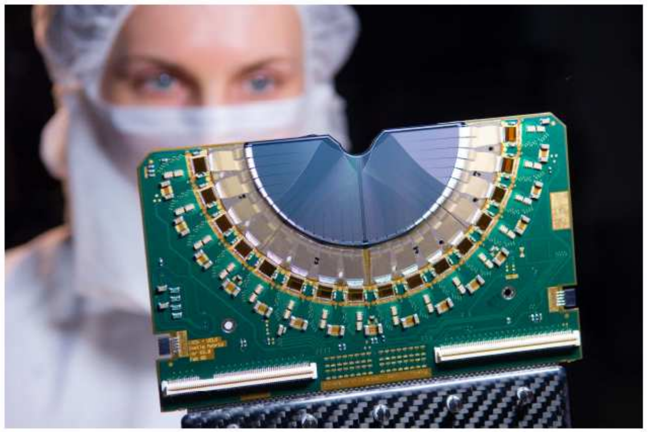
# Measurements of $\gamma$ at LHCb with ADS/GLW Strategies



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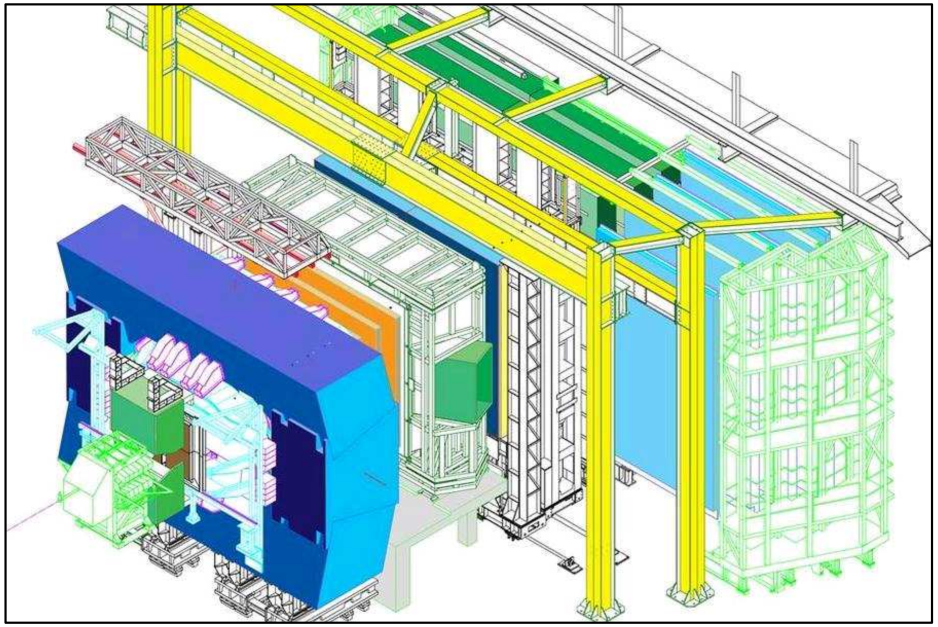
On behalf of the LHCb collaboration

CKM08 Conference, Rome, September 2008

# Outline

- $B^{\pm} \rightarrow DK^{\pm}$ at LHCb
  - Sub-detectors important to this measurement
- Overview of Simulation Data
  - Monte Carlo used within studies reported here
- Selection and Sensitivity Predictions
  - $B^{\pm} \rightarrow D(hh)K^{\pm}$
  - Four-Body ADS: $B^{\pm} \rightarrow D(K\pi\pi\pi)K^{\pm}$
  - $B^{0} \rightarrow D(hh)K^{*0}$
- Summary

# $B^{\pm} \rightarrow DK^{\pm}$ at LHCb



- LHCb statistics will enable full exploitation of all $B^{\pm} \rightarrow DK^{\pm}$ strategies, especially ADS/GLW
  - $\sigma_{bb}$ ~ 500 μb at 14 TeV
  - $L_{int}$ ~ 2 x $10^{32}$ $cm^{-2}s^{-1}$
  - $10^{12}$ $bb$ pairs per 2 $fb^{-1}$(canonical year)
- Sensitivity to $\gamma$ dependent on ability to gather high statistics samples of $B^{\pm} \rightarrow DK^{\pm}$ whilst controlling the background

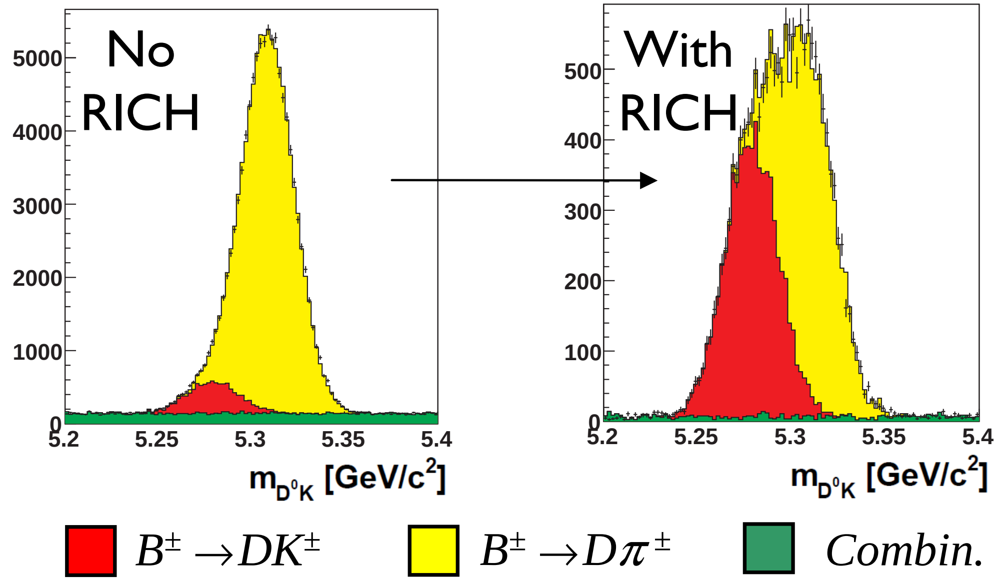
- Good performance is achievable e.g. total efficiency (including acceptance, trigger and selection) for $B^{\pm} \rightarrow D(K\pi)K^{\pm}$ from simulation studies: $\varepsilon_{Tot}$ ~ 0.5 %
- Counting experiments – no need for tagging or proper time determination
- $B^{\pm} \rightarrow DK^{\pm}$ performance is reliant upon two vital aspects of the LHCb detector…

| | LHCb | Babar | Belle |
|---|---|---|---|
| $B^{-} \rightarrow D(K\pi)K^{-}$ Fav. Yields | ~28,000 | 918* | 1,220* |
| Luminosity ($fb^{-1}$) | 2 | 420** | 710** |

*As shown at ICHEP 08
**arXiv:0706.2786v1

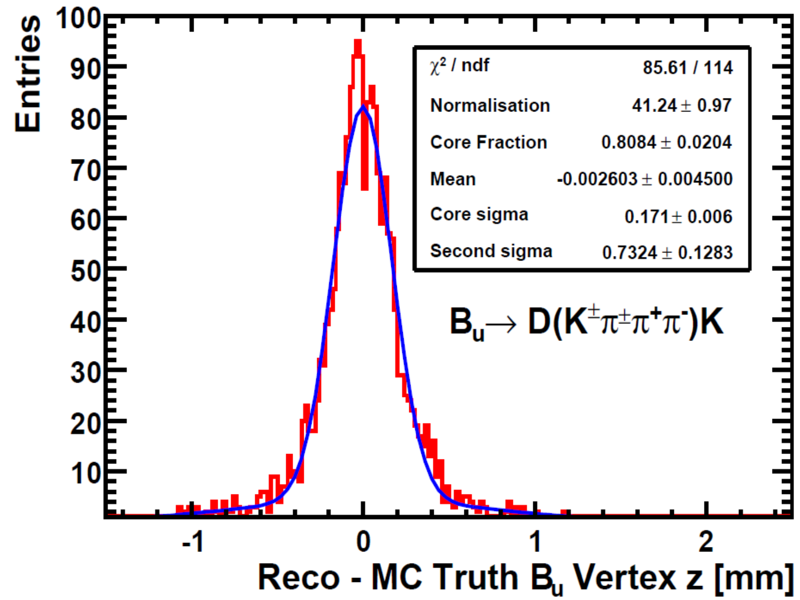
# The RICH

- Dangerous background from $B^{\pm} \to D\pi^{\pm}$
- BR($B^{\pm} \to D\pi^{\pm}$) ~ 10 x BR($B^{\pm} \to DK^{\pm}$)
- RICH Kaon ID: $\varepsilon_{avg}$ > 90% $\forall$ momenta
- B/S $\leq$ 0.5 typical for favoured modes




# Tracking System

- Excellent vertex and $p$ determination utilising Si vertex and tracking plane sub-detectors
- Vertex Resolutions:
  - Primary vertex $\sigma_z$ ~ 50 μm
  - $B$ decay vertex $\sigma_z$ ~ 200 μm
- Mass Resolutions:
  - $B^{\pm}$ ~ 15 MeV
  - $D^0$ ~ 6.5 MeV



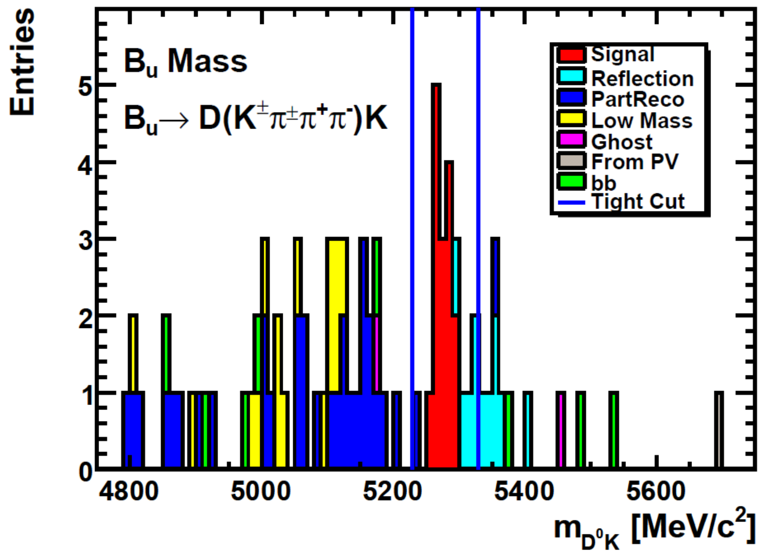
# Simulation Details

- Results presented here from the LHCb Monte Carlo studies
  - Pythia: Simulation of $pp$ interaction at $\sqrt{s} = 14$ TeV
  - EvtGen: $b$-quark evolution and decay
  - GEANT: Full detector response simulation
  - + digitisation and trigger simulation packages

- Background estimates for selections from statistically limited $B$-inclusive sample
  - ~34 million $bb$ events within detector geometry
  - Equivalent to ~ 15 mins of LHCb running at nominal luminosity

- While large signal and dominating background samples also generated

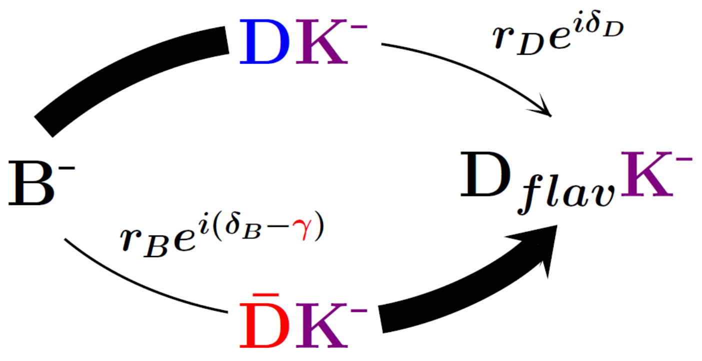
- Typical selection requirements imposed upon:
  - Track $|p|$, $p_t$, and RICH PID,
  - Bachelor $K^{\pm}$ $p_t$ and impact parameter
  - $B$ and $D$ $m_{\text{inv}}$
  - $B$ and $D$ vertex quality ($\chi^2$)



$$B^{\pm} \to D(hh)K^{\pm}$$

# Two Strategies…

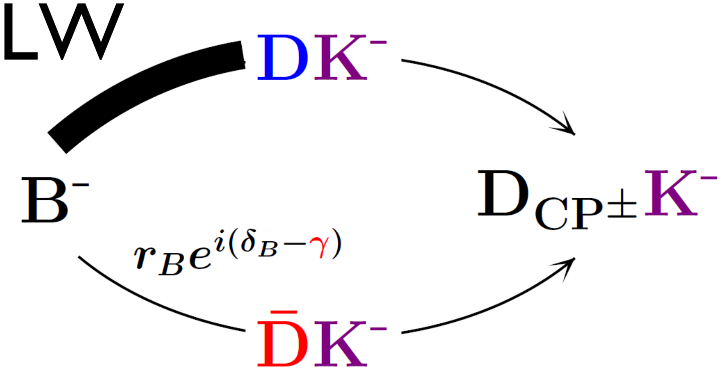
## ADS




- $D_{flav} = K^+\pi, K^-\pi^+$ (4 distinct final states)
- Particular sensitivity with suppressed rate
- Dependence on 5 parameters:
  - $r_B$
  - $\delta_B$
  - $N^{K\pi}$ (normalisation)
  - $\delta_{D(K\pi)}$…and of course $\gamma$

$r_{D(K\pi)}$ well measured (0.060 ± 0.003)

## GLW




- $D_{CP} = K^+K^-, \pi\pi^+$
- Parameters identical for both final states
  (consider yields together – 2 distinct rates)
- 1 additional parameter:
  - $N^{hh}$ (normalisation)

## ADS + GLW

$$\frac{N^{K\pi}}{N^{hh}} = \frac{\mathrm{BR}(D \to K\pi) \times \varepsilon_{K\pi}}{\mathrm{BR}(D \to hh) \times \varepsilon_{hh}}$$

- Exploiting relation between $N^{K\pi}$ and $N^{hh}$:
  - 5 parameters
  - 6 distinct rates
  - $\gamma$ solvable!

# $B^{\pm} \to D(hh)K^{\pm}$ Sensitivity (2 $fb^{-1}$)

## Method

- A $\chi^2$ fit to the 6 rates is performed
- Yield and bkgds as shown in table

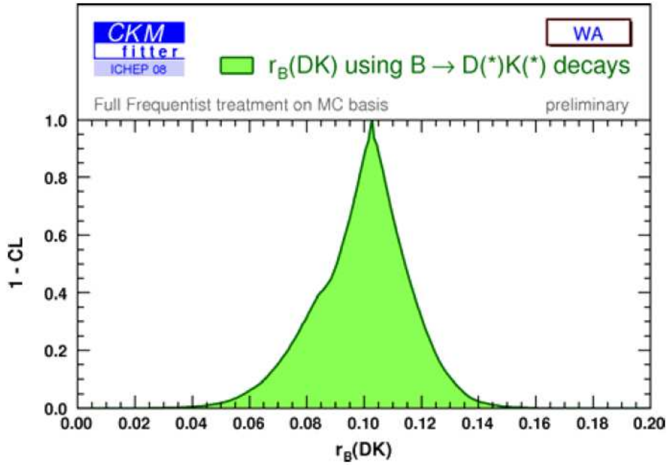
## Constraints

- $\delta_{D(K\pi)} = (22\,^{+14}_{-16})°$ from CLEO-c*
- Constrain $\delta_{D(K\pi)}$ to $(^{+14}_{-16})°$ of input

## Assumed Inputs

- $r_B$ = 0.10 (UTfit average 0.10 ± 0.02)
- $\delta_B$ = 130° (PDG)
- $r_{D(K\pi)}$ = 0.0616 (PDG)
- $\delta_{D(K\pi)}$ centred about (-180)°
- $\gamma$ = 60°

| Mode | Sig. Yield | Bkg Est. |
|---|---|---|
| $B^+ \to D(K\pi)K^+$ (fav) | 28k | 17,520 ± 993 |
| $B^+ \to D(K\pi)K^+$ (sup) | 650** | 780 ± 509 |
| $B^+ \to D(KK)K^+$ | 3k | 3,664 ± 1,026 |
| $B^+ \to D(\pi\pi)K^+$ | 1k | 3,570 ± 1,480 |




Plot taken from O. Deschamps' ICHEP 2008 talk

$r_B = 0.103\,^{+0.017}_{-0.023}$

[LHCb-2006-066]
[LHCb-2008-031]

## Results

| $\delta_{D(K\pi)}$ (°) | -190 | -174 | -158 | -144 | -130 |
|---|---|---|---|---|---|
| $\sigma_\gamma$ (°) | 12.7 | 10.8 | 13.8 | 12.6 | 10.8 |

*(A phase shift of 180° is required when used within the ADS formalism)

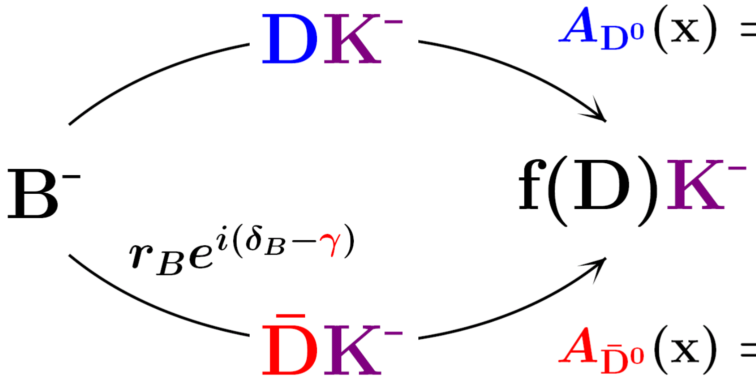
**Assuming $\delta_D$ = -158°

# $B^{\pm} \to D(K3\pi)K^{\pm}$

- Also an ADS mode
- Although, the D decay is now *multi-bodied*…

# What's Different?

- First, consider a point (**x**) in D-decay phase space (akin to that of a 2-body decay (e.g. $K\pi$))




$$A_{\mathrm{D^0}}(\mathbf{x}) = \langle \mathrm{f}|\mathbf{D^0}\rangle_{(\mathrm{x})}$$

$$\zeta(\mathbf{x}) = \arg\left(A_{\mathrm{D^0}}(\mathbf{x})^* A_{\bar{\mathrm{D}}^0}(\mathbf{x})\right)$$

$$A_{\bar{\mathrm{D}}^0}(\mathbf{x}) = \langle \mathrm{f}|\bar{\mathbf{D}}^\mathbf{0}\rangle_{(\mathrm{x})}$$

$$\mathcal{M}^2 \sim |A_{\mathrm{D^0}}(\mathbf{x})|^2 + r_{\mathrm{B}}^2|A_{\bar{\mathrm{D}}^0}(\mathbf{x})|^2 + 2r_{\mathrm{B}}|A_{\mathrm{D^0}}(\mathbf{x})||A_{\bar{\mathrm{D}}^0}(\mathbf{x})|\cos(\delta_{\mathrm{B}} - \gamma + \zeta(\mathbf{x}))$$

- This is just the generalised 2-body ADS eqn., but what about multi-body final states…
- Total rate given by integrating over ALL allowable phase space:

$$\Gamma \propto A_{\mathrm{f}}{}^2 + r_{\mathrm{B}}^2 \bar{A}_{\mathrm{f}}{}^2 + 2r_{\mathrm{B}} A_{\mathrm{f}} \bar{A}_{\mathrm{f}} R_f \cos(\delta_{\mathrm{B}} - \gamma + \delta_{\mathrm{D}})$$

where:

$$A_{\mathrm{f}}{}^2 = \int |A_{\mathrm{D^0}}(\mathbf{x})|^2 \, d\mathbf{x}$$

$$\bar{A}_{\mathrm{f}}{}^2 = \int |A_{\bar{\mathrm{D}}^0}(\mathbf{x})|^2 \, d\mathbf{x}$$

$$R_f e^{i\delta_{\mathrm{D}}} = \frac{\int |A_{\mathrm{D^0}}(\mathbf{x})||A_{\bar{\mathrm{D}}^0}(\mathbf{x})| e^{i\zeta(\mathbf{x})} \, d\mathbf{x}}{A_{\mathrm{f}} \bar{A}_{\mathrm{f}}}$$

$$0 \leq R_f \leq 1$$

The "Coherence Factor"

[Phys Rev. D 68, 033003 (2003)]

# Incorporating $K3\pi$ Multi-Body ADS

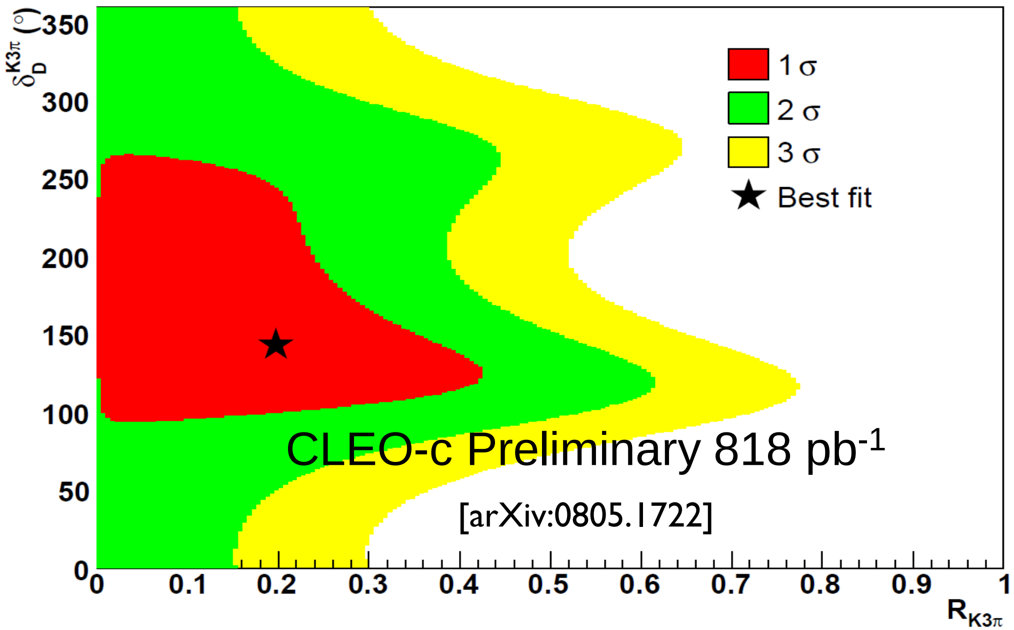
## Method

- Add these additional 4 rates, incorporating $R_{K3\pi}$, into the 2-body $\chi^2$ fit
- Yield and bkgds essentially equivalent to $K\pi$

| Mode | Sig. Yield | Bkg Est. |
|---|---|---|
| $B^+ \to D(K3\pi)K^+$ | 31k | 20,200 ± 2,500 |
| $B^+ \to D(K3\pi)K^+$ | 530 | 1,200 ± 360 |

## Constraints

- Determination of $R_{K3\pi}$ possible at CLEO-c (see J. Libby's talk in previous session)
- Preliminary results shown opposite
- Additional terms added into $\chi^2$ to incorporate constraints 1), 2) & 3)




$$<R_{K3\pi} cos(\delta^{K3\pi})> = -0.60 \pm 0.19 \pm 0.24 \quad 1)$$

$$(R_{K3\pi})^2 = -0.20 \pm 0.23 \pm 0.09 \quad 2)$$

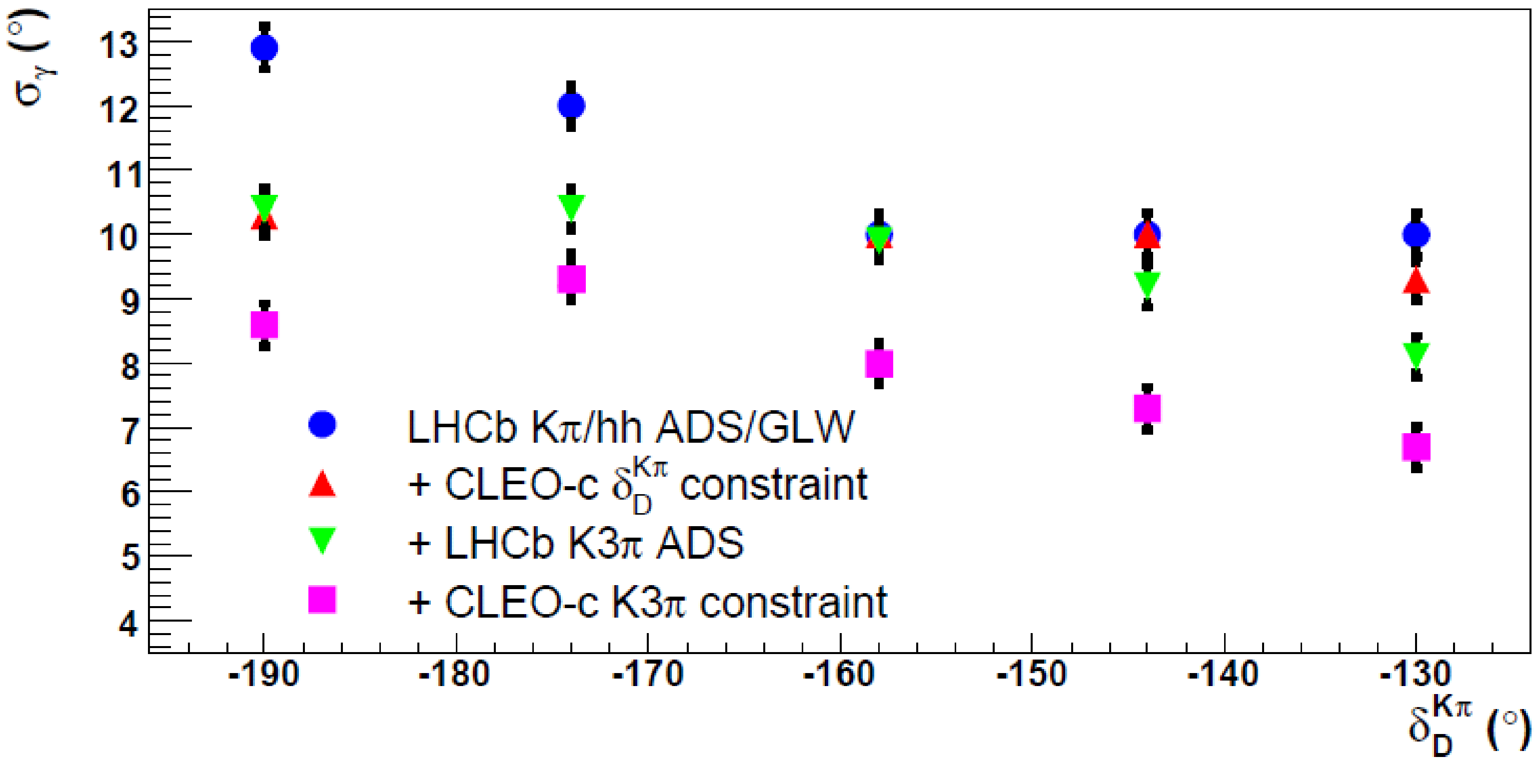
$$R_{K3\pi} cos(\delta^{K\pi} - \delta^{K3\pi}) = 0.00 \pm 0.16 \pm 0.07 \quad 3)$$

## Assumed Inputs

- $r_{D(K3\pi)}$ = 0.0568 (PDG)

[LHCb-2007-004]
[LHCb-2008-031]

# Combining 2 $fb^{-1}$ Results



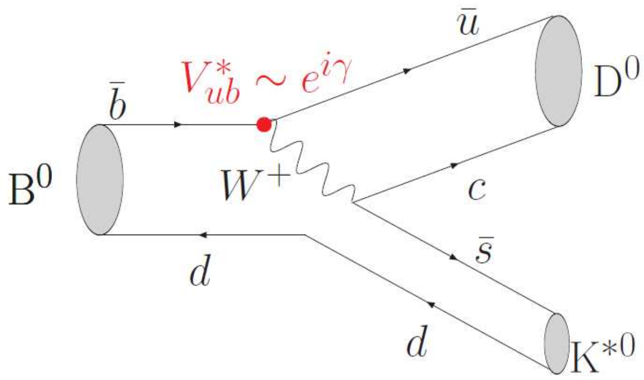

Bottom Line: Improvement in sensitivity from including $K3\pi$ mode is equivalent to 70 – 100 % more data after one year of running

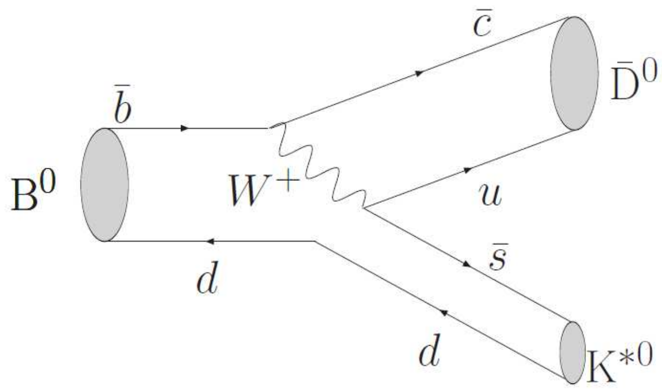
$$\sigma(\gamma) \sim (7.0 - 9.5)^\circ \quad \text{for } 2\ fb^{-1}$$

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

- Can be utilised in a way akin to that of $B^{\pm} \rightarrow D(hh)K^{\pm}$

- Particular sensitivity expected since both diagrams are colour suppressed ($r_{B0}$ ~ 0.4)



# $B^0 \to D(hh)K^{*0}$ Sensitivity (2 fb$^{-1}$)

## Method

- A $\chi^2$ fit to the 6 rates is performed
- Yield and bkgds as shown in table

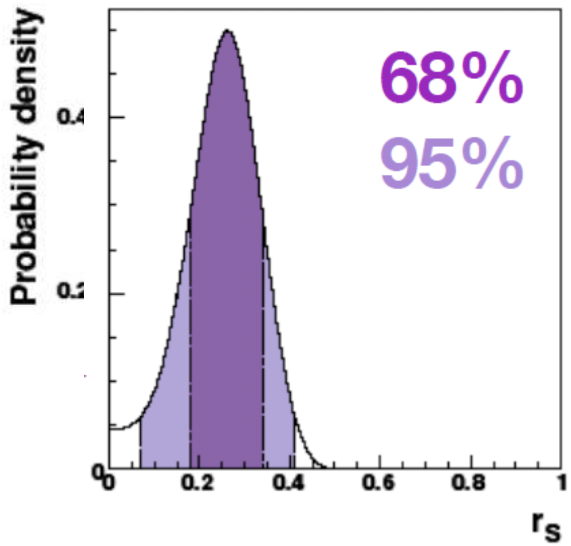
| Mode | Sig. Yield | B/S (90% CL) |
|---|---|---|
| $B^0 \to D(K\pi)K^{*0}$ (fav) | 3.4k | [0.4, 2.0] |
| $B^0 \to D(K\pi)K^{*0}$ (sup) | $O(500)$ | [2.0, 13.0] |
| $B^0 \to D(KK)K^{*0}$ | $O(500)$ | [0, 4.0] |
| $B^0 \to D(\pi\pi)K^{*0}$ | $O(100)$ | [0, 14.0] |

## Constraints

- $\delta_{D(K\pi)} = (22\,^{+14}_{-16})^\circ$ from CLEO-c*
- Constrain $\delta_{D(K\pi)}$ to $(^{+14}_{-16})^\circ$ of input

## Assumed Inputs

- $r_{B0} = 0.40$
- $r_{D(K\pi)} = 0.0616$ (PDG)
- $\delta_{D(K\pi)}$ centred about $(-180)^\circ$
- $\gamma = 60^\circ$




Plot taken from G. Marchiori's ICHEP 2008 talk

[0.18, 0.34] @ 68% CL
[0.07, 0.41] @ 95% CL
(UTfit)

[LHCb-2007-050]
[LHCb-2008-031]

## Results

| $\delta_{B0}$ (°) | 0 | 45 | 90 | 135 | 180 |
|---|---|---|---|---|---|
| $\sigma_\gamma$ (°) | 6.2 | 10.8** | 12.7** | 9.5 | 5.2 |

**(Values where the distribution of $\gamma$ fit results returned was non-Gaussian; the RMS values are therefore quoted )

*(A phase shift of 180° is required when used within the ADS formalism)

# Summary

- With just 2 $fb^{-1}$ of data, LHCb will be able to harness the power of the ADS+GLW methods to perform precision measurements of $\gamma$

$$\sigma_\gamma(B^\pm) \sim (7.0 - 9.5)^\circ$$

$$\sigma_\gamma(B^0) \sim (5.0 - 13.0)^\circ$$

- External constraints from CLEO-c hugely important in this measurement ($\delta_{D(K\pi)}$ , $\boldsymbol{R_{K3\pi}}$ , $\delta_{D(K3\pi)}$ )

- Yet more modes to consider:
  - $D \rightarrow K\pi\pi^0$ (ADS)
  - $B^\pm \rightarrow D^*K^\pm$ (Bondar-Gershon)

- Ultimate precision will be achieved from "global" fit to all LHCb $B^\pm \rightarrow DK^\pm$ results (G. Wilkinson's talk in this session)