Flavour physics at CLEO-c

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On behalf of the CLEO-c collaboration

- Introduction to CLEO-c
- Measurements related to D-mixing
- Measurements related to the determination of γ via $B^{\pm} \to DK^{\pm}$
  - $D \to K^{-}\pi^{+}\pi^{+}\pi^{-}$
  - $D \to K^{0}_{S}\pi^{+}\pi^{-}$

Introduction to CLEO-c

- Detector at the Cornell Electron Storage Ring (CESR)
- Operating at energies around $c\bar{c}$ threshold
- Relevant data sets for flavour measurements:
  - E_{CM} = 4170 MeV $\mathscr{L}_{\mathrm{int}} \sim 600\ \mathrm{pb}^{-1}$
    Determination of form factor f_{Ds} at CLEO-c is a critical test of lattice QCD and sensitive to new physics

CLEO c arXiv:0712.1175v1 [hep ex]
f_{Ds}=(274 ± 10 ± 5) MeV

LQCD- arXiv:0706.1726 [hep lat]
f_{Ds}=(241 ± 3) MeV

  - $\psi(3770)$ $\mathscr{L}_{\mathrm{int}} = 818\ \mathrm{pb}^{-1}$ **[This talk]**

$$e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0 \qquad C = -1$$

- **Quantum correlated state:**
  For example, reconstruct one D decay to a *CP* eigenstate uniquely identifies the other D to be of opposite *CP*

CLEO-c results on *D*-mixing

D mixing

- Rate of D mixing parameterised by:

$$x = 2\frac{M_+ - M_-}{\Gamma_+ + \Gamma_-} \text{ and } y = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}$$

where $M_\pm$ ($\Gamma_\pm$) are mass (width) of the CP $= \pm 1$ eigenstates

- Time-dependent wrong-sign rate $D^0 \rightarrow K^-\pi^+$:
  - Sensitivity via interference between DCS and mixing amplitudes
  - Ambiguity from strong phase: $y' = y\cos\delta - x\sin\delta$

$$A_{DCS}/A_{CF} = \langle K^-\pi^+|\overline{D^0}\rangle \;/\; \langle K^-\pi^+|D^0\rangle = -re^{-i\delta}$$

- Direct comparison with y measurements from CP-eigenstate lifetimes and time-dependent measurements of $D\rightarrow K^0{}_S\pi\pi$ Dalitz plot **not possible** without determination of δ
- **δ and other mixing parameters can be measured in quantum correlated $D\bar{D}$ decay at CLEO-c**
  - **D. Asner and W. Sun, Phys. Rev. D73, 034024 (2006)**

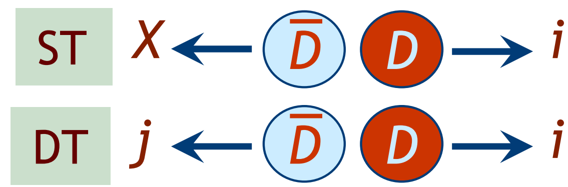
Coherent vs. Incoherent Decay

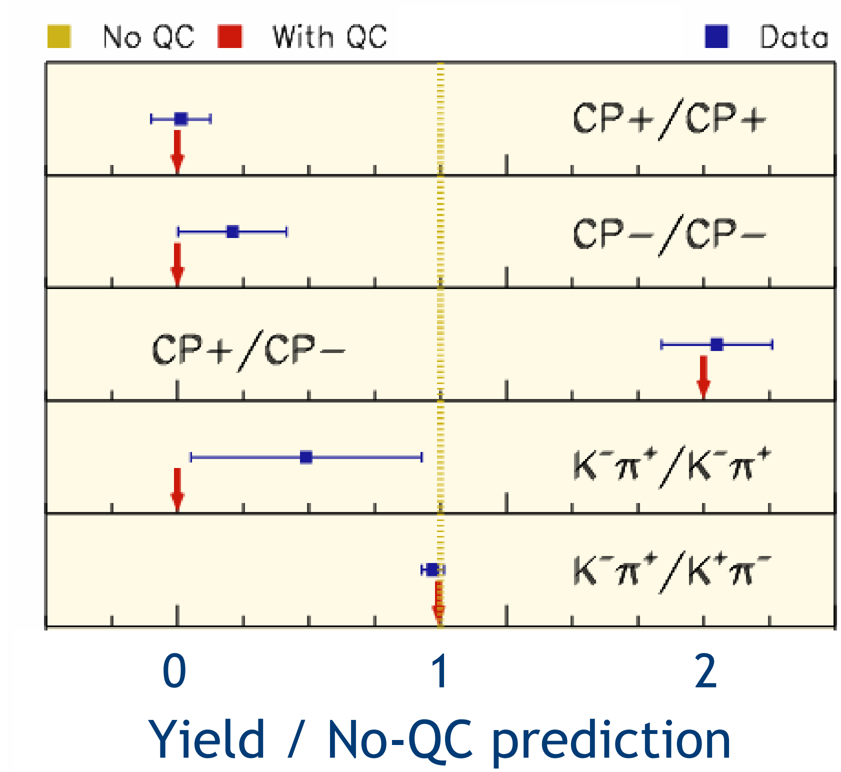
- We use yields for
  - single tags (one D reconstructed)
  - double tags (D and $\bar{D}$ reconstructed)

DT	$K^-\pi^+$	e^+	$CP+$	$CP-$
$K^-\pi^+$	R_M / R_{WS}	$\frac{\text{QC rate}}{\text{incoherent rate}}$		
$K^+\pi^-$	$1 + 2R_{WS} - 4r\cos\delta\,(r\cos\delta + y)$			
e^-	$1 - r(y\cos\delta + x\sin\delta)$	1		
$CP+$	$1 + (2r\cos\delta + y) / (1 + R_{WS})$	$1 + y$	0	
$CP-$	$1 - (2r\cos\delta + y) / (1 + R_{WS})$	$1 - y$	2	0
ST	1	1	1	1

$R_M = (x^2 + y^2)/2$ and $R_{WS} = r^2 + ry' + R_M$

- Compare coherent/incoherent BFs
- Sources of incoherent BFs:
  - Externally measured BFs
  - Single tags at $\psi(3770)$





Quantum correlations are seen in data!

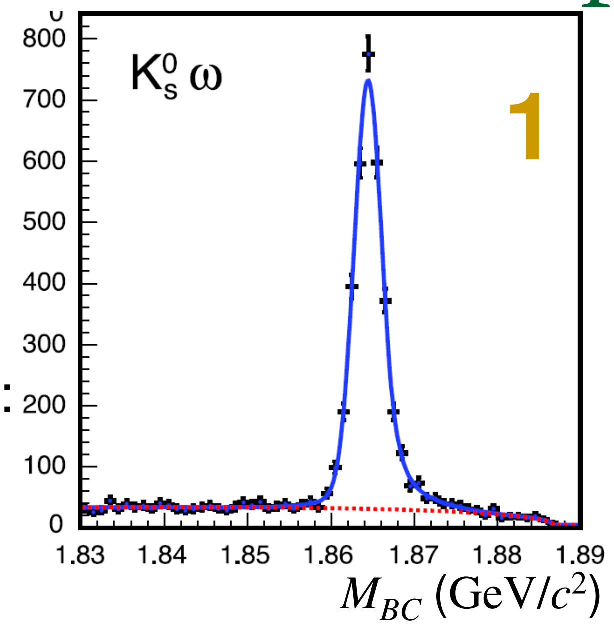
Yield measurements in 281 pb^{-1}

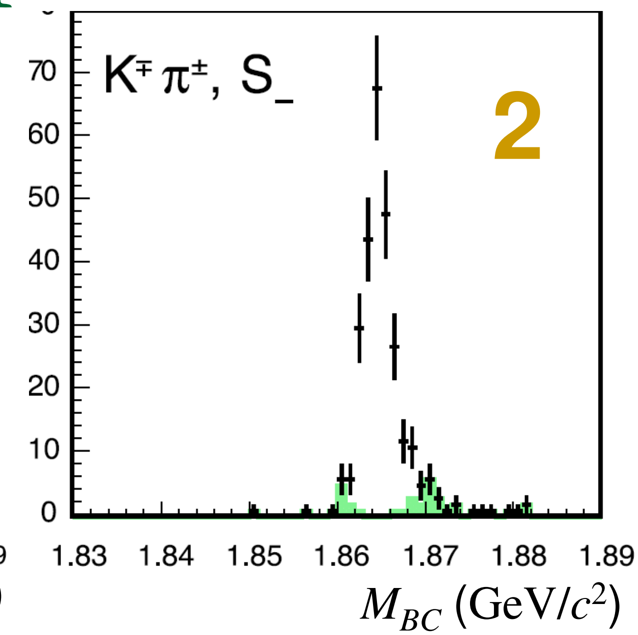
arXiv:0802.2264 [hep-ex]
arXiv:0802.2268 [hep-ex]

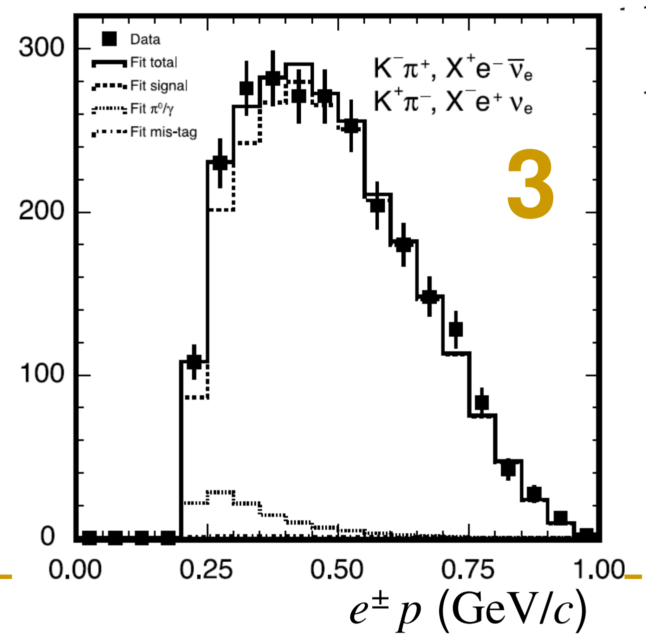
1. Fully-reconstructed single tags:
   - Fit beam-constrained mass distribution

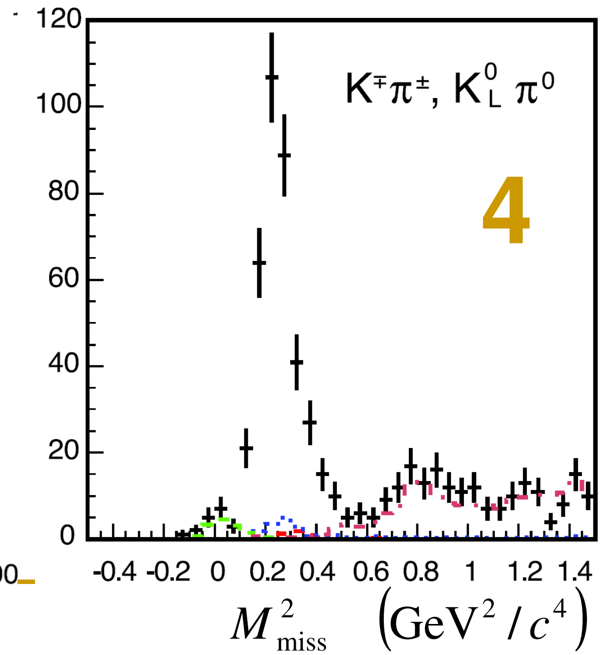
$$M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2}$$

2. Fully-reconstructed double tags:
   - Two fully-reconstructed STs
3. Inclusive semileptonic DTs:
   - One fully-reconstructed ST
   - Plus one electron candidate
   - Fit $e^{\pm}$ momentum spectrum
4. $K^0_L \pi^0$ double tags:
   - One fully-reconstructed ST
   - Plus one π^0 candidate
   - Compute missing mass^2
     - Signal peaks at $M^2(K^0)$.









External inputs

- External inputs improve y and $\cos\delta$ precision
- All correlations among measurements included in fit
- Standard fit includes:
  - Info on r needed to obtain $\cos\delta$:
    - $R_{WS} = r^2 + ry' + R_M$
    - $R_M = (x^2 + y^2)/2$
    - Assume $x\sin\delta = 0 \Rightarrow y' \approx y\cos\delta$
  - $K\pi$ and CP-eigenstate BFs
- Extended fit averages y and y':
  - CP+ lifetimes (y)
  - $K^0_S\pi^+\pi^-$ Dalitz analysis (x, y)
  - $K\pi$ CP-conserving fits (y', r^2, R_M)

Parameter	Average (%)
$R_{\rm WS}$	0.409 ± 0.022
$R_{\rm M}$	0.0173 ± 0.0387

Parameter	Value (%)
$\mathcal{B}(K^-\pi^+)$	3.81 ± 0.09
$\mathcal{B}(K^0_S\pi^0)$	1.15 ± 0.12
$\mathcal{B}(K^0_S\eta)$	0.380 ± 0.060
$\mathcal{B}(K^0_S\omega)$	1.30 ± 0.30
$\mathcal{B}(K^0_L\pi^0)$	1.003 ± 0.083
$\mathcal{B}(K^-K^+)/\mathcal{B}(K^-\pi^+)$	10.10 ± 0.16
$\mathcal{B}(\pi^-\pi^+)/\mathcal{B}(K^-\pi^+)$	3.588 ± 0.057

Parameter	Value (%)
y	0.662 ± 0.211
x	0.811 ± 0.334
r^2	0.339 ± 0.012
y'	0.34 ± 0.30
x'^2	0.006 ± 0.018

Results

First determination

arXiv:0802.2264 [hep-ex]
arXiv:0802.2268 [hep-ex]

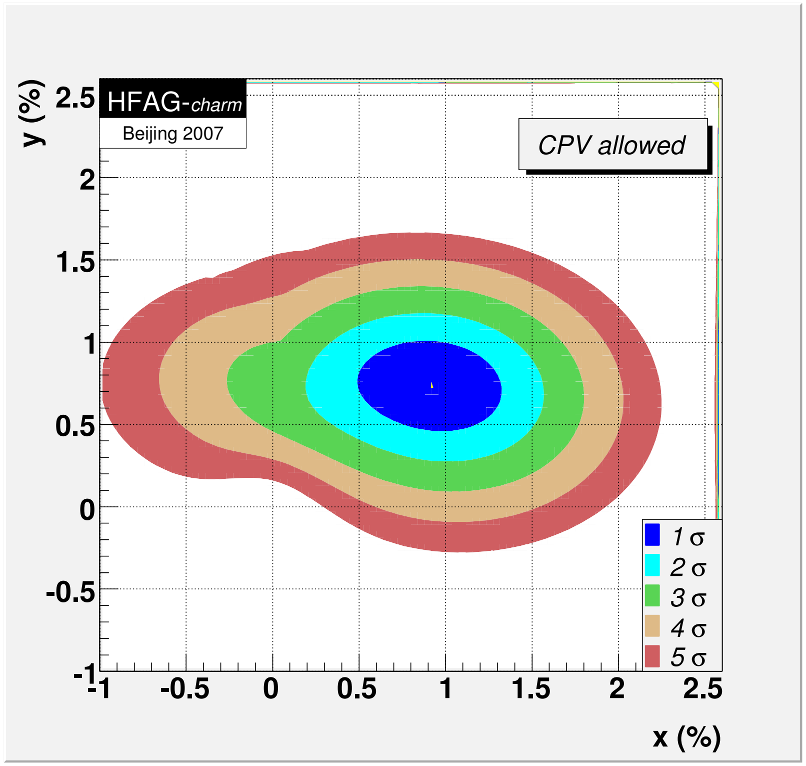
Parameter	Standard Fit	Extended Fit
y (10^{-3})	$-45 \pm 59 \pm 15$	$6.5 \pm 0.2 \pm 2.1$
r^2 (10^{-3})	$8.0 \pm 6.8 \pm 1.9$	$3.44 \pm 0.01 \pm 0.09$
$\cos\delta$	$1.03 \pm 0.19 \pm 0.06$	$1.10 \pm 0.35 \pm 0.07$
x^2 (10^{-3})	$-1.5 \pm 3.6 \pm 4.2$	$0.06 \pm 0.01 \pm 0.05$
$x\sin\delta$ (10^{-3})	0 (fixed)	$4.4 \pm 2.4 \pm 2.9$
$\chi^2_{\rm fit}/\text{ndof}$	$30.1/46$	$55.3/57$

- Standard fit result important component in average of charm mixing
- Extended fit leads to measurement of:

$$\delta = \left(22^{+11+9}_{-12-11}\right)^\circ$$

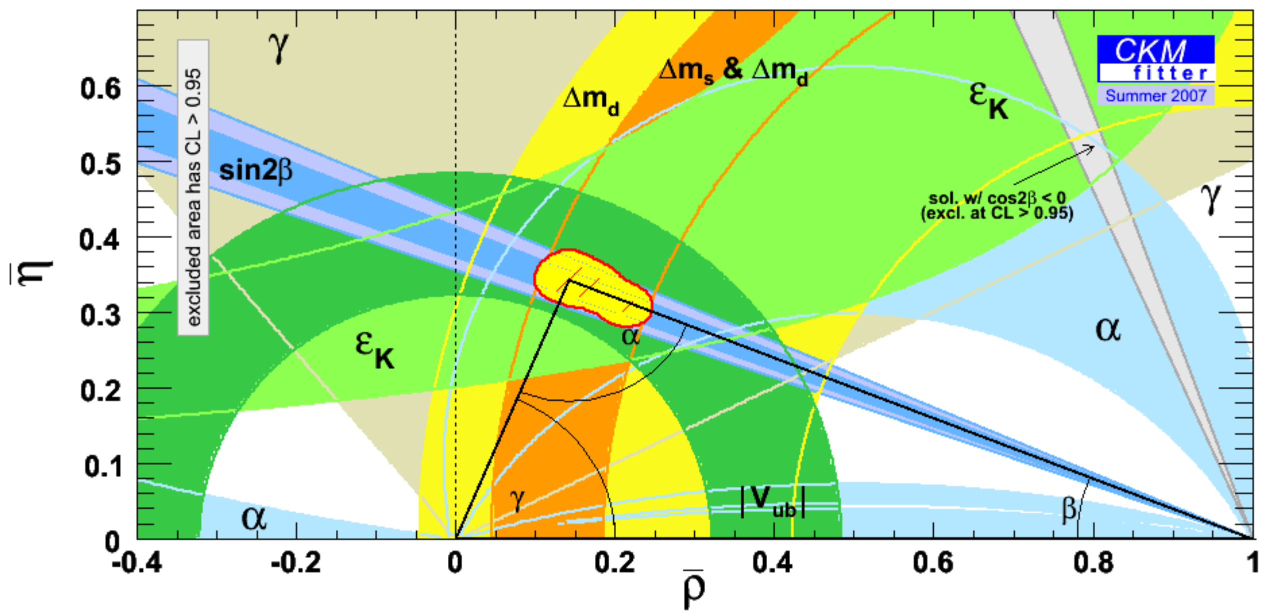
From likelihood scan of physically allowed region

- Future improvements:
  - Full $\psi(3770)$ data set – 818 pb^{-1}
  - WS semileptonics vs. $K\pi$
  - Additional K^0_L modes
  - C-even information from 4170 MeV data



CLEO-c results related to γ determination

Status of direct determination of γ

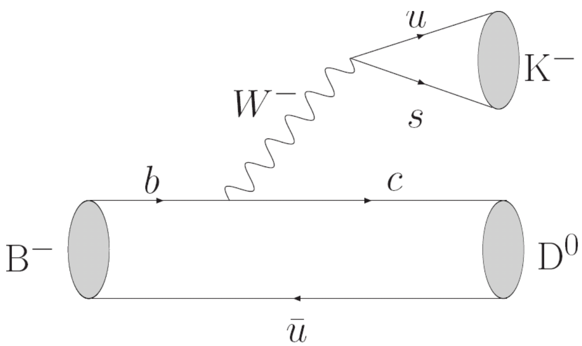


- γ is the least well determined angle of the unitarity triangle with an uncertainty of ~30° from direct measurements
  - σ_β = 1°

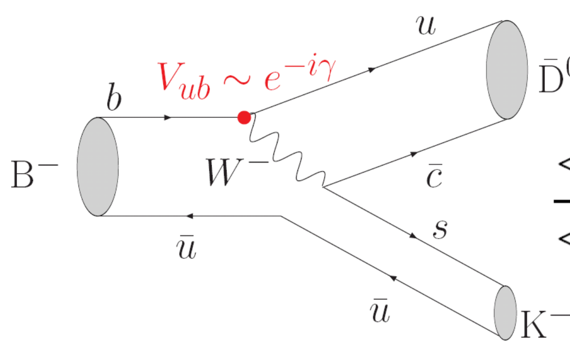
- Comparison of measurements of γ in tree and loop processes sensitive to new physics
  - **Side opposite - B-mixing measurements loop only**

γ from $B^{\pm} \to DK^{\pm}$

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



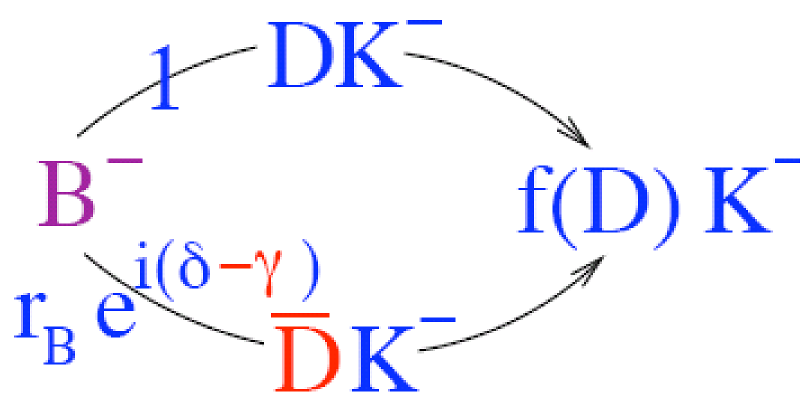
$B^- \longrightarrow \overline{D}^0 K^-$



Colour/CKM suppressed – r_B~0.1

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

- Extraction through interference between $b \to c$ and $b \to u$ transitions
- Require decay of D^0 and $\overline{D^0}$ to a common final state, f(D)
- A theoretically clean determination of γ
  - **SM 'standard candle'**

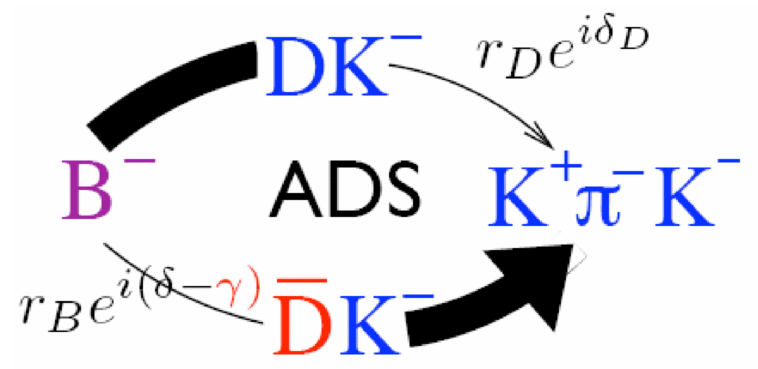


Atwood-Dunietz-Soni (ADS) Method

f(D) = non-CP Eigenstate (e.g. $K^+\pi^-$)

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

r_D ~0.06



$$\Gamma(B^- \rightarrow (K^-\pi^+)_D K^-) \propto 1 + (r_B r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B - \delta_D^{K\pi} - \gamma) \quad (1)$$

$$\Gamma(B^- \rightarrow (K^+\pi^-)_D K^-) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B + \delta_D^{K\pi} - \gamma) \quad (2)$$

$$\Gamma(B^+ \rightarrow (K^+\pi^-)_D K^+) \propto 1 + (r_B r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B - \delta_D^{K\pi} + \gamma) \quad (3)$$

$$\Gamma(B^+ \rightarrow (K^-\pi^+)_D K^+) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B + \delta_D^{K\pi} + \gamma) \quad (4)$$

- From counting these 4 rates, together with those from CP eigenstates (*KK, ππ*), a determination of γ can be made
- Key measurement of LHCb and future e^+e^- B-factories
  - For example ~10° precision with one year of LHCb running [LHCb-2008-011]

Four-body ADS

- $B \rightarrow D(K\pi\pi\pi)K$ can also be used for ADS style analysis
  - Double the branching fraction of $B \rightarrow D(K\pi)K$
- However, need to account for the resonant substructure
  - $D \rightarrow K^*\rho$, $K^- a_1(1260)^+$, etc
  - in principle each point in the phase space has a different strong phase associated with it

- Atwood and Soni (hep-ph/0304085) showed how to modify the usual ADS equations for this case
  - Introduce **coherence parameter $R_{K3\pi}$** which dilutes interference term sensitive to γ

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

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

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

Event selection

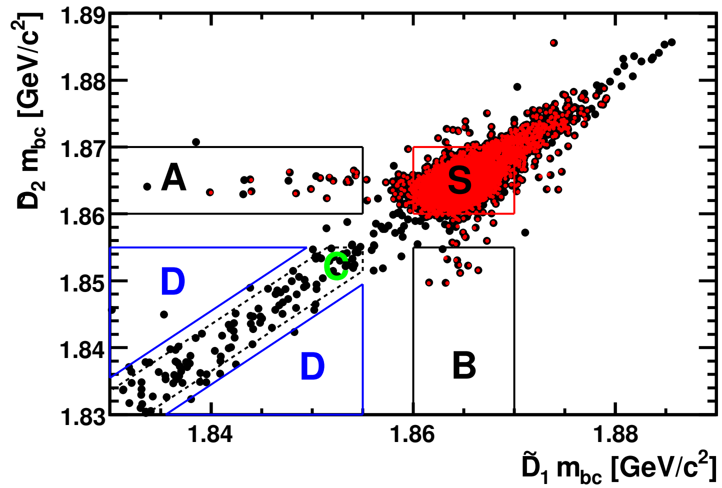
- Selections performed over all $\psi(3770)$ data, corresponding to 818 pb^{-1}.
- Consider 8 different CP tags:

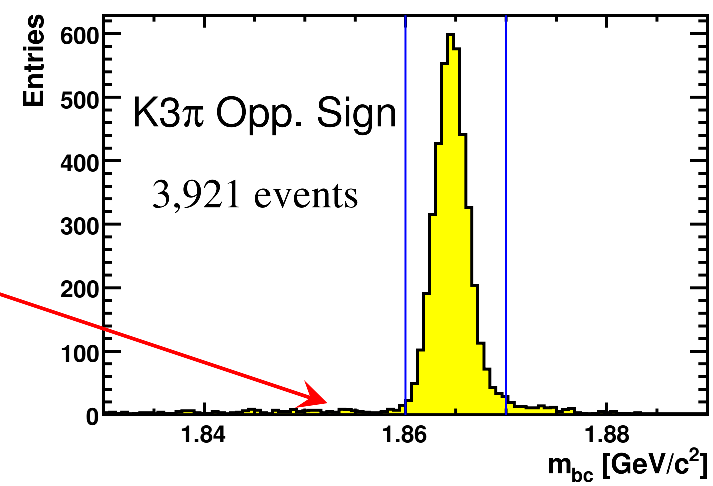
CP Tag	Yield
KK, $\pi\pi$	758
$K_s\pi^0$	695
$K_S\omega(\pi^+\pi^-\pi^0)$	251
$K_S\pi^0\pi^0$	260
$K_S\phi(K^+K^-)$	31
$K_S\eta(\{\gamma\gamma, \pi^+\pi^-\pi^0\})$	157
$K_S\eta'(\pi^+\pi^-\eta)$	31
	2,183

CP = 1, *CP* = -1

- Assess flat background from mass side bands and peaking from MC:

$$m_{bc}^2 = (E_{beam})^2/c^4 - (p_D)^2/c^2$$





- **Very low background levels**

$R_{K3\pi}$ preliminary results

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

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

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

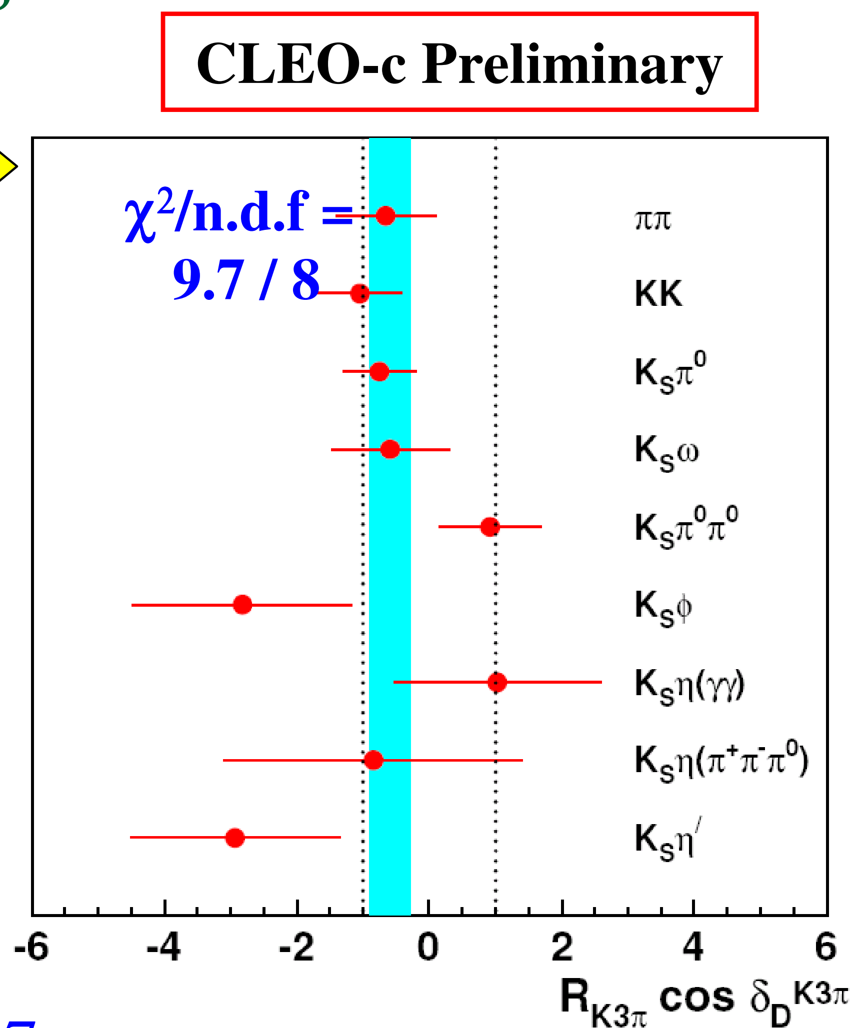
2) $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$

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

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

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

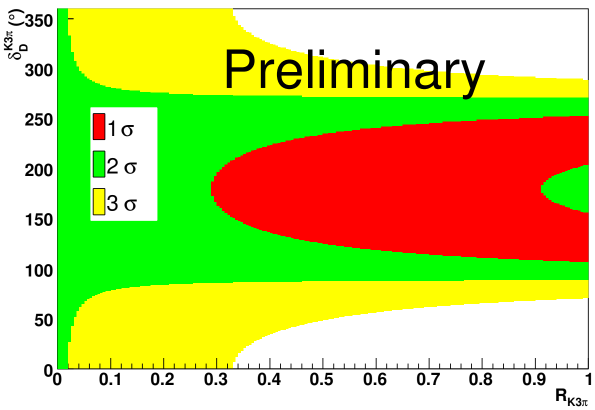
$$R_{K3\pi}\cos(\delta^{K\pi} - \delta^{K3\pi}) = 0.00 \pm 0.16 \pm 0.07$$



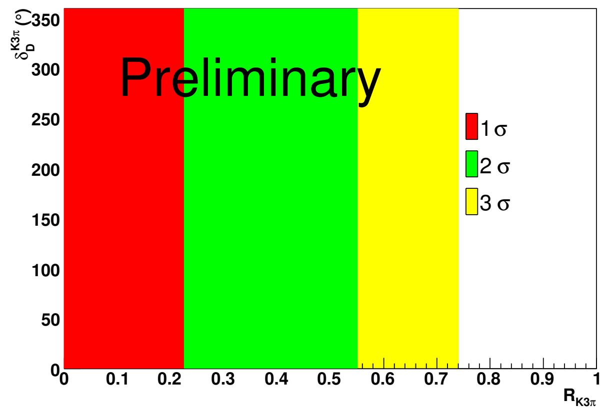
Used to constrain coherence factor by taking $\delta_D^{K\pi}$ from TQCA

Parameter Space Constraints

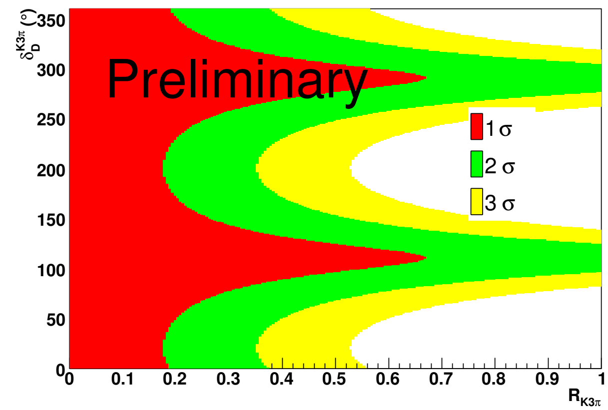
$K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. CP



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



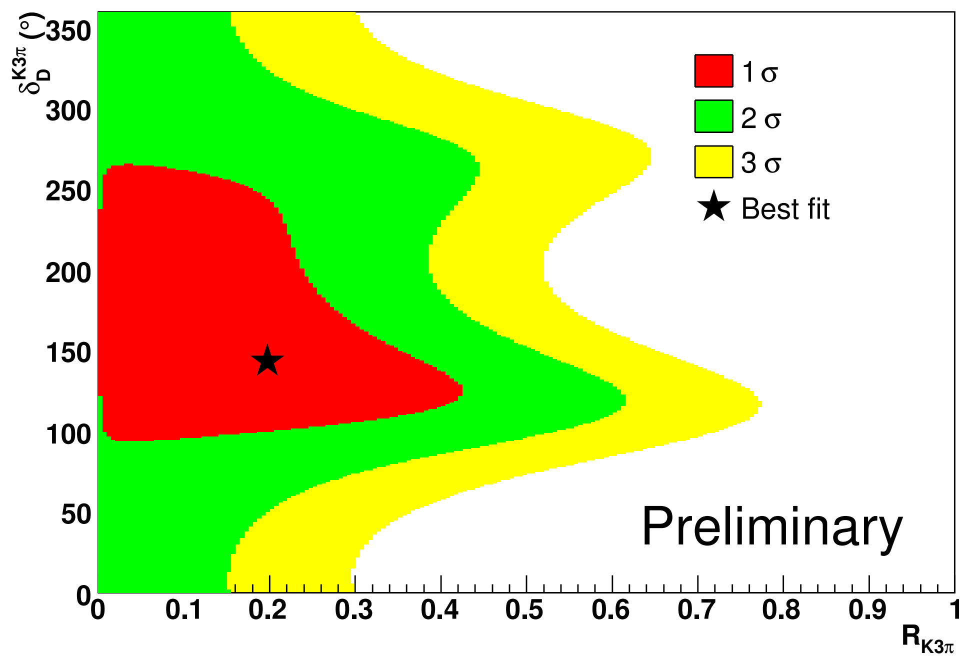
$K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. $K^{\pm}\pi^{\mp}$



Combination of the separate results together

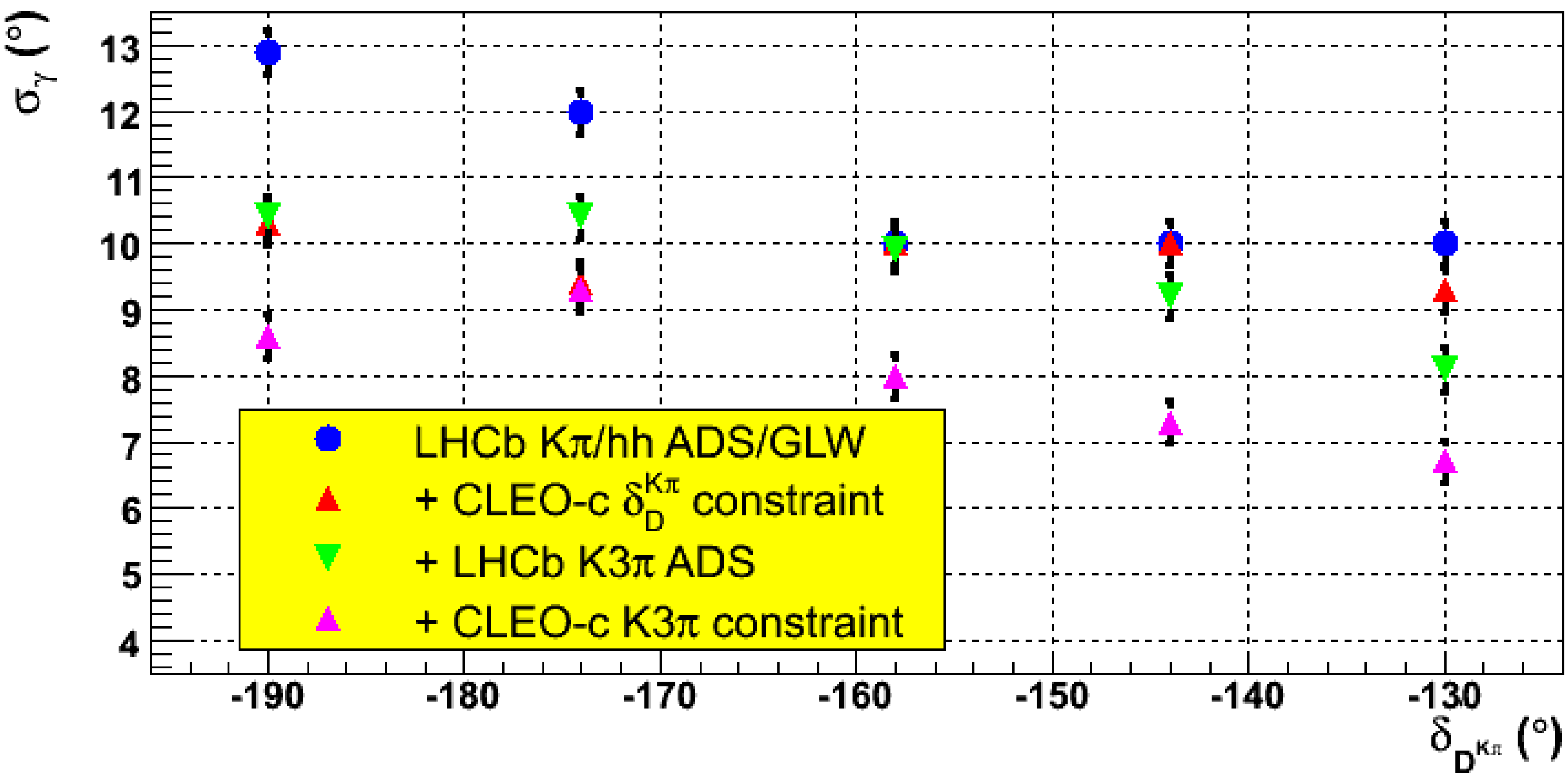
Low coherence preferred

Allows accurate determination of r_B useful for all $B^{\pm} \rightarrow DK^{\pm}$



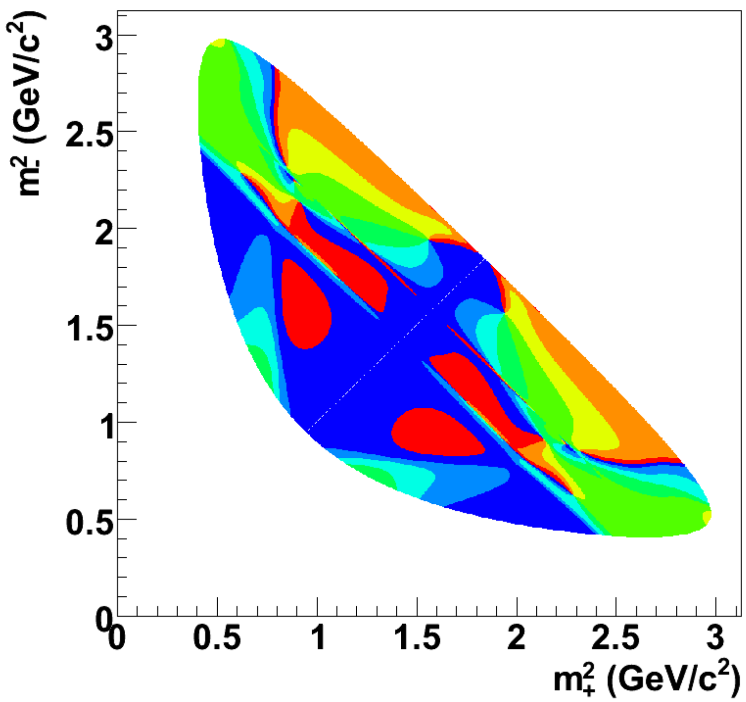
Impact of CLEO-c at LHCb

- 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 running results see significant improvement with the addition of $B \to D(K3\pi)K$ and the CLEO-c constraints



3-Body Dalitz: $B^{\pm} \rightarrow D(K_s\pi^+\pi^-)K^{\pm}$

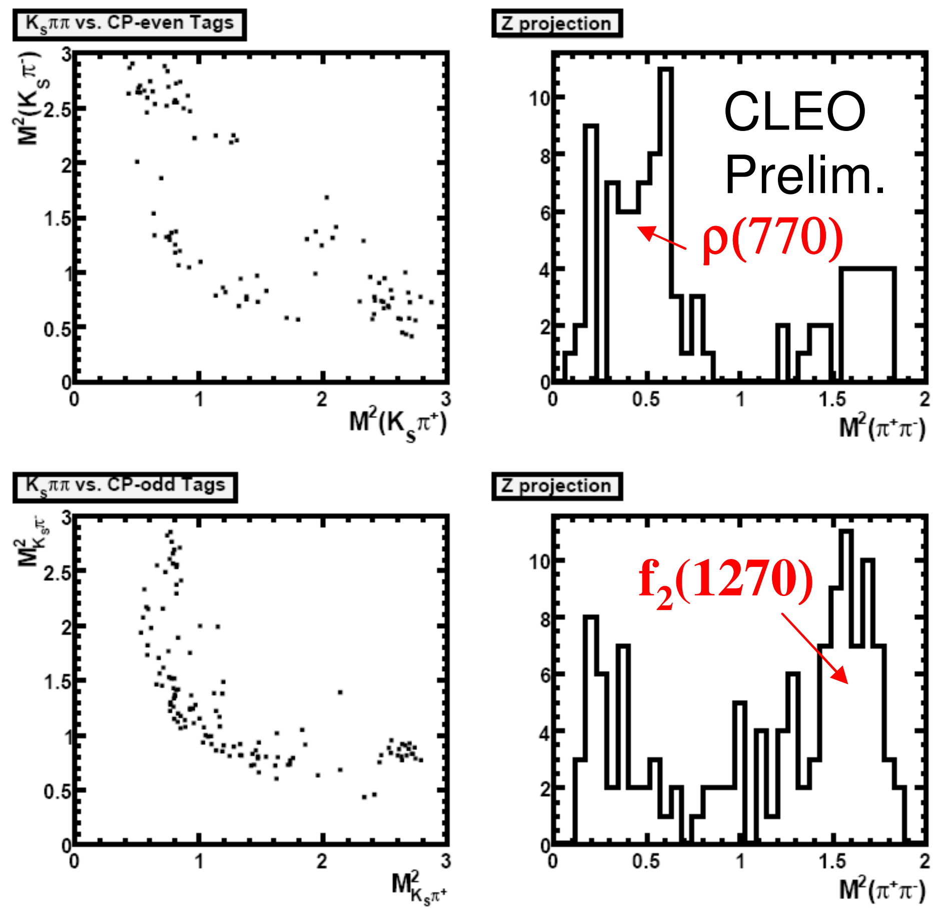
- Exploit interference over Dalitz space
- Amplitude fit to *D* Dalitz plots from *B+* and *B-* to extract r_B, γ and δ_B.
- Need to assume an isobar model for D-decay amplitudes
  - Measure amplitudes well with flavour tag sample
- Current best constraints from the B-Factories
  - **But model assumptions lead to a ~10° error**



- Binned analysis of Dalitz space removes model error
  - **Need to measure strong phases averaged over bins at CLEO-c**
  - Most sensitive binning w.r.t. strong phase diff.

CLEO-c Impact on $B^{\pm} \rightarrow D(K_s\pi^+\pi^-)K^{\pm}$

- As in the coherence factor analysis, CP tagged decays are the key to accessing the parameter of interest.
- Specifically, the average value of $\cos(\Delta\delta_D)$ in each bin of the CP tagged Dalitz plot can be accessed from measuring the number of events in that bin with different CP-tags
- Measurements of $K_s\pi^+\pi^-$ vs. $K_s\pi^+\pi^-$ give sensitivity to $\sin(\Delta\delta_D)$



Preliminary studies presented at CHARM 07 indicate precisions that lead to 3-5° uncertainties on γ

Conclusion

- First determination of strong phase difference for $D \rightarrow K\pi$
  - Essential for interpretation of D-mixing

- CLEO-c data vital for for the purpose of γ extraction strategies with $B^{\pm} \rightarrow D(\mathit{Multi\text{-}Body})K^{\pm}$

- A first determination of the $D \rightarrow K\pi\pi\pi$ coherence factor, $\boldsymbol{R_{K3\pi}}$, has been made (and its associated global strong phase, $\delta_D^{K3\pi}$).
  - Further improvements to this result are foreseen with the addition of K_L CP modes in the selection.
  - Additional ADS modes are being studied ($D \rightarrow K\pi\pi^0$).

- In addition, CLEO-c is measuring the average cosine and sine of $K_s\pi\pi$ strong phase differences to allow model independent determination of γ with $B^{\pm} \rightarrow D(K_s\pi\pi)K^{\pm}$

Backup

TQCA extended fit likelihoods