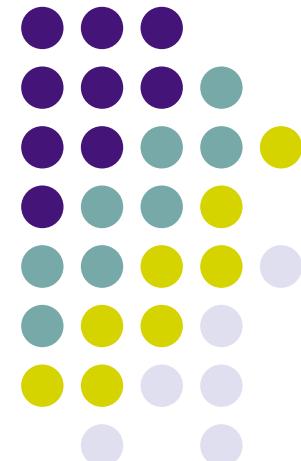


# Prospects for $\gamma$ at LHCb

Val Gibson  
(University of Cambridge)

On behalf of the LHCb collaboration



Physics at the LHC  
Split, October 3<sup>rd</sup> 2008

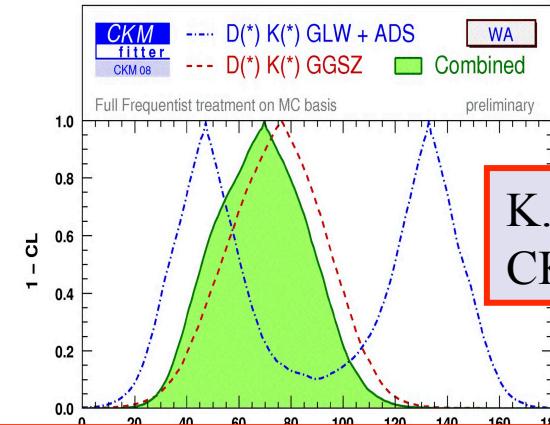


UNIVERSITY OF  
CAMBRIDGE

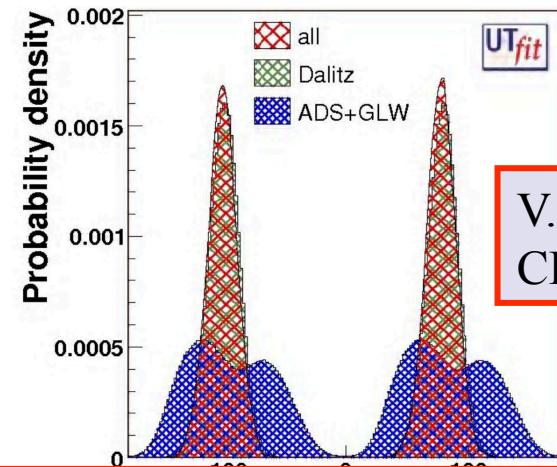
# Introduction



- $\gamma$  plays a unique role in flavour physics
  - Can be measured via both tree processes and those involving loops.
- Trees
  - Benchmark Standard Model reference point
- Loops
  - Sensitive to New Physics
- Very impressive measurements from the B factories
- To fully test SM and unitarity need
  - $\sigma_\gamma \sim$  few degrees precision
  - measurements in  $B^\pm$ ,  $B^0$  and  $B_s$  systems



$$\gamma = (70^{+27}_{-29})^\circ, [2\sigma] = (29^\circ, 113^\circ)$$

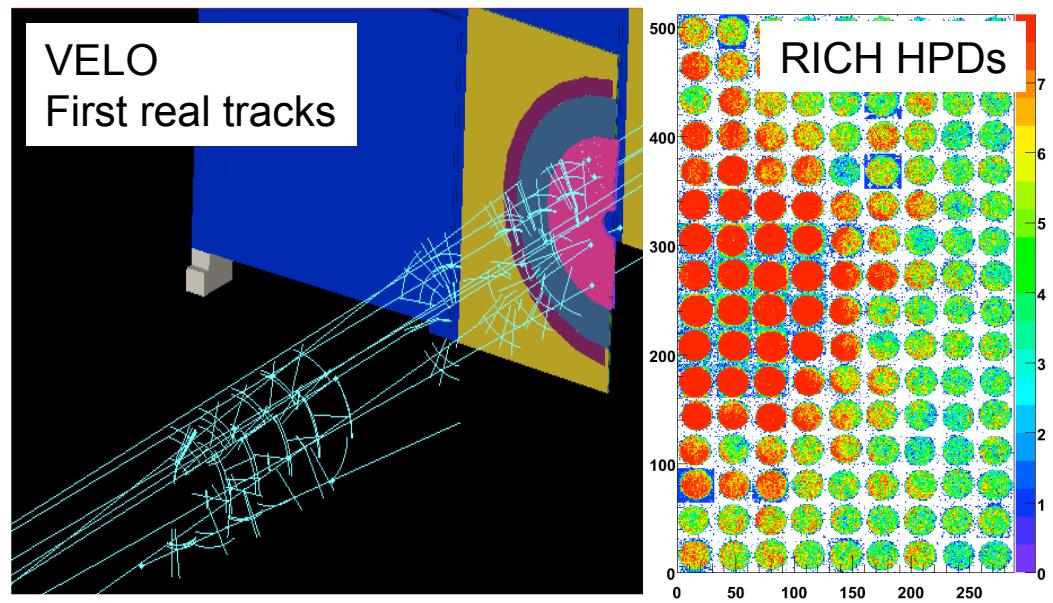
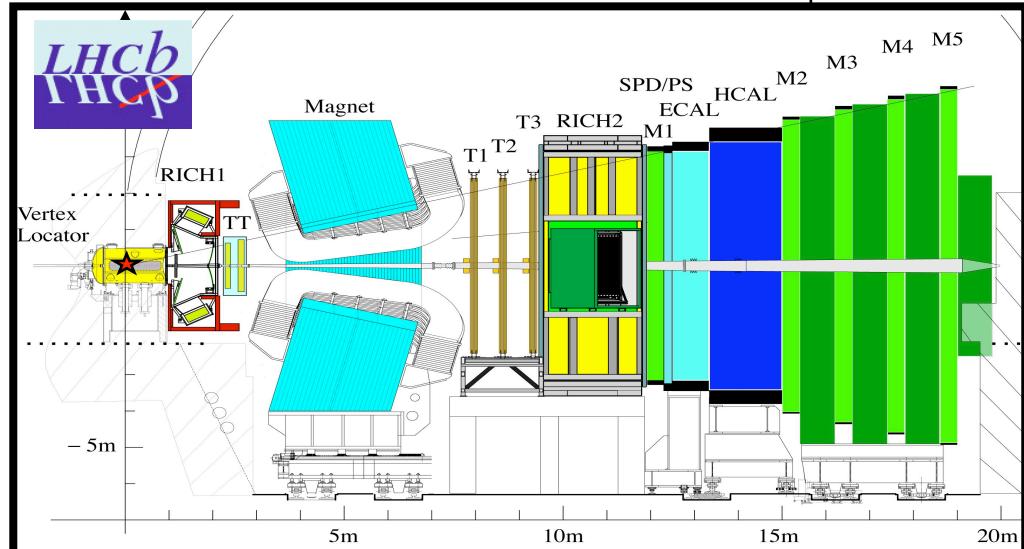


$$\gamma = (78 \pm 12)^\circ, [2\sigma] = (54^\circ, 100^\circ)$$

# LHCb



- High statistics
  - $\sigma_{b\bar{b}} \sim 500 \mu\text{b}$  at 14 TeV
  - $\mathcal{L} \sim 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
  - $10^{12} b\bar{b}$  per  $2 \text{ fb}^{-1}$  (1 year)
  - All B species ( $B^\pm, B^0, B_s, B_c, \Lambda_b \dots$ )
  
- Excellent tracking system
  - VELO and tracking detectors
  - Mass resolution,  $\sigma_{B(D)} \sim 15 (7) \text{ MeV}$
  - $B$  vertex resolution,  $\sigma_z \sim 200 \mu\text{m}$
  - Proper time resolution,  $\sigma_\tau \sim 40 \text{ fs}$
  
- Excellent particle identification
  - 2 RICH detectors
  - $\pi/K$  separation over  $p \sim 2\text{--}100 \text{ GeV}$
  
- Trigger
  - High  $p_T$  hadron trigger at L0



Prospects for gamma at LHCb

# $\gamma$ with trees

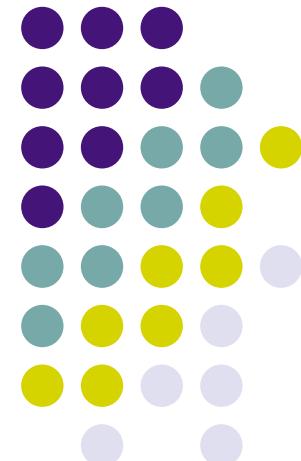
## $B \rightarrow DK$ Strategies

Time integrated analyses, no tagging, based on:

“ADS”: Atwood, Dunietz, Soni; Phys. Rev. Lett. 78 (1997) 3257;  
Phys Rev. D63 (2001) 036005.

“GLW”: Gronau, London, Wyler; Phys. Lett. B253 (1991) 483;  
Phys. Lett. B265 (1991)172.

“Dalitz” or “GGSZ”: Giri, Grossman, Soffer, Zupan, Phys. Rev. D68 054018 (2003)



# $B \rightarrow DK$ Strategies



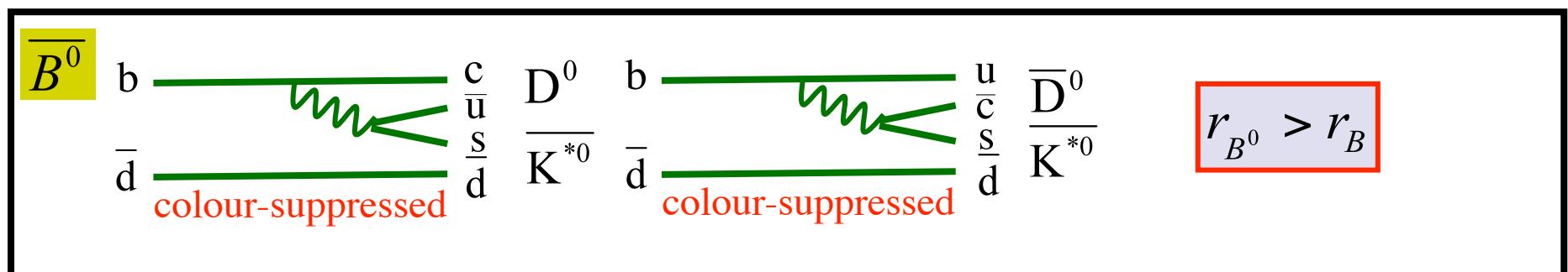
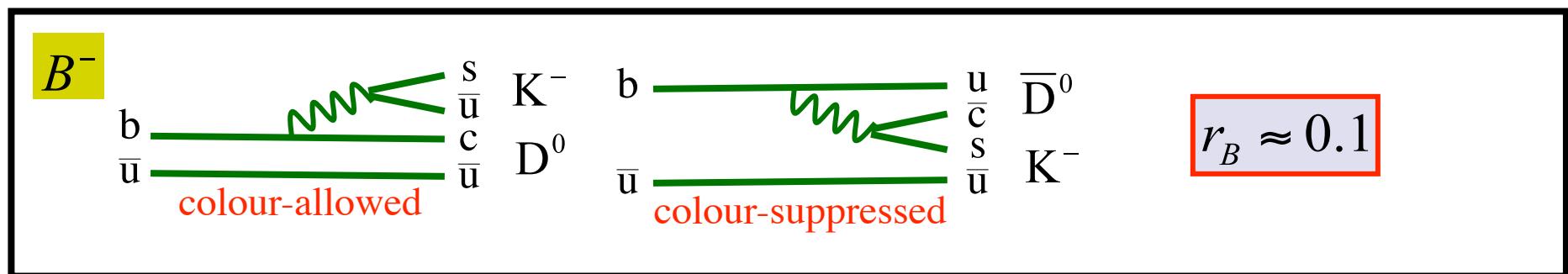
- Measure  $\gamma$  through interference in  $B \rightarrow (D^0/\overline{D}{}^0)K$  decays
- Provided  $D^0$  and  $\overline{D}{}^0$  decay to common final state
- Common parameters

CKM angle  $\gamma$

Amplitude ratio,  $r_B$

Strong phase difference,  $\delta_B$

$$\frac{\langle B \rightarrow \overline{D}{}^0 K \rangle}{\langle B \rightarrow D^0 K \rangle} = r_B e^{i(\delta_B - \gamma)}$$



# $B^\pm \rightarrow D(hh)K^\pm$ (ADS+GLW)

LHCb-2008-011  
LHCb-2008-031



- 6 rates, 5 parameters

$$\gamma = 60^\circ$$

$$r_B = 0.10$$

$$\delta_B = 130^\circ \text{ (PDG)}$$

D decay parameters:

$$r_{K\pi} = 0.0616 \text{ (PDG)}$$

$$\delta_{K\pi} = -158^\circ$$

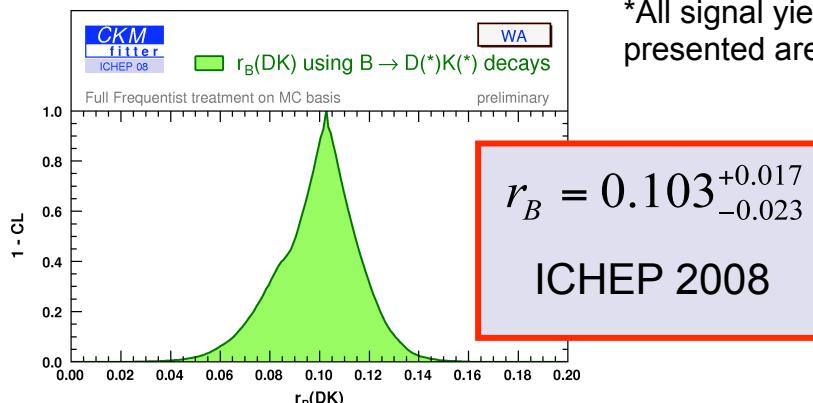
(ADS formalism requires  $-180^\circ$  phase shift w.r.t published result below)

- Constraints

$$\delta_{K\pi} = (22^{+11+9}_{-12-11})^\circ \text{ from CLEO-c}$$

PRL 100(2008) 221801

Mode	Sig. Yield*	B/S
$B^+ \rightarrow D(K\pi)K^+$ (fav.)	28k	0.6
$B^+ \rightarrow D(K\pi)K^+$ (sup.)	650	1.2
$B^+ \rightarrow D(KK)K^+$	3k	1.2
$B^+ \rightarrow D(\pi\pi)K^+$	1k	3.6



\*All signal yields presented are for  $2 \text{ fb}^{-1}$

Sensitivity $2 \text{ fb}^{-1}$					
$\delta_{K\pi} (\circ)$	-190	-174	-158	-144	-130
$\sigma_\gamma (\circ)$	12.7	10.8	13.8	12.6	10.8

# $B^0 \rightarrow D(hh)K^{*0}$ (ADS+GLW)

LHCb-2007-050  
LHCb-2008-031



- 6 rates, 5 parameters

$$\gamma = 60^\circ$$

$$r_{B^0} = 0.40$$

$$\delta_{B^0} \text{ (scan)}$$

D decay parameters:

$$r_{K\pi} = 0.0616 \text{ (PDG)}$$

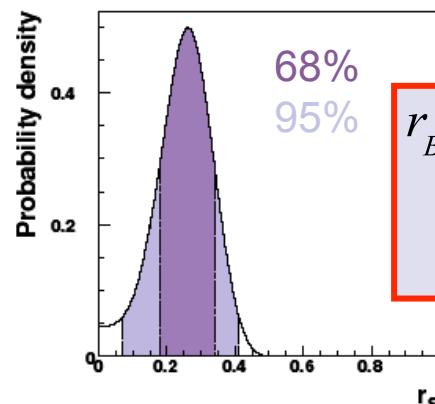
$$\delta_{K\pi} = -158^\circ$$

(ADS formalism requires  $-180^\circ$  phase shift w.r.t published result below)

- Constraints

$\delta_{K\pi} = (22^{+11+9}_{-12-11})^\circ$  from CLEO-c  
PRL 100(2008) 221801

Mode	Sig. Yield	B/S
$B^0 \rightarrow D(K\pi)K^{*0}$ (fav.)	3.4k	[0.4,2.0]
$B^0 \rightarrow D(K\pi)K^{*0}$ (sup.)	O(500)	[2.0,13.0]
$B^0 \rightarrow D(KK)K^{*0}$	O(500)	[0,0.4]
$B^0 \rightarrow D(\pi\pi)K^{*0}$	O(100)	[0,14.0]



$r_{B^0} = [0.18, 0.34] @ 68\% \text{ c.l.}$   
 $= [0.07, 0.41] @ 95\% \text{ c.l.}$   
 ICHEP 2008

Sensitivity 2 fb <sup>-1</sup>					
$\delta_{B^0} (\circ)$	0	45	90	135	180
$\sigma_\gamma (\circ)$	6.2	10.8	12.7	9.5	5.2

# $B^\pm \rightarrow D(K3\pi)K^\pm$ (ADS)

LHCb-2007-004  
LHCb-2008-031



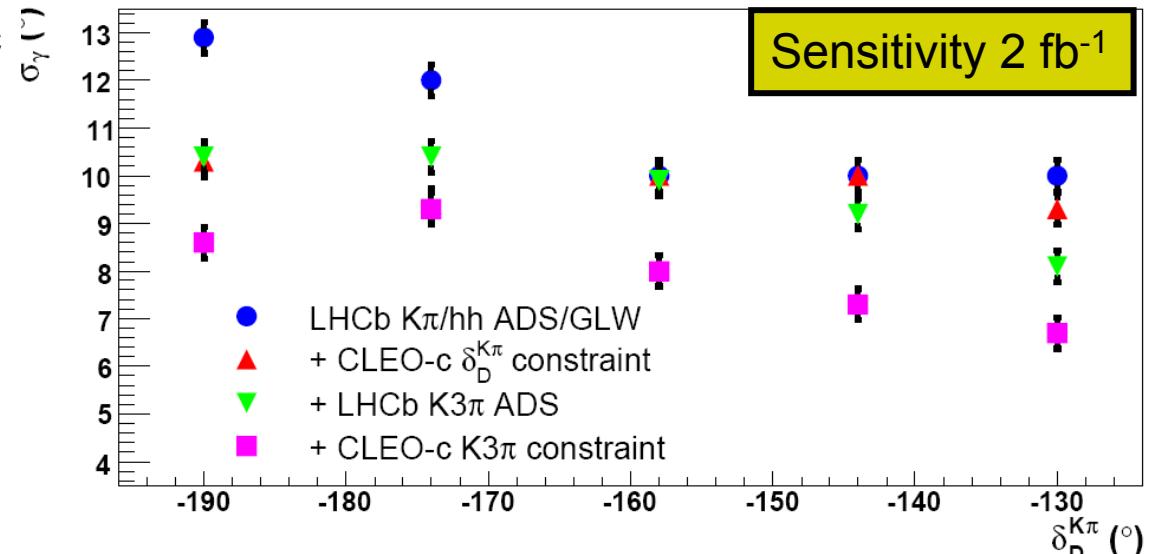
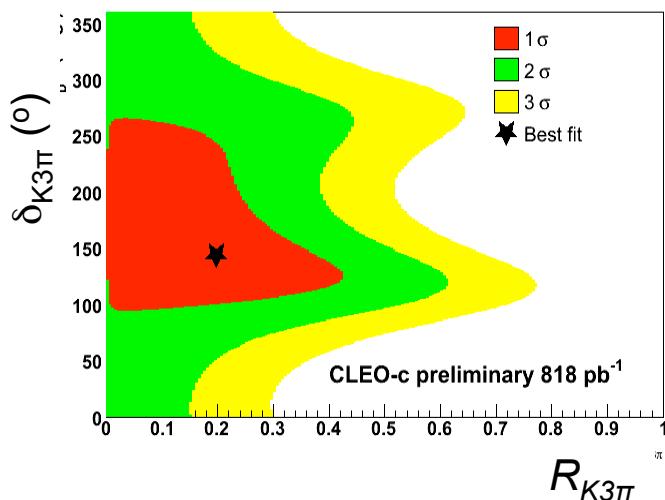
- $\text{Br}(D \rightarrow K3\pi) = 8.1\%$  c.f.  $\text{Br}(D \rightarrow K\pi) = 3.89\%$
- 4 rates, multi-body final state
  - Integrate over ALL phase space
  - “*Coherence factor*”  $R_{K3\pi}$
- $r_{K3\pi} = 0.0568$  (PDG)

$$\Gamma[B^- \rightarrow D(K^+\pi^-\pi^+\pi^-)K^-] \propto r_B^2 + r_{K3\pi}^2 + 2r_B r_{K3\pi} R_{K3\pi} \cos(\delta_B + \delta_{K3\pi} - \gamma)$$

Atwood and Soni, PRD 68 033003(2003)

- Sensitivity to  $r_B$  even if  $R_{K3\pi}=0$  (incoherent)
- Constraints

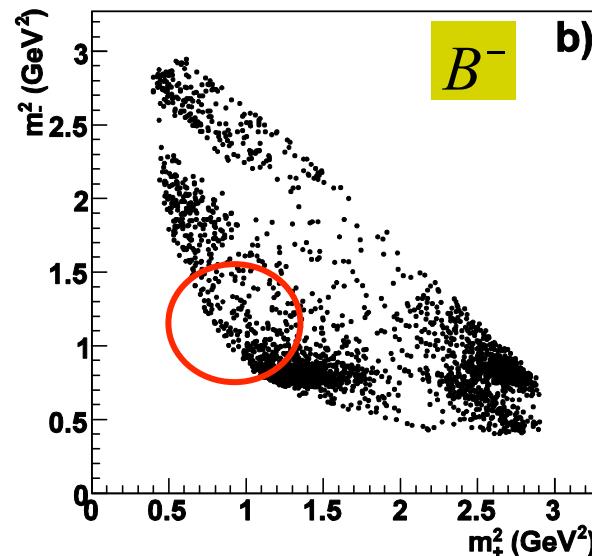
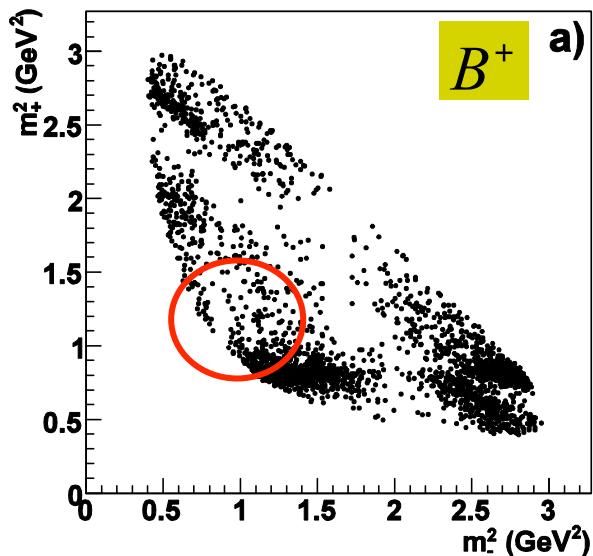
Prelim: arXiv:0805.1722 CLEO-c



# $B^\pm \rightarrow D(K_s \pi^+ \pi^-) K^\pm$ (“Dalitz”)



- $K_s \pi^+ \pi^-$  Dalitz plots contain a CP-violating contribution from the decay path interference which is sensitive to  $\gamma$ .



LHCb 2 fb $^{-1}$

- Two analysis methods:
  - Unbinned fit based on amplitude model
  - Model independent binned fit using results from  $\Psi(3770)$  on D decays

Giri et. al., PRD 68 (2003) 054018;

Bondar and Poluektov, EPJ C47 (2006) 347; hep-ph/0703267; arXiv:0801.0840

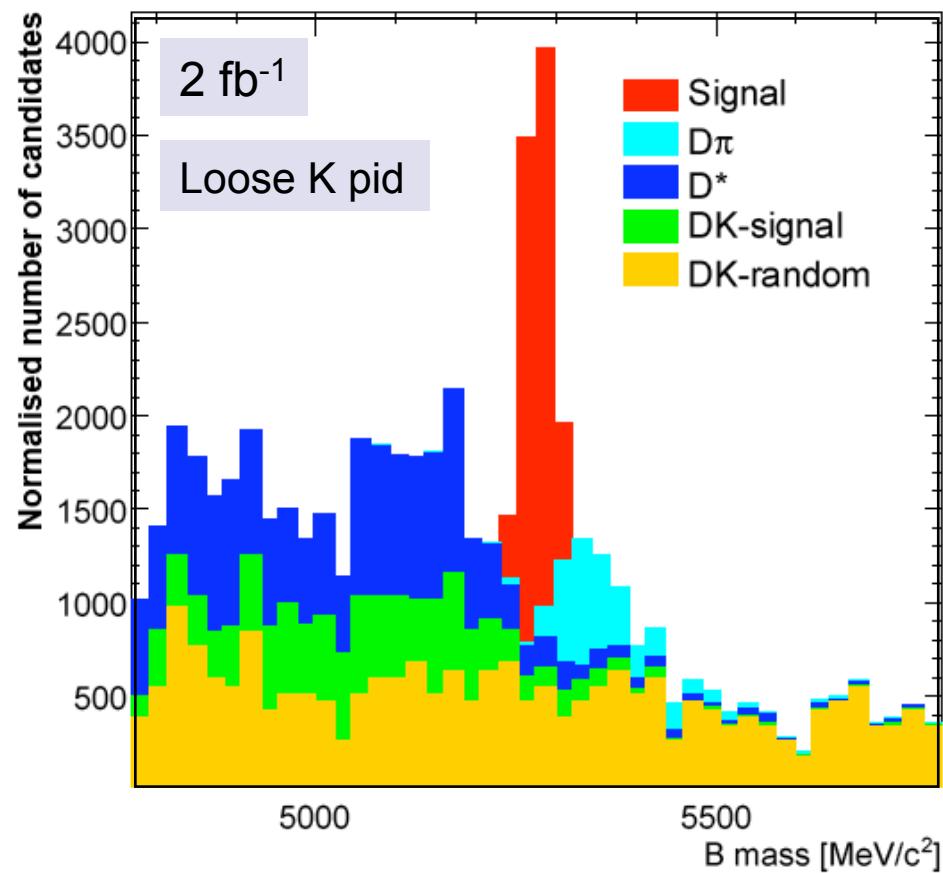
# $B^\pm \rightarrow D(K_s \pi^+ \pi^-) K^\pm$ (“*Dalitz*”)

LHCb-2008-028



- Signal yield  $\sim 5k$  (total) per year
- $B^\pm \rightarrow D(K_s \pi^+ \pi^-) \pi^\pm$  background suppressed with RICH and max. momentum cut ( $p < 100$  GeV/c)
- Dominant physics background  
 $B \rightarrow D(K_s \pi^+ \pi^-) X$  plus random “ $K$ ”  
 $\sim 16\%$  prob. of picking up “ $K$ ” from underlying event or other  $B$ .

Background type	B/S
$B^\pm \rightarrow D(K_s \pi^+ \pi^-) \pi^\pm$	< 0.095 (90% c.l.)
$B \rightarrow D^* X + K$	< 0.05 (90% c.l.)
DK-signal	< 0.09 (90% c.l.)
DK-random	$0.35 \pm 0.03$



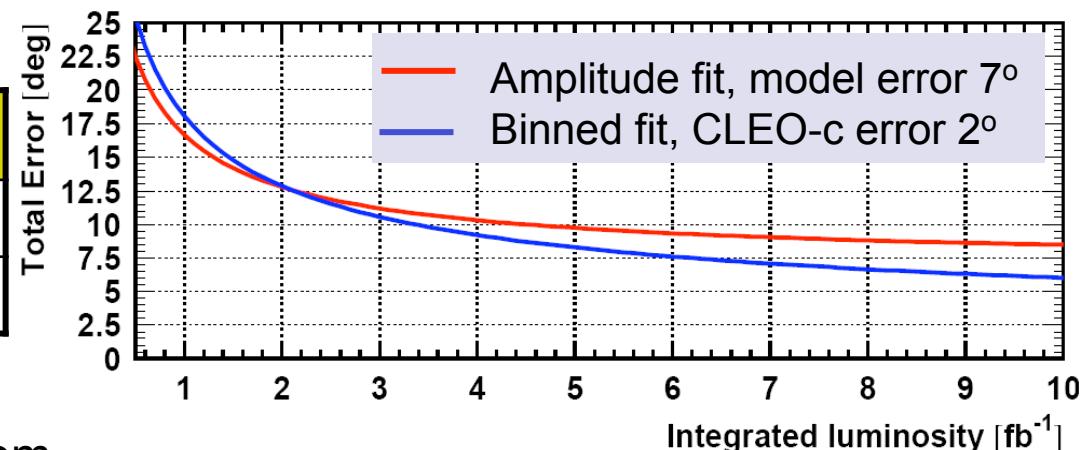
# $B^\pm \rightarrow D(K_s \pi^+ \pi^-) K^\pm$ (“*Dalitz*”)

LHCb-2007-048  
LHCb-2007-141



- Amplitude Fit: Generate and fit events assuming isobar model.
  - Models of BaBar [PRL 95 (2005) 121802] and Belle [hep-ex/0411049] give consistent results.
  - Total error will include model uncertainty, currently  $\sim 7^\circ$  [BaBar PRD 78 (2008) 034023]
- Binned Fit: Removes model dependence by relating bins of Dalitz plot to experimental observables
  - Slight degradation in statistical precision
  - Residual error on  $\gamma$  from CLEO-c statistics  $\sim 1\text{-}2^\circ$  [Asner, ICHEP 08]

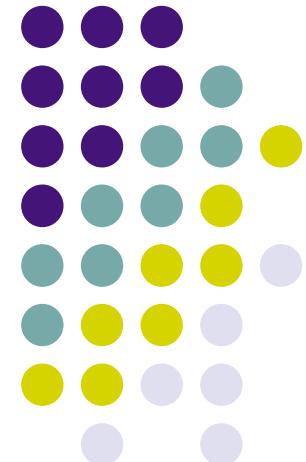
Sensitivity 2 fb $^{-1}$			
	$\sigma_\gamma$ ( $^\circ$ )	$\sigma_{r_B}$	$\sigma_{\delta_B}$ ( $^\circ$ )
Amp. Fit	9.8	0.018	9.3
Binned Fit	12.8	0.020	12.6



Fit assumes pure combinatorial background same level as DK-random

# $\gamma$ with trees

Time Dependent  $B \rightarrow D h$  Strategies



$B_s \rightarrow D_s K$ : Aleskan, Dunietz and Kayser, Z. Phys. C54 (1992) 653.

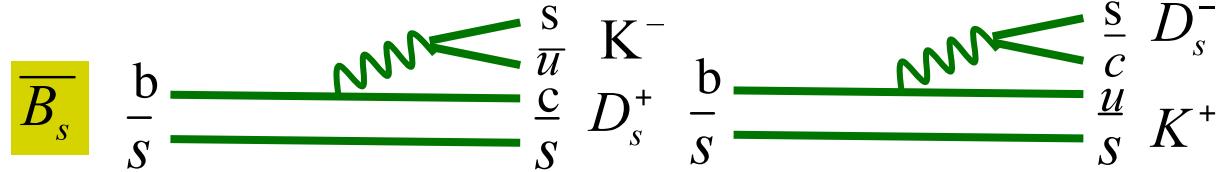
$B^0 \rightarrow D\pi$  and  $B_s \rightarrow D_s K$  “Uspin Approach”: Fleischer, Nuc. Phys. B671 (2003) 459.

# $B_s \rightarrow D_s K$

LHCb-2007-017  
LHCb-2007-041



- Measure  $\gamma + \phi_s$  from interference between mixing and decay amplitudes.

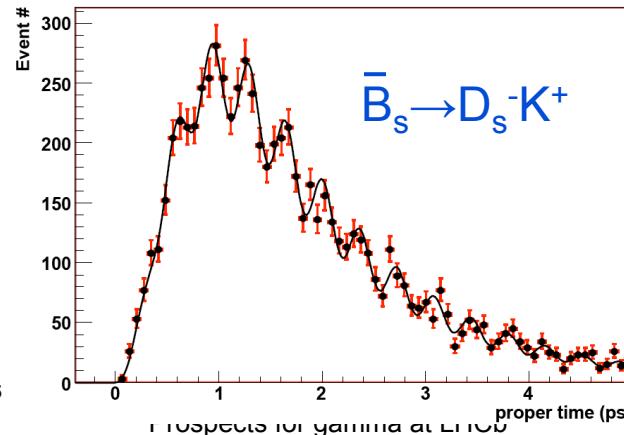
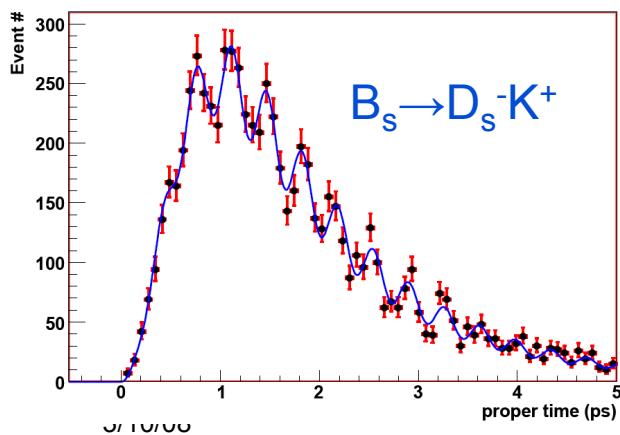


$$r_{DK} \sim \frac{1}{\lambda} \left| \frac{V_{ub}}{V_{cb}} \right| \approx 0.4$$

Mode	Sig. yield	B/S
$B_s \rightarrow D_s K$	6.2k	0.7
$B_s \rightarrow D_s \pi$	140k	0.2

- Large interference effects

- $\phi_s$  input from  $B_s \rightarrow J/\Psi \phi$  ( $\sigma_{\phi_s} \sim 0.03$  mrad for  $2 \text{ fb}^{-1}$  see A.Satta talk)
- Include  $B_s \rightarrow D_s \pi$  (20x Br) to determine  $\Delta m_s$  and tagging dilution
- Simultaneous fit to  $B_s \rightarrow D_s \pi$  and  $B_s \rightarrow D_s K$  decay time distributions (tagged and untagged)



Input parameters:  
 $\gamma = 60^\circ$ ,  $\Delta m_s = 17.5 \text{ ps}^{-1}$

Sensitivity	$2 \text{ fb}^{-1}$	$10 \text{ fb}^{-1}$
$\sigma_\gamma (\text{ }^\circ)$	10.3	4.6
$\sigma_{\Delta m_s} (\text{ps}^{-1})$	0.007	0.003

# $B^0 \rightarrow D\pi$

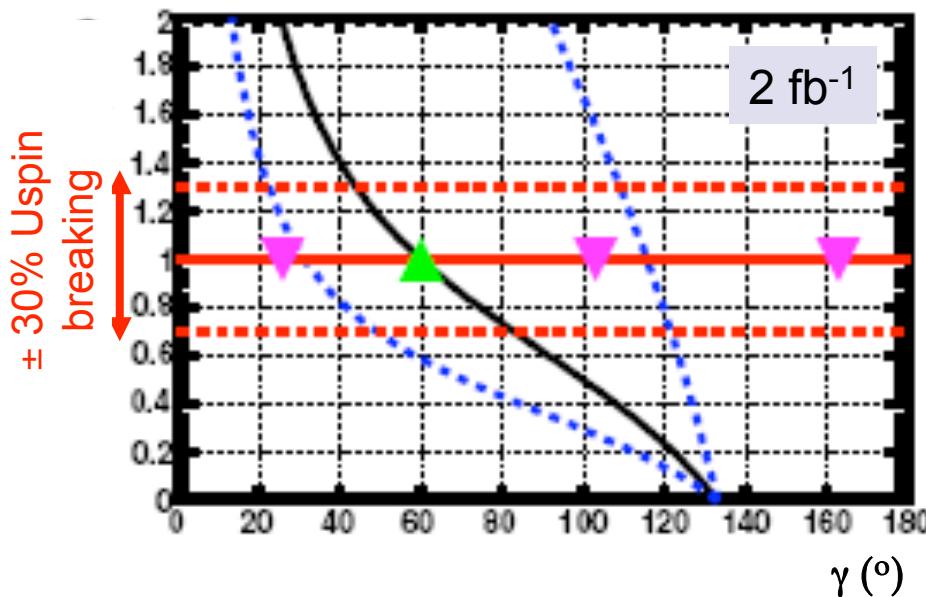
LHCb-2008-035  
LHCb-2007-044



- Measure  $\gamma + \phi_d$  analogous to  $B_s \rightarrow D_s K$
- $\phi_d$  input from  $B^0 \rightarrow J/\Psi K_s$  ( $\sigma_{\sin \phi_d} = 0.02$  for  $2 \text{ fb}^{-1}$  LHCb-2007-045)
- Problems
  - Interference small
  - 8 fold ambiguity ( $\Delta \Gamma$  small)
- Potential solutions
  - “Conventional approach”: compare with other channels e.g.  $B^0 \rightarrow D^* \pi$
  - “Uspin approach”:  $B^0 \rightarrow D\pi$  and  $B_s \rightarrow D_s K$

$$r_{D\pi} \sim -\lambda \left| \frac{V_{ub}}{V_{cb}} \right| \approx -0.02$$

Mode	Sig. yield	B/S
$B_s \rightarrow D_s K$	6.2k	0.7
$B \rightarrow D\pi$	1340k	0.22



Uspin approach shows very promising results.

Sensitivity	$2 \text{ fb}^{-1}$	$10 \text{ fb}^{-1}$
$\sigma_\gamma (\text{°})$ for $\delta = 60^\circ$	$\pm 9^{+3}_{-4}$	$\pm 5 \pm 3$
$\sigma_\gamma (\text{°})$ for $\delta = 10^\circ$	+30 +22 -20 -10	+12 +4 -8 -15

Input :  $\gamma = 60^\circ$  ( $\pm \text{stat.} \pm 30\%$  Uspin breaking)

# $\gamma$ with trees : Global Sensitivity

LHCb-2008-031



Perform global fit to  $B \rightarrow DK$  with common parameters.

Include results from  $B^0$  and  $B_s$  time dependent analyses.

## Input measurements:

### $B^\pm \rightarrow D^0 K^\pm$

- $D^0 \rightarrow K\pi, KK, \pi\pi$  (LHCb-2008-011)
- $D^0 \rightarrow K\pi\pi\pi$  (LHCb-2007-004)
- $D^0 \rightarrow K_s\pi\pi$  (LHCb-2007-048)

### $B^0 \rightarrow D^0 K^{*0}$

- $D^0 \rightarrow K\pi, KK, \pi\pi$  (LHCb-2007-050)

## Time dependent measurements:

- $B^0 \rightarrow D\pi$  (LHCb-2008-035)
- $B_s \rightarrow D_s K$  (LHCb-2007-041)

## Parameters (input value):

### $B^\pm \rightarrow D^0 K^\pm$

- $\gamma$  ( $60^\circ$ )
- $r_B$  – ratio of magnitude of diagrams (0.1)
- $\delta_B$  – strong phase difference ( $130^\circ$ )

$B^0 \rightarrow D^0 K^{*0}$  analogues:  $r_{B^0}$  (0.4),  $\delta_{B^0}$  (scan)

## $D^0$ decay parameters for $K\pi, K\pi\pi\pi$ :

- $r_{K\pi}, r_{K3\pi}$  well known (PDG)
- $\delta_{K\pi} (-158^\circ), \delta_{K3\pi} (144^\circ)$
- $R_{K3\pi}$  – coherence factor

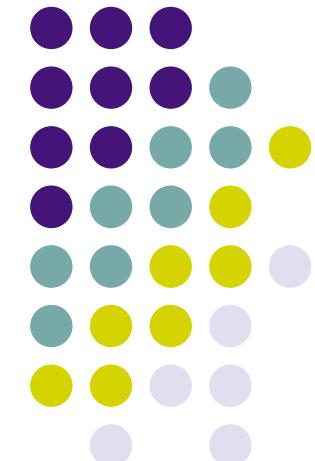
Constrained by  
CLEO-c

“Conventional” approach used for  $B^0 \rightarrow D\pi$  ( $\sigma_\gamma = 20^\circ$  with  $2 \text{ fb}^{-1}$ ) to avoid large correlations with  $B_s \rightarrow D_s K$ .

$\delta_{B^0}$ ( $^\circ$ )	0	45	90	135	180
$\sigma_\gamma$ for $0.5 \text{ fb}^{-1}$ ( $^\circ$ )	8.1	10.1	9.3	9.5	7.8
$\sigma_\gamma$ for $2 \text{ fb}^{-1}$ ( $^\circ$ )	4.1	5.1	4.8	5.1	3.9
$\sigma_\gamma$ for $10 \text{ fb}^{-1}$ ( $^\circ$ )	2.0	2.7	2.4	2.6	1.9

# $\gamma$ with loops

New physics in  $B \rightarrow hh$  and  $B \rightarrow hhh$  modes



$B^0 \rightarrow \pi\pi$  and  $B_s \rightarrow KK$ :

“Uspin Approach”, Fleischer, Phys. Lett B458 (1999) 306.

$B^+ \rightarrow K^+\pi^-\pi^+$  and  $B^0 \rightarrow K_s\pi^-\pi^+$ :

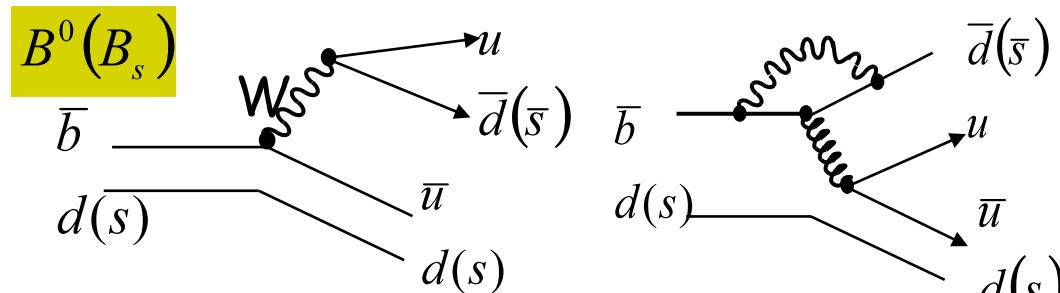
“Dalitz Approach”, Bediaga, Guerrer and Miranda, Phys Rev D76 073011 (2007).

# $B^0 \rightarrow \pi\pi$ and $B_s \rightarrow KK$

LHCb-2007-059

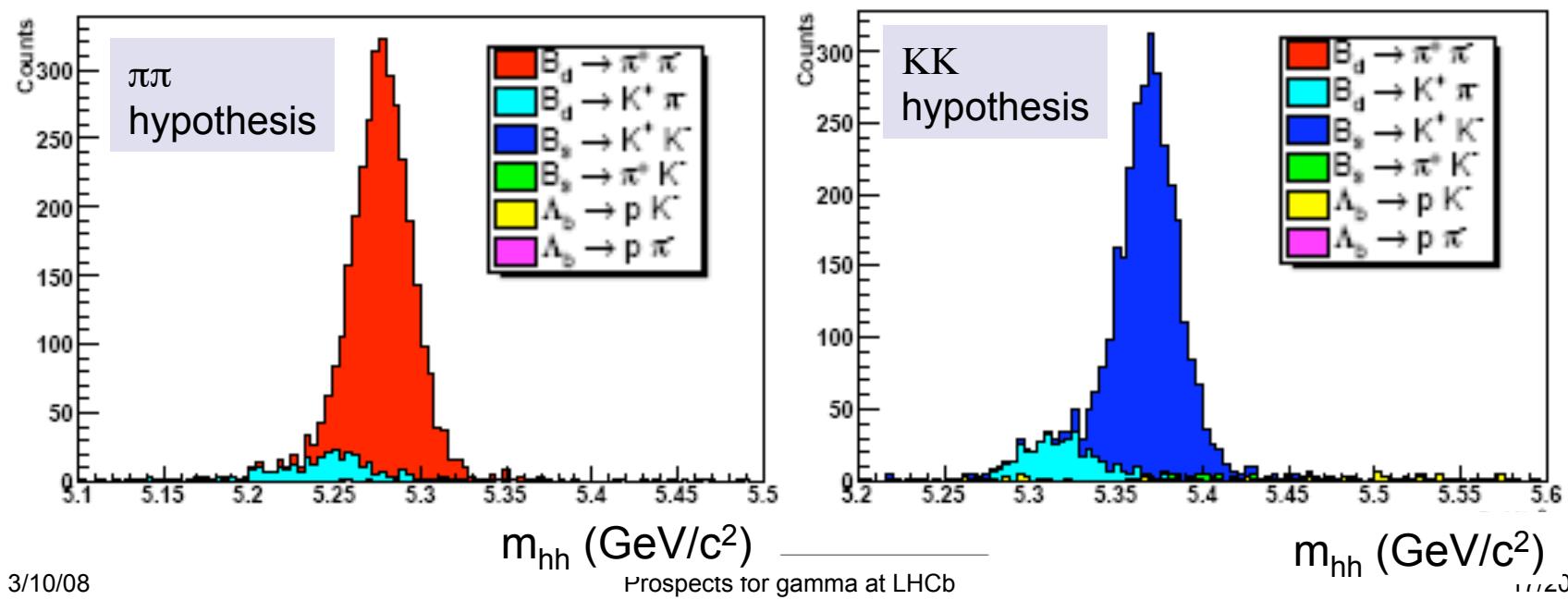


- Measure  $\gamma$  from interference between mixing and tree and penguin decay diagrams



- Demonstrates excellence of RICH pid

Mode	Sig. yield (untagged)	B/S (incl. bb <sup>-</sup> )
$B^0 \rightarrow \pi\pi$	36k	0.5
$B_s \rightarrow KK$	36k	0.15
$B^0 \rightarrow K\pi$	140k	< 0.06
$B_s \rightarrow \pi K$	10k	1.9



# $B^0 \rightarrow \pi\pi$ and $B_s \rightarrow KK$

LHCb-2007-059



- Fit CP asymmetries of  $B^0 \rightarrow \pi\pi$  and  $B_s \rightarrow KK$  events

$$A_f^{CP}(\tau) = \frac{A_f^{dir} \cdot \cos(\Delta m \cdot \tau) + A_f^{mix} \cdot \sin(\Delta m \cdot \tau)}{\cosh\left(\frac{\Delta\Gamma}{2} \cdot \tau\right) - A_f^{\Delta\Gamma} \cdot \sinh\left(\frac{\Delta\Gamma}{2} \cdot \tau\right)}$$

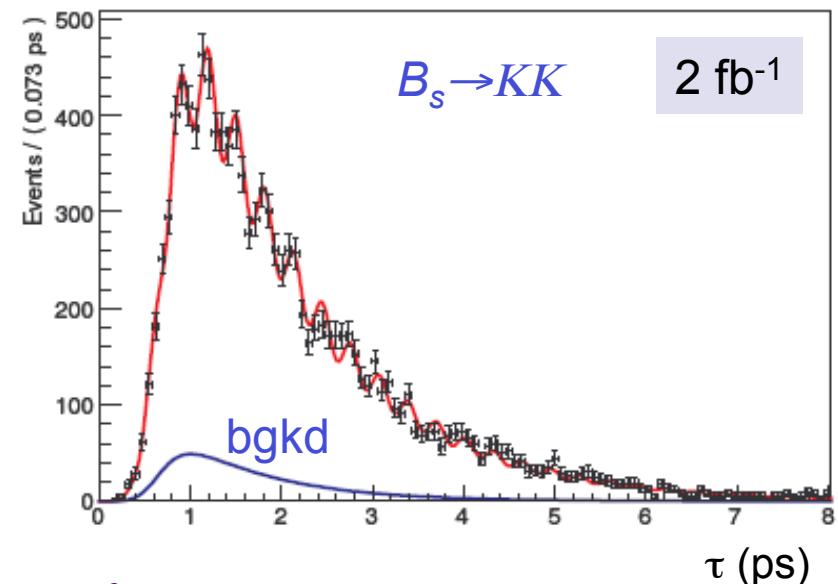
- 4 observables:  $A_{\pi\pi}^{dir}, A_{\pi\pi}^{mix}, A_{KK}^{dir}, A_{KK}^{mix}$

- Parameters

- $\gamma$
- penguin to tree amplitude ratio  $d_{\pi\pi} e^{i\theta_{\pi\pi}}, d_{KK} e^{i\theta_{KK}}$
- Input  $\phi_d$  and  $\phi_s$

- Weak Uspin constraint
- $d_{\pi\pi} = d_{KK} \pm 20\%$ ,  $\theta_{\pi\pi}, \theta_{KK}$  indep.

Measures  $\gamma$  and tests Uspin symmetry



Sensitivity	2 fb <sup>-1</sup>	10 fb <sup>-1</sup>
$\sigma_\gamma$ (°)	10	5
$\sigma_{d_{\pi\pi}}$	0.18	0.09
$\sigma_{\theta_{\pi\pi}}$ (°)	9	5
$\sigma_{\Delta\Theta}$ (°)	17	8

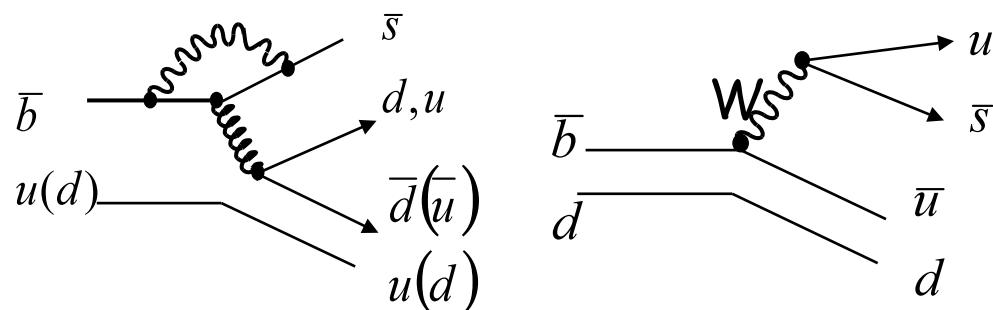
# $B^+ \rightarrow K^+ \pi^+ \pi^-$ and $B^0 \rightarrow K_s \pi^+ \pi^-$

G.Guerrer  
CKM 2008



- Measure  $\gamma$  from a Dalitz analysis of  $B^+ \rightarrow K^+ \pi^+ \pi^-$  and  $B^0 \rightarrow K_s \pi^+ \pi^-$  decays

- K\* resonance (dominant contributions)



- Extract penguin contribution from  $B^+ \rightarrow K^+ \pi^+ \pi^-$

- Use Dalitz anisotropy to measure CP asymmetry including phase differences

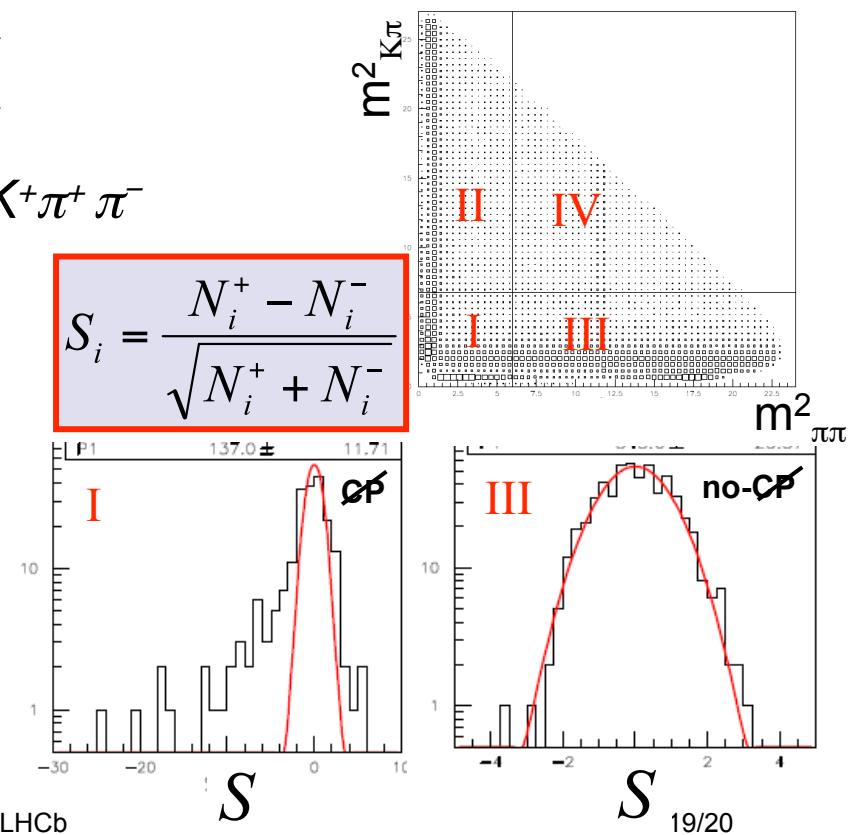
- Dalitz analysis of  $B^0/\bar{B}^0 \rightarrow K_s \pi^+ \pi^-$

- Untagged analysis possible since  $B^0$  and  $\bar{B}^0$  interference regions do not overlap

- Promising results:  $\sigma_\gamma \sim 5^\circ$  with  $2 \text{ fb}^{-1}$

- Background still to be studied

Mode	Sig. yield	B/S
$B^+ \rightarrow K\pi\pi$	494k	0.3
$B^0 \rightarrow K_s\pi\pi$	90k	t.b.d.



# Summary



LHCb offers exciting prospects for a precision measurement of  $\gamma$

- $\gamma$  with trees
  - Standard Model benchmark
  - External input from CLEO-c of upmost importance
  - A combined sensitivity of  $\sigma_\gamma \sim 2-3^\circ$  is expected with  $10 \text{ fb}^{-1}$  of data
  - Many channels still to be investigated

$$D \rightarrow K\pi\pi^0, D \rightarrow K_s KK, D \rightarrow K_s K\pi, B \rightarrow D^{(*)} K^{(*)}, B_s \rightarrow D_s^{(*)} K_1 \text{ etc}$$

- $\gamma$  with loops
  - Sensitive to New Physics
  - $B \rightarrow hh$  analysis can measure  $\gamma$  ( $\sigma_\gamma \sim 5^\circ$  with  $10 \text{ fb}^{-1}$ ) and test Uspin symmetry
  - $B \rightarrow hhh$  very promising first studies

First challenge: reconstruct hadronic final states with real data..... coming soon

# Backup Slides



# CP Formalism and $\delta_{K\pi}$



In  $D \rightarrow K\pi$  decays the DCS to CF amplitudes is defined as

$$\frac{\langle K^+ \pi^- | H | D^0 \rangle}{\langle K^- \pi^+ | H | D^0 \rangle} = r_{K\pi} e^{-i\delta_{K\pi}}$$

Two conventions for CP operation adopted

①  $CP|D^0\rangle = |\overline{D^0}\rangle$   $\rightarrow$   $\frac{\langle K^+ \pi^- | H | D^0 \rangle}{\langle K^+ \pi^- | H | \overline{D^0} \rangle} = r_{K\pi} e^{-i\delta_{K\pi}}$  ADS Formalism

②  $CP|D^0\rangle = -|\overline{D^0}\rangle$   $\rightarrow$   $\frac{\langle K^+ \pi^- | H | D^0 \rangle}{\langle K^+ \pi^- | H | \overline{D^0} \rangle} = r_{K\pi} e^{-i(\pi + \delta_{K\pi})}$  CLEO-c Formalism

i.e. Measurement of CLEO-c  $\delta_{K\pi}$  must be offset by  $180^\circ$  when input to the ADS analysis

# $\gamma$ with trees : Global Sensitivity

LHCb-2008-031



Weight (in %) of each contributing analysis with  $2 \text{ fb}^{-1}$  for two values of  $\delta_{B^0}$

Analysis	$\delta_{B^0} = 0^\circ$	$\delta_{B^0} = 45^\circ$
$B^\pm \rightarrow D^0(hh)K^\pm, B^\pm \rightarrow D^0(K3\pi)K^\pm$	25	38
$B^\pm \rightarrow D^0(K_s\pi\pi)K^\pm$	12	25
$B^0 \rightarrow D^0(hh)K^{*0}$	44	8
$B_s \rightarrow D_s K^\pm$	16	24
$B^0 \rightarrow D\pi$	3	5

Sensitivity of  $B^0 \rightarrow D^0 K^{*0}$  improves by a factor of two in going from  $\delta_{B^0} = 45^\circ \rightarrow 180^\circ$ . Residual dependence remains in global fit, but diluted due to other measurements.

# $B^+ \rightarrow K^+ \pi^+ \pi^-$ and $B^0 \rightarrow K_s \pi^+ \pi^-$

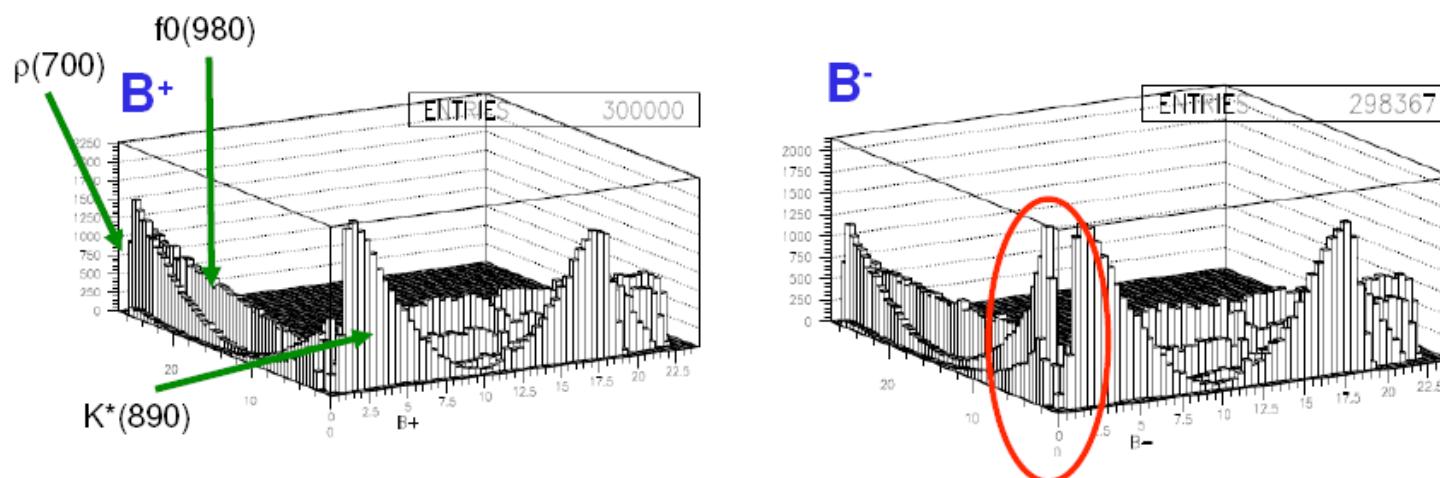
G.Guerrer  
CKM 2008



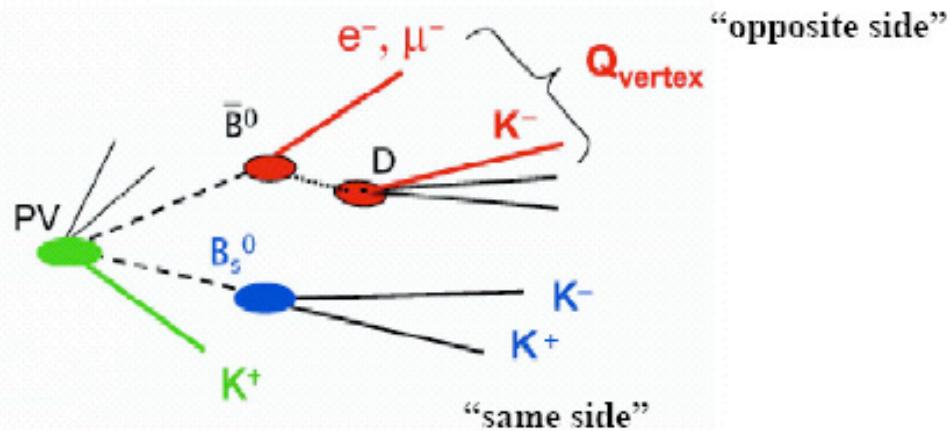
## Dalitz anisotropy: $K\pi\pi$ example

- fast MC sample inspired by BaBar parameters and 1 nominal year of LHCb statistics (~300k)

mode	$B^+$		$B^-$	
	$a_+$	$\delta_+$	$a_-$	$\delta_-$
$K^*(890)\Pi$	1.00	0.00	1.00	0.00
$K(1430)\Pi$	2.08	0.1	2.08	0.1
$\rho(770)K$	0.874	-0.55	0.874	0.49
$f_0(980)K$	1.02	2.29	1.02	2.29
$\chi_K$	0.3	-2.52	0.3	-2.52
NR	0.6	-1.85	0.6	-1.85



# B Tagging



Method (For $B_s$ )	$\mu^\pm$	$e^\pm$	$K^\pm$ same	$K^\pm$ opp	Jet charge
$\varepsilon D^2(\%)$	1.5	0.7	3.1	2.5	0.8

Expect  $\varepsilon D^2 \sim 7\text{-}9\%$  for  $B_s$  & 4-5% for  $B_d$