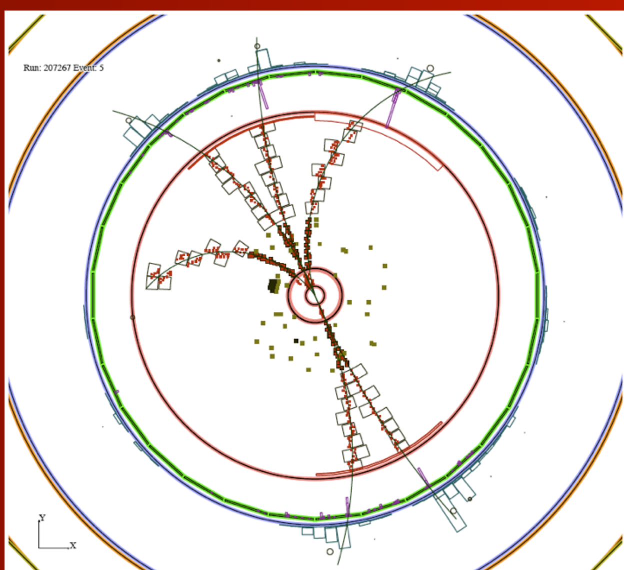
Improving the Precision of γ/ϕ_3 via CLEO-c Measurements

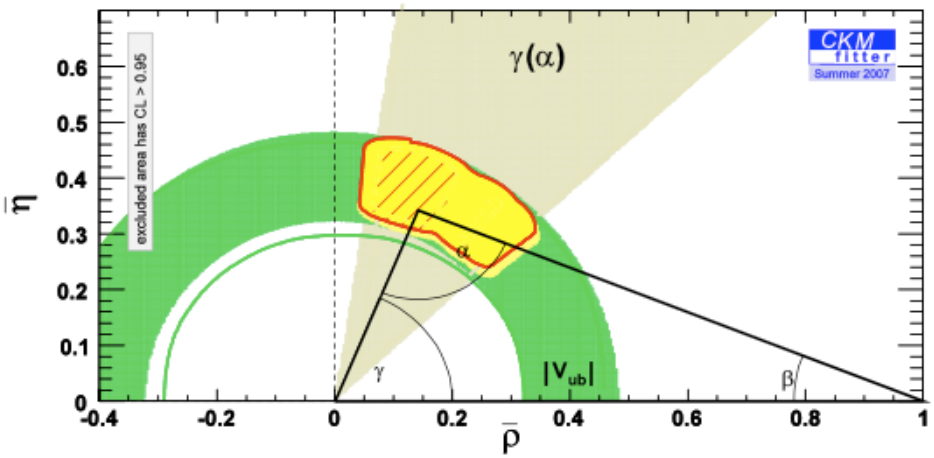
Paras Naik

University of BRISTOL



1 August 2008, 34th ICHEP

Status of the Measurement of the CKM phase γ



Constraints from tree quantities

$$\gamma : \left(76.8^{+30.4}_{-31.5}\right)^\circ$$

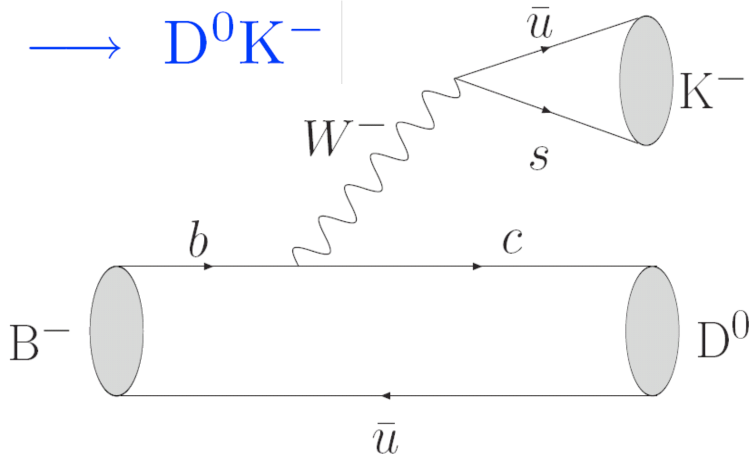
Fit from direct measurements only (CKM Fitter, Summer 2007)

CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], updated results and plots available at: http://ckmfitter.in2p3.fr

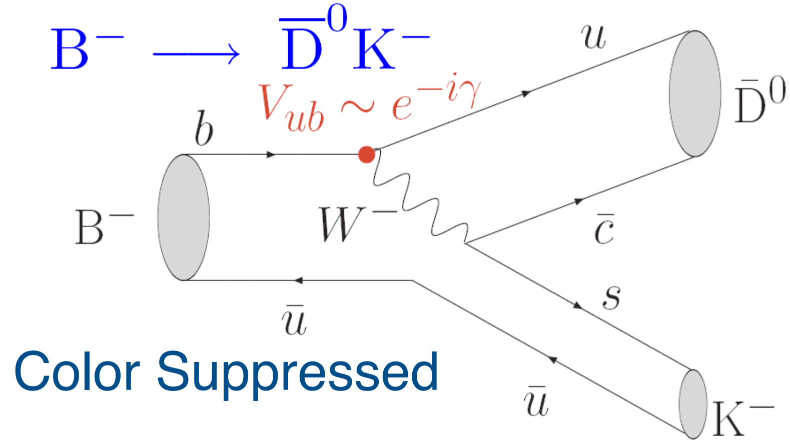
- Of the three CKM phases, γ is the least constrained.
- A precision measurement of γ is essential in order to test the internal consistency of the CKM triangle.
- In addition, tree measurements of γ compared to loop measurements may provide a first indication of New Physics in the flavor sector.
- The precision measurement of γ is one of the most important measurements of LHCb and e^+e^- flavor factories

Measuring the CKM phase γ via B → DK

$B^- \longrightarrow D^0K^-$



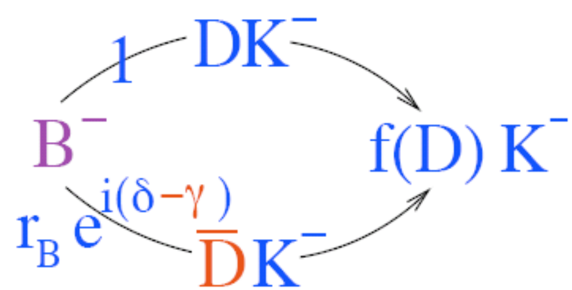
$B^- \longrightarrow \overline{D}^0K^-$



$$\frac{< B^- \longrightarrow \overline{D}^0K^- >}{< B^- \longrightarrow D^0K^- >} = r_B e^{i(\delta_B - \gamma)}$$

$$r_B \equiv \left| \frac{A(B^- \rightarrow \bar{D}^0K^-)}{A(B^- \rightarrow D^0K^-)} \right| \sim 0.1$$

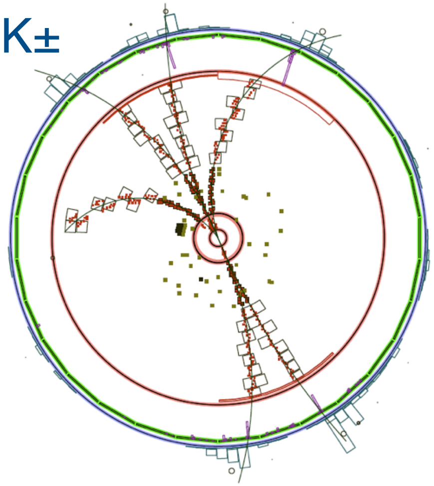
- The CKM phase γ can be determined through the interference between the *b*→*c* and *b*→*u* transitions
- Require the neutral D mesons to decay to the same final state f(D)
- This method is theoretically clean



- **Success of this method requires that the D decay is well understood**

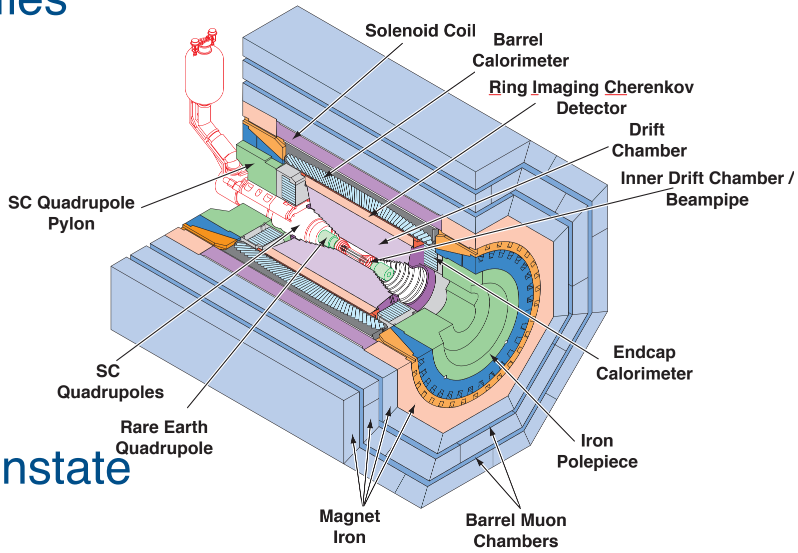
The role of CLEO-c

- **CLEO-c analyses are vital for the purpose of CKM phase γ extraction strategies via $B^{\pm} \rightarrow D_{multi\text{-}body}K^{\pm}$**
- We present a first determination of the $D \rightarrow K\pi\pi\pi$ coherence factor, $R_{K3\pi}$ (and its associated global strong phase $\delta_D^{K3\pi}$)
  - Will significantly increase precision on γ in future measurements
- CLEO-c has also measured the bin-averaged cosines (c_i) and sines (s_i) of $D \rightarrow K^0_S\pi\pi$ strong phase differences to allow a model-independent determination of γ with $B^{\pm} \rightarrow D_{K_S\pi\pi} K^{\pm}$
  - Will reduce the largest systematic error for γ via $B^{\pm} \rightarrow D_{K_S\pi\pi} K\pm$
  - c_i determined from CP-tagged decays
  - c_i and s_i determined from $K^0_S\pi\pi$-tagged decays
- CLEO-c measurement of the $D \rightarrow K\pi$ strong phase $\delta_D^{K\pi}$ also helps to determine γ via $B^{\pm} \rightarrow D_{K\pi}K^{\pm}$ decays



CLEO-c

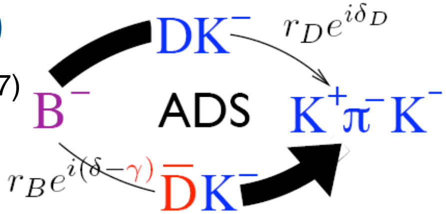
- Hermetic detector based at CESR (the Cornell Electron Storage Ring)
- Operating at energies around $c\bar{c}$ threshold
- We study $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\overline{D^0}$ decays
  - $C = -1$ for these decays at $\psi(3770)$ threshold
  - Total integrated luminosity of this sample is 818 pb^{-1}
- Quantum correlated (QC) states
  - Example: Properly reconstructing one neutral D decay to a CP eigenstate uniquely identifies the other D decay to be of opposite CP
- Double Tag
  - We fully reconstruct the event for both neutral D decays in our analyses
- CP-Tagged
  - Reconstruct other neutral D to a CP eigenstate



ADS Method

- **The study of neutral D decays at CLEO-c is useful for measurements of the CKM phase γ via $B^\pm \rightarrow DK^\pm$ decays**
- Atwood-Dunietz-Soni (ADS) Method uses $f(D) = K^+\pi^-$ (non-CP eigenstate)

Phys. Rev. Lett. 78 (1997) 3257-3260



$$\frac{< D^0 \longrightarrow K^+\pi^- >}{< \overline{D}^0 \longrightarrow K^+\pi^- >} = r_D e^{i\delta_D}$$

$$r_D \equiv \left| \frac{A(D^0 \rightarrow K^+\pi^-)}{A(\overline{D}^0 \rightarrow K^+\pi^-)} \right| \sim 0.06$$

$$\delta_D = (22^{+11+9}_{-12-11})^\circ$$ CLEO-c (281 pb^{-1})

Phys. Rev. Lett. **100** (2008) 221801

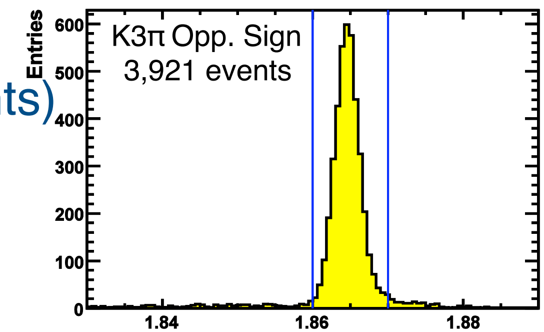
- The four rates for the different combinations of $B^\pm$ and neutral D decays to Kπ, together with those from D decays to CP eigenstates (KK and ππ), determine γ
- A key measurement of LHCb and flavor factories
  - 10° statistical precision with one year of LHCb running [LHCb-2008-011]
- The ADS method can be extended to the mode $f(D) = K^+\pi^-\pi^+\pi^-$
  - However, we need to account for the resonant substructure
  - In principle, each point in phase space has a different strong phase associated with it

Using D → Kπππ Decays at CLEO

- Atwood and Soni [Phys. Rev. D **68** (2003) 033003] showed how to modify the ADS formalism for the case of $K^+\pi^-\pi^+\pi^-$
- Introduce the **coherence parameter** $R_{K3\pi}$ which dilutes the interference term sensitive to γ

$$\Gamma(B^- \to (K^+\pi^-\pi^-\pi^+)_D K^-) \propto r_B^2 + (r_D^{K3\pi})^2 + 2 r_B r_D^{K3\pi} R_{K3\pi} \cos(\delta_B + \delta_D^{K3\pi} - \gamma)$$

- $R_{K3\pi}$ then ranges between:
  - 0 = incoherent (several significant resonant components)
  - 1 = coherent (dominated by a single mode)



Very clean environment!

- **If $R_{K3\pi}$ is close to 0, the rates still provide an extremely useful constraint on r_B.**
  So, still a very informative measurement!
- **Determinations of $R_{K3\pi}$ and $\delta_D^{K3\pi}$ can be made at CLEO-c** from an analysis of double-tagged neutral D decays at threshold.

$$A(D^0 \to K^-\pi^+\pi^-\pi^+)$$
$$\bar{A}(D^0 \to K^+\pi^-\pi^+\pi^-)$$

$$R_{K3\pi} e^{i\delta_D^{K3\pi}} = \frac{\int A(s)\bar{A}(s) e^{i\delta(s)} ds}{\sqrt{\int |A(s)|^2 ds \int |\bar{A}(s)|^2 ds}}$$

Preliminary Results for $R_{K3\pi}$ at CLEO-c

1) $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. CP

: 1 sigma spread
------ : physically allowed region

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

2) $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$

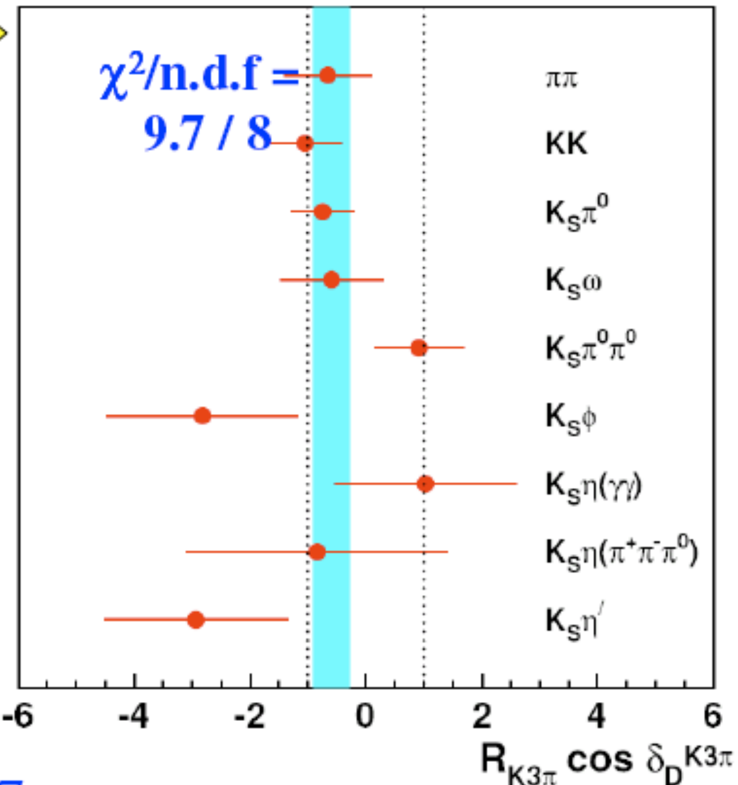
$$(R_{K3\pi})^2 = -0.20 \pm 0.23 \pm 0.09$$

$$(R_{K3\pi} < 0.22 \text{ at 1 sigma})$$

3) $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. $K^{\pm}\pi^{\mp}$

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

CLEO-c Preliminary (818 pb^{-1})

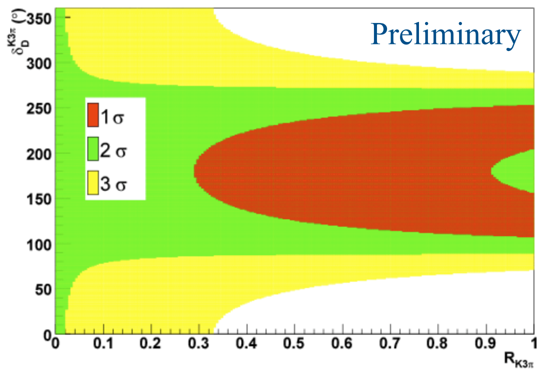


arXiv:0805.1722v1 (hep-ex)

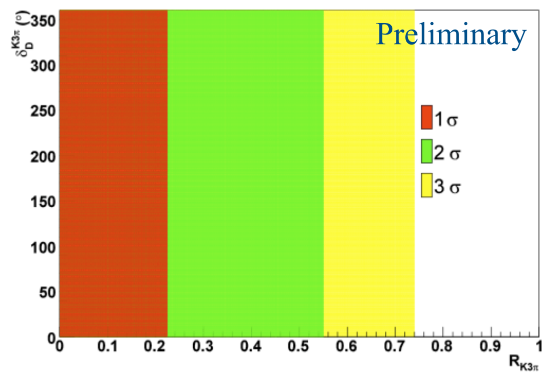
- We use result (3) to constrain $R_{K3\pi}$ and $\delta^{K3\pi}$ using $\delta^{K\pi}$ from CLEO-c Phys. Rev. Lett. **100** (2008) 221801

$\delta_D^{K3\pi}$ vs. $R_{K3\pi}$ Parameter Space Constraints

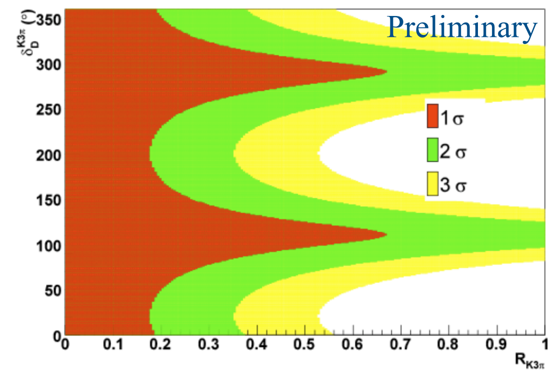
$K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. CP



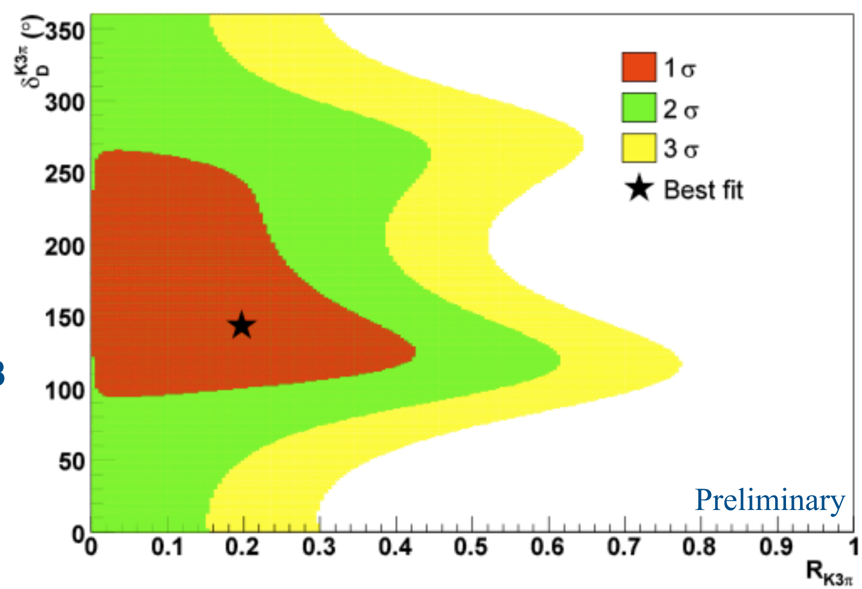
$K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$



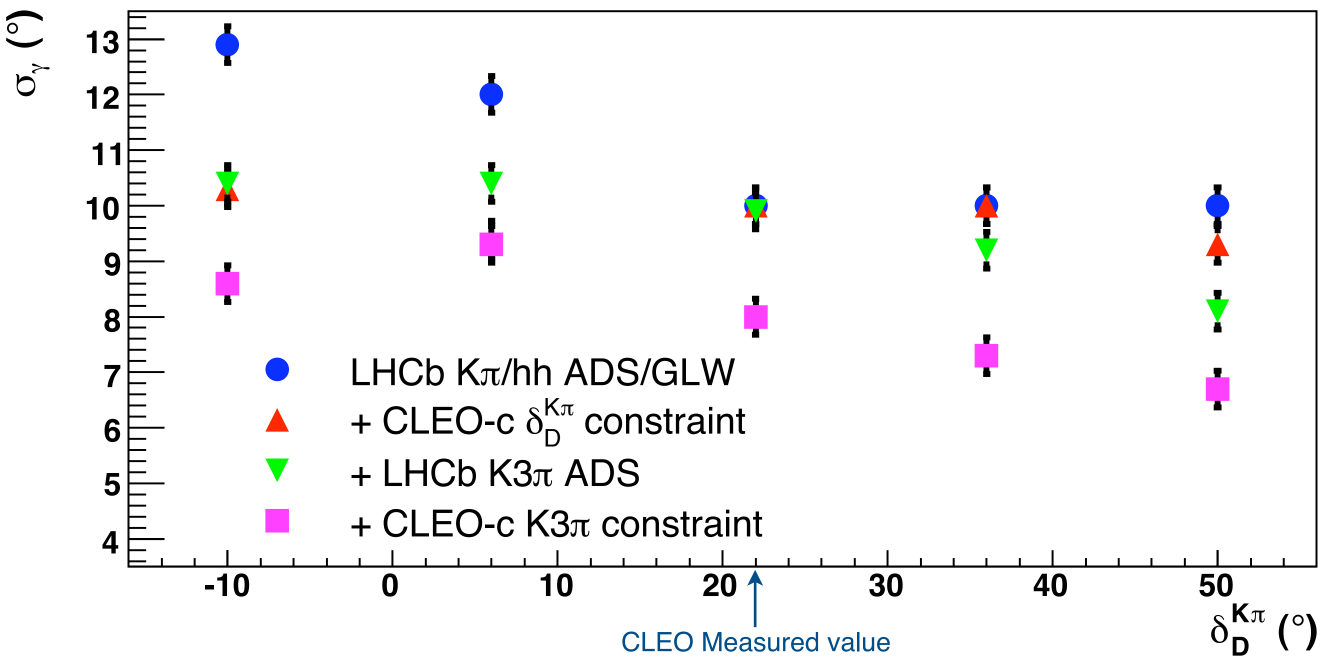
$K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. $K^{\pm}\pi^{\mp}$



- We combine the results to make confidence plots for $R_{K3\pi}$
- Low coherence is preferred
- Allows accurate determination of r_B useful for all $B^{\pm} \to DK^{\pm}$ decays
- **Improving the measurement of r_B improves the measurements of γ via ADS 2-body and Dalitz plot methods.**



Example: Impact of CLEO-c Kπππ at LHCb

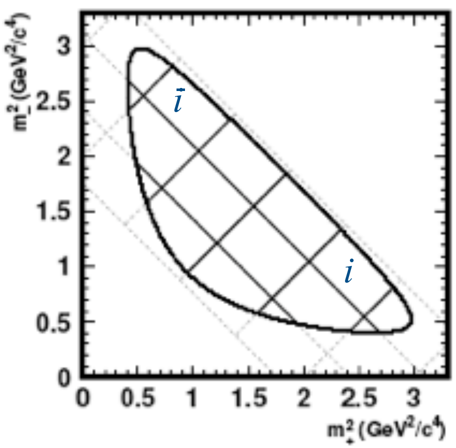


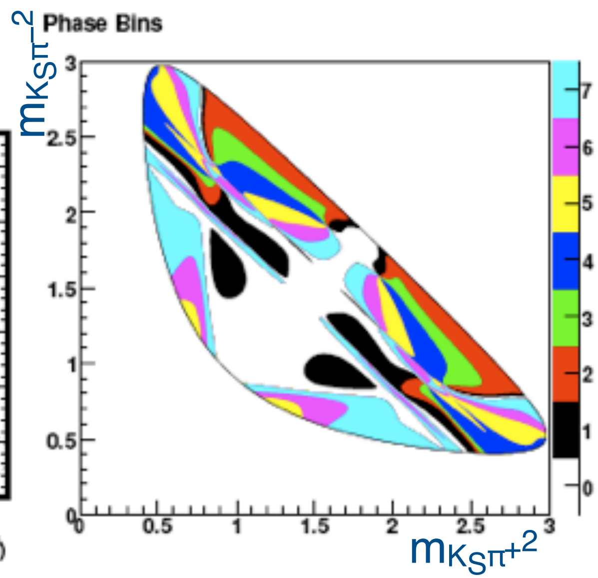
- These D→K3π measurements have been input to ADS simulation studies by LHCb
- Estimated yields documented in LHCb-2006-066 and LHCb-2007-004
- One nominal year of LHCb running: results see significant improvement with the addition of B→D(K3π)K and the CLEO-c constraints
  - **Added info from CLEO equivalent to ~doubling the LHCb data!**

Using $D \to K_S\pi\pi$ Decays at CLEO

- $f(D) = K_S\pi\pi$ can be used as well
- Then a Dalitz plot analysis may be used to extract γ.
- Now, the interference depends on the D^0, $\overline{D^0}$ phase difference ($\delta_{x,y} - \delta_{y,x}$), as a function of position in the Dalitz plot.
- To date, this has been taken from results of uncorrelated Dalitz plot analyses, which suffer from a model dependence.
- Giri, et al. [Phys. Rev. D **68** (2003) 054018] and Bondar and Poluektov [Eur. Phys. J. C **47**, 347-353(2006) & arXiv:0801.0840v1 (hep-ex)] demonstrate a way to do a binned Dalitz plot analysis of neutral $D \to K_S\pi\pi$ which does not suffer from model dependence.
- **CLEO-c data has an essential role in the model-independent approach.**

Binned Analysis of $D \to K^0_S\pi^+\pi^-$ at CLEO-c





- It can be shown that:

$$c_i = \frac{(M_i^+/S_+ - M_i^-/S_-)}{(M_i^+/S_+ + M_i^-/S_-)} \frac{(K_i + K_{\bar{i}})}{2\sqrt{K_i K_{\bar{i}}}}.$$

$S_+(S_-)$, number of single tags for CP even(odd) modes.
$M_i^+(M_i^-)$, yields in each bin of Dalitz plot in CP even(odd) modes.
$K_i(K_{\bar{i}})$, yields in each bin of Dalitz plot in flavor modes.

- Instead of square bins, we use bins of some range in δ_D

$$c_i = \frac{1}{\sqrt{T_i T_{\bar{i}}}} \int_{D_i} |A_D(x,y)||A_D(y,x)| \cos(\delta_{x,y} - \delta_{y,x}) dx dy$$

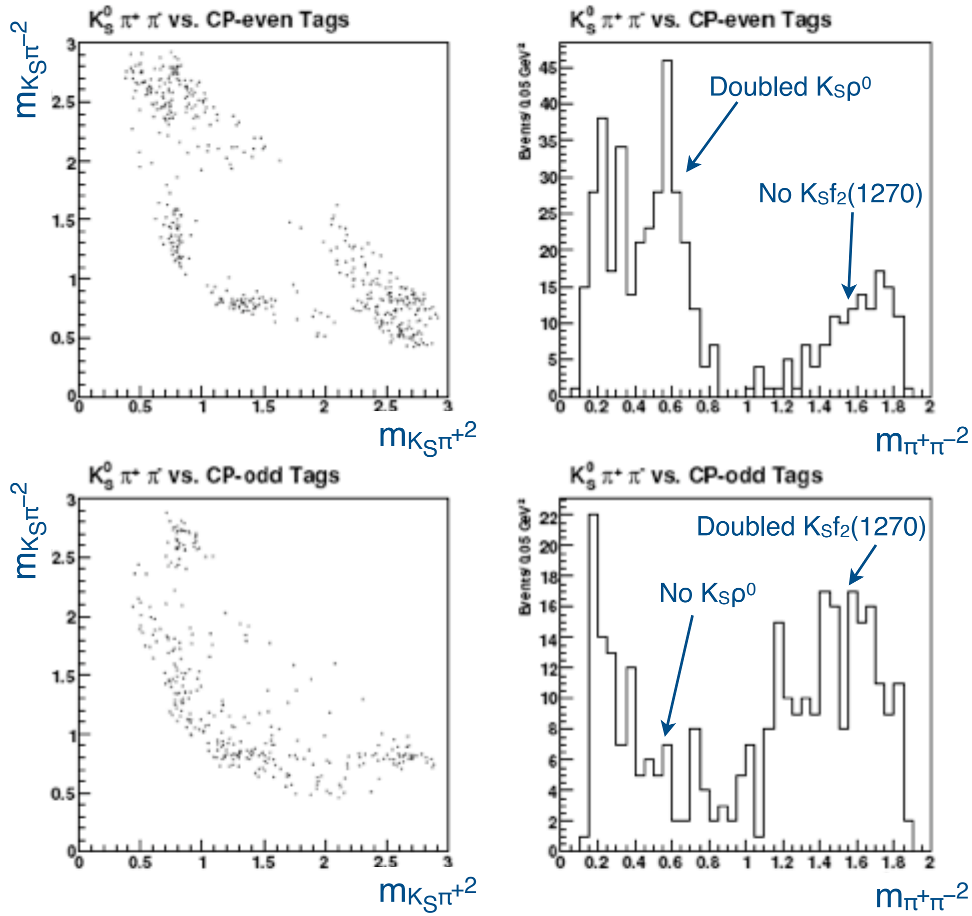
$$s_i = \frac{1}{\sqrt{T_i T_{\bar{i}}}} \int_{D_i} |A_D(x,y)||A_D(y,x)| \sin(\delta_{x,y} - \delta_{y,x}) dx dy$$

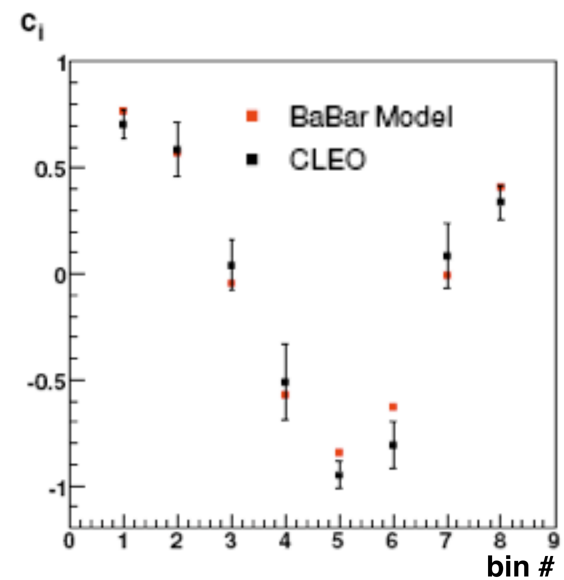
$$T_i \equiv \int_i |A_D(x,y)|^2 dx dy$$

Preliminary CP tagged $K^0_S\pi^+\pi^-$ results

- Results for c_i using 8 bins:

CLEO-c Preliminary (818 pb^{-1})
http://beach2008.sc.edu/includes/documents/sessions/he.talk.pdf





c_1	0.706±0.069±0.028
c_2	0.586±0.126±0.037
c_3	0.041±0.120±0.043
c_4	-0.510±0.178±0.074
c_5	-0.949±0.063±0.029
c_6	-0.807±0.108±0.039
c_7	0.085±0.154±0.046
c_8	0.339±0.082±0.024

- ~ 800 CP-tagged events

BABAR Collaboration, Arxiv:hep-ex/0607104

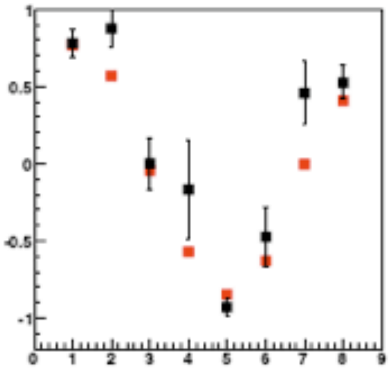
CLEO-c Preliminary $K^0_S\pi^+\pi^-$ vs. $K^0_S\pi^+\pi^-$ results

- The CP-tagged sample of $K^0_S\pi^+\pi^-$ can only give us values for c_i
- Using a $K^0_S\pi^+\pi^-$ vs. $K^0_S\pi^+\pi^-$ sample, we can extract c_i and s_i simultaneously

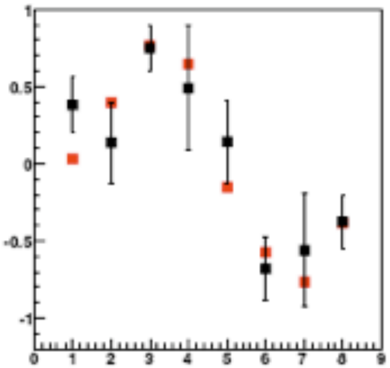
$$M_{i,j} = \frac{1}{2N_{D,\bar{D}}\mathcal{B}_f^2}\left(K_i K_{\bar{j}} + K_{\bar{i}} K_j - 2\sqrt{K_i K_{\bar{j}} K_{\bar{i}} K_j}(c_i c_j + s_i s_j)\right).$$

■ BaBar Model   Arxiv:hep-ex/0607104
■ CLEO

c_i



s_i



CLEO-c Preliminary (818 pb^{-1})

http://beach2008.sc.edu/includes/documents/sessions/he.talk.pdf

	Value		Value
c_1	0.779±0.087±0.062	s_1	0.380±0.179±0.085
c_2	0.874±0.120±0.113	s_2	0.137±0.260±0.084
c_3	0.003±0.166±0.152	s_3	0.749±0.145±0.053
c_4	-0.165±0.323±0.152	s_4	0.490±0.400±0.093
c_5	-0.929±0.058±0.044	s_5	0.141±0.268±0.085
c_6	-0.472±0.196±0.099	s_6	-0.679±0.203±0.059
c_7	0.459±0.204±0.170	s_7	-0.558±0.367±0.106
c_8	0.526±0.109±0.114	s_8	-0.376±0.169±0.060

- ~ 450 $(K^0_S\pi^+\pi^-)^2$
- Combine CP-tagged $K^0_S\pi^+\pi^-$ and $K^0_S\pi^+\pi^-$ vs. $K^0_S\pi^+\pi^-$ samples: systematic uncertainty on γ from c_i, s_i expected to be ~2°. Adding $K^0_L\pi^+\pi^-$ statistics reduces this to ~1°.

Summary

- **CLEO-c data is vital for the purpose of γ extraction strategies with $B^{\pm} \rightarrow D_{\text{multi-body}}K^{\pm}$**
- A **first determination** of the $D \rightarrow K\pi\pi\pi$ coherence factor, $R_{K3\pi}$, has been made (and its associated global strong phase $\delta_D^{K3\pi}$)
  - Results already have a significant impact; further improvements to this result are foreseen with the addition of K_L CP modes in the selection
  - Additional ADS modes are being studied ($D \rightarrow K\pi\pi^0$)
- CLEO-c is also **measuring the average cosine and sine of $D \rightarrow K^0_S\pi\pi$ strong phase differences** to allow a model-independent determination of γ with $B^{\pm} \rightarrow D_{K_S\pi\pi} K^{\pm}$
  - Further improvements to this result are foreseen with the addition of $K^0_L\pi\pi$ candidates
  - D decay-model systematic error of 6°-15° from currently available $D \rightarrow K^0_S\pi\pi$ Dalitz plot analyses will be replaced with a residual D decay systematic error of 1°-2°!

Measuring $R_{K3\pi}$ at CLEO-c

- Determinations of $R_{K3\pi}$ and $\delta_D^{K3\pi}$ can be are made from analysis of double-tagged $D^0\overline{D^0}$ at CLEO-c.
- The coherent production of this state causes the double-tagged rates of $K\pi\pi\pi$ vs. X to be altered in the following ways:

Double Tag Rate	Sensitive To
$K^\pm\pi^\mp\pi^+\pi^-$ vs. $K^\pm\pi^\mp\pi^+\pi^-$	$(R_{K3\pi})^2$
$K^\pm\pi^\mp\pi^+\pi^-$ vs. CP	$R_{K3\pi}cos(\delta^{K3\pi})$
$K^\pm\pi^\mp\pi^+\pi^-$ vs. $K^\pm\pi^\mp$	$R_{K3\pi}cos(\delta^{K\pi}-\delta^{K3\pi})$

- We perform selections of these double-tags
- In addition, it is also necessary to perform selections of the opposite sign $K^\pm$ modes to determine normalisation factors

Uncertainty due to $K^0\pi\pi$ decay

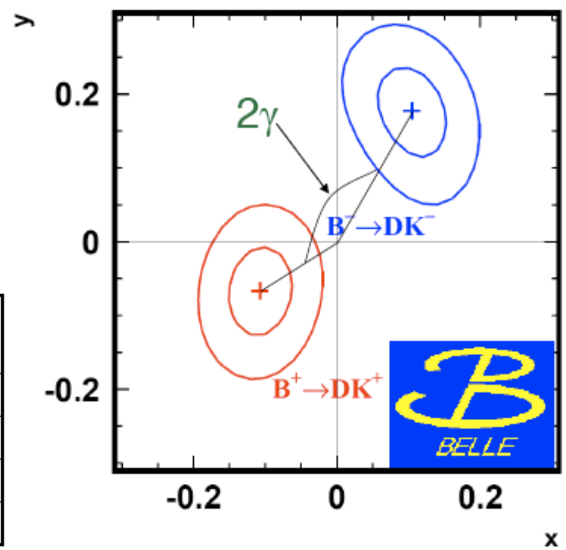
Bondar, et al. says uncertainty due to $K^0\pi\pi \sim 5°$

Binning	Q	B-stat. err.		D_{CP}-stat. err.		$(K^0_S\pi^+\pi^-)^2$-stat. err.	
		σ_x	σ_y	σ_x	σ_y	σ_x	σ_y
$\mathcal{N} = 8\ (\Delta\delta_D)$	0.79	0.027	0.037	0.004	0.007	0.005	0.010

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

5° uncertainty assumed $\sigma_x = \sigma_y = 0.010$

arXiv:0803.3375 [hep-ex]



Model-independent studies have been performed for LHCb with 8 $\Delta\delta_d$ bins (LHCb-2007-141). We use the same code to evaluate γ systematic uncertainties from the measured c_i and s_i

These uncertainties have less impact (using Belle's central values)

Parameter	RMS toy	RMS B&P (scaled to actual yields)
x_+	0.005	0.004
y_+	0.005	0.007
x_-	0.005	0.004
y_-	0.014	0.007