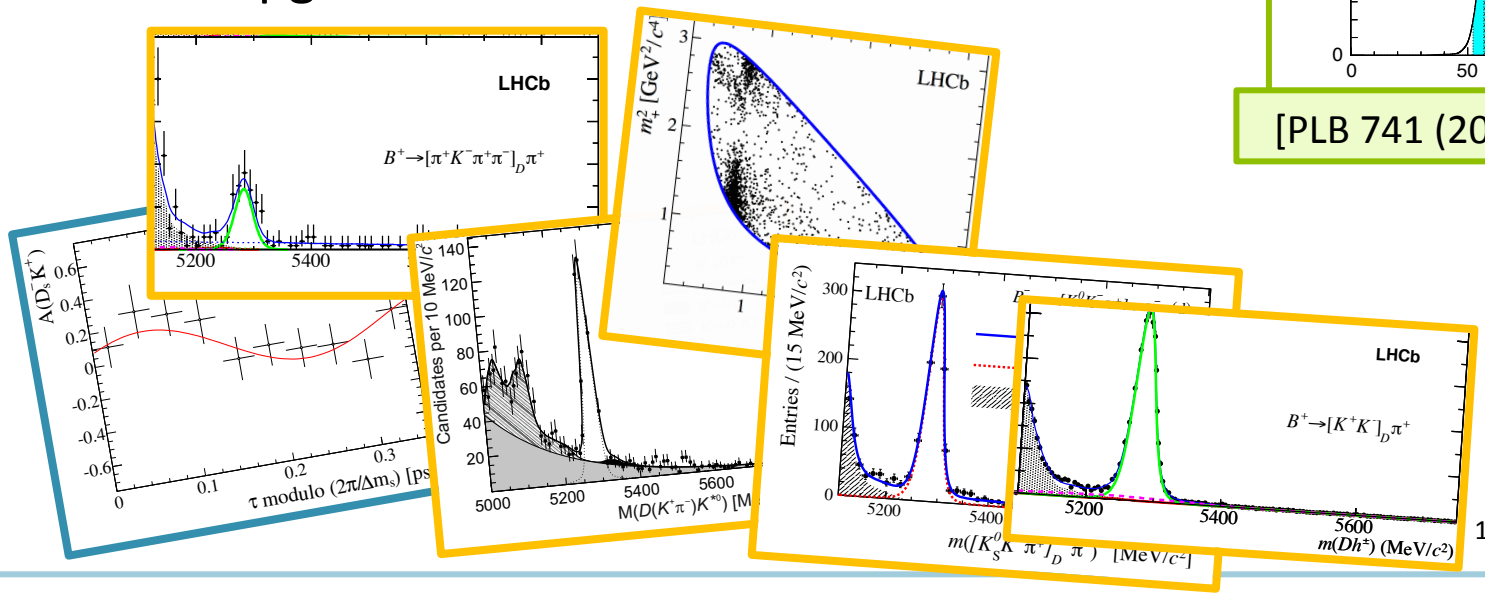
$$\gamma = (73\,^{+9}_{-10})^\circ$$

- Compare to γ measurement with B→hh decays (loop diagrams)
  - $\gamma = (73\,^{+9}_{-10})^\circ$ versus $\gamma = (63.5\,^{+7.2}_{-6.7})^\circ$
  - Need better precision to find new physics
- Expected sensitivity[1]
  - Run II: 4-11°
  - Upgrade: 1°

$$\gamma = (63.5\,^{+7.2}_{-6.7})^\circ$$



[PLB 741 (2015) 1]



[1][CERN-LHCC-2012-007]

Thank you!

γ results

[JHEP 10 (2014) 097]

GGSZ

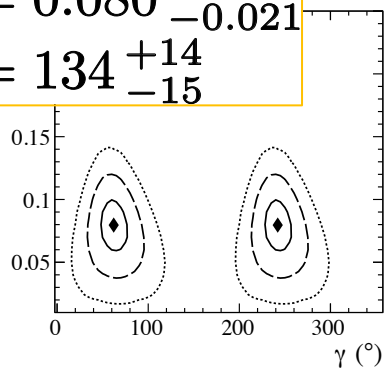
$B^{\pm} \to DK^{\pm}$

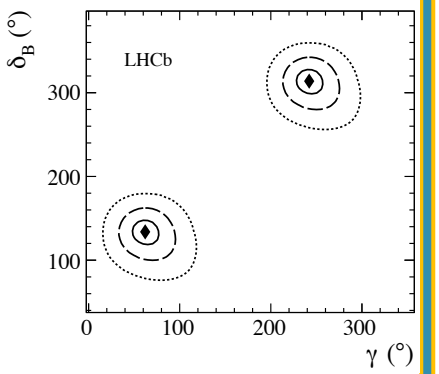
$D \to K^0_S h^{\pm} h^{\mp}$

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

$r_B^K = 0.080^{+0.019}_{-0.021}$

$\delta_B^K = 134^{+14}_{-15}$





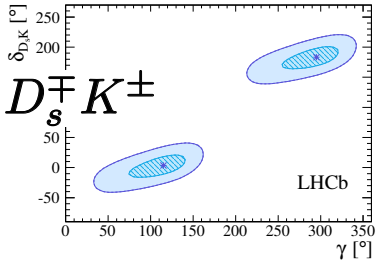
[JHEP 11 (2014) 060]

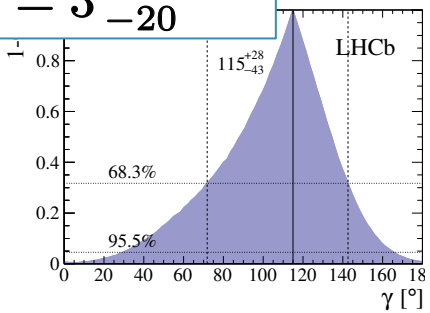
$B^0_s \to D^{\mp}_s K^{\pm}$

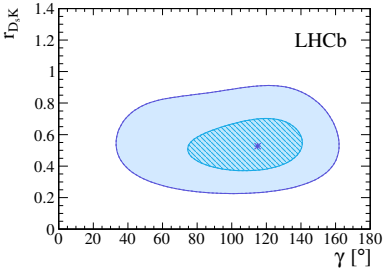
$\gamma = 115^{+28}_{-43}$

$r_{B_s}^{D_s K} = 0.53^{+0.17}_{-0.16}$

$\delta_{B_s}^{D_s K} = 3^{+19}_{-20}$





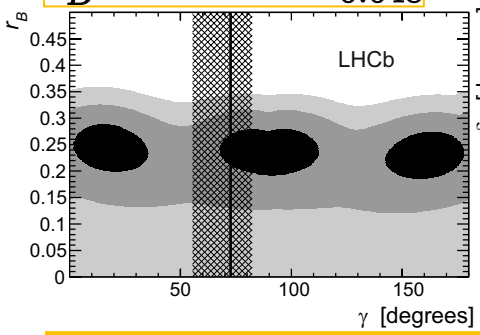


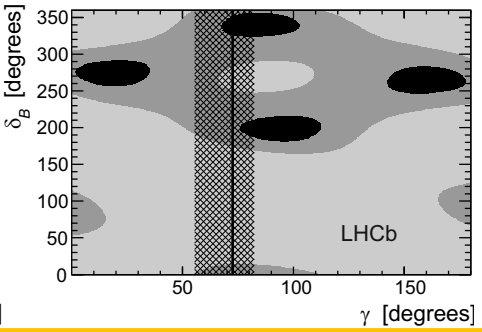
[PRD 90 (2014) 112002]

ADS/GLW

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

$r_{B^0}^{K^{*0}} = 0.240^{+0.055}_{-0.048}$



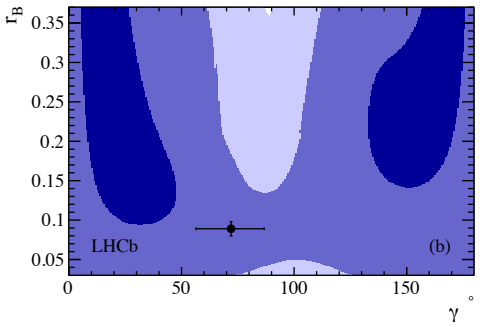


[PLB 733 (2014) 36]

GLS

$B^{\pm} \to DK^{\pm}$

$D \to K^0_S K^{\pm} \pi^{\mp}$



[PLB 712 (2012) 203-212]

ADS/GLW

[PLB 723 (2013) 44]

ADS $r_B^K = 0.097^{+0.011}_{-0.011}$

Formalism

	GLW	ADS
$A^{DK,f}$	$\frac{2\,r_B \sin\delta_B \sin\gamma}{1+{r_B}^2+2\,r_B\cos\delta_B\cos\gamma}$	$\frac{2\,r_B r_D \sin(\delta_B-\delta_D)\sin\gamma}{1+(r_B r_D)^2+2\,r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}$
$R^f_{K/\pi}$	$R_{\rm cab}\,\frac{1+(r_B)^2+2\,r_B\cos\delta_B\cos\gamma}{1+(r^\pi_B)^2+2\,r^\pi_B\cos\delta^\pi_B\cos\gamma}$	$R_{\rm cab}\,\frac{1+(r_B r_D)^2+2\,r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}{1+(r^\pi_B r_D)^2+2\,r^\pi_B r_D\cos(\delta^\pi_B-\delta_D)\cos\gamma}$
$R^{DK,f}_{\pm}$		$\frac{{r_B}^2+{r_D}^2+2\,r_B r_D\cos(\delta_B+\delta_D\pm\gamma)}{1+(r_B r_D)^2+2\,r_B r_D\cos(\delta_B-\delta_D\pm\gamma)}$

GLS

$$R^{D\pi}_{\rm fav/sup} = \frac{1+(r^\pi_B r_D)^2+2r^\pi_B r_D\kappa\cos(\delta_B-\delta_D)\cos\gamma}{(r^\pi_B)^2+{r_D}^2+2r^\pi_B r_D\kappa\cos(\delta_B+\delta_D)\cos\gamma}$$