The Crucial Role of CLEO-c in the Measurement of γ

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On behalf of the CLEO-c collaboration

Outline

- Measurement of γ using $B^{\pm}\rightarrow D^0K^{\pm}$ decays
- The importance of CLEO-c
- Preliminary results from $D^0\rightarrow K_SKK$ at CLEO-c

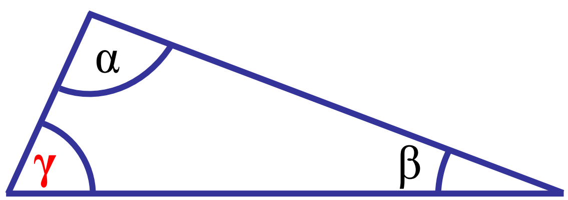
Measurement of γ using $B^{\pm} \rightarrow D^0 K^{\pm}$ decays

CKM Matrix & Unitarity Triangle

- **CKM matrix** quantifies flavour mixing between quarks
- Unitary: $V_{\text{CKM}}^{\dagger} V_{\text{CKM}} = 1$

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- A visual representation of the relation between the first and third columns is the **unitarity triangle**:

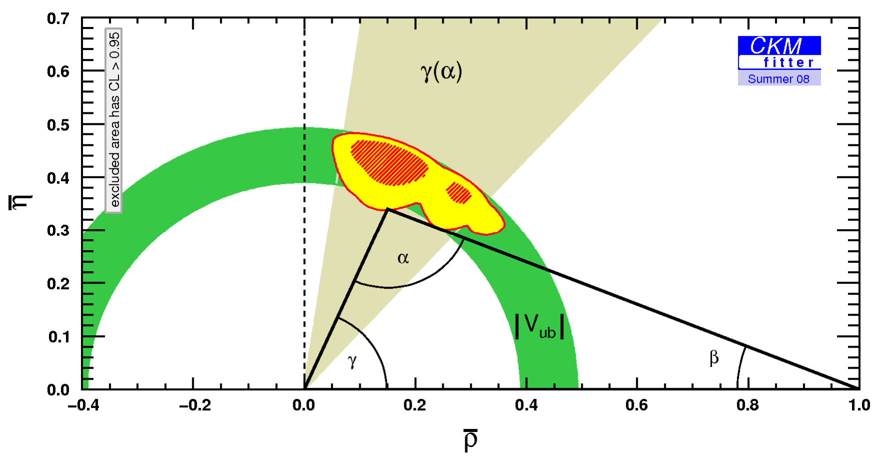


BaBar	Belle
α	φ_1
β	φ_2
γ	φ_3

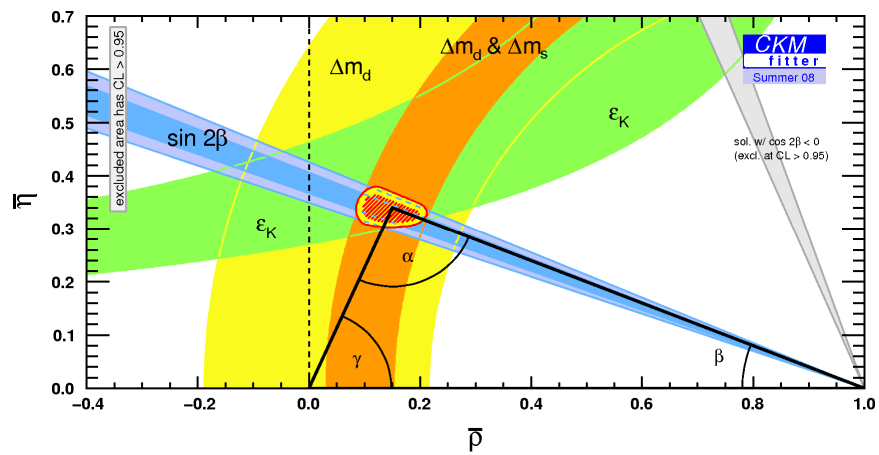
- **CP violation** in the SM results in an area greater than zero (e.g. $\gamma \neq 0, \pi$)

γ

- γ currently the least well known CKM angle
- State of the art (dir. meas.): $\gamma = (70^{+27}_{-29})^\circ$ [CKMfitter, 2009]



Tree measurements



Loop measurements

[CKMfitter, 2009]

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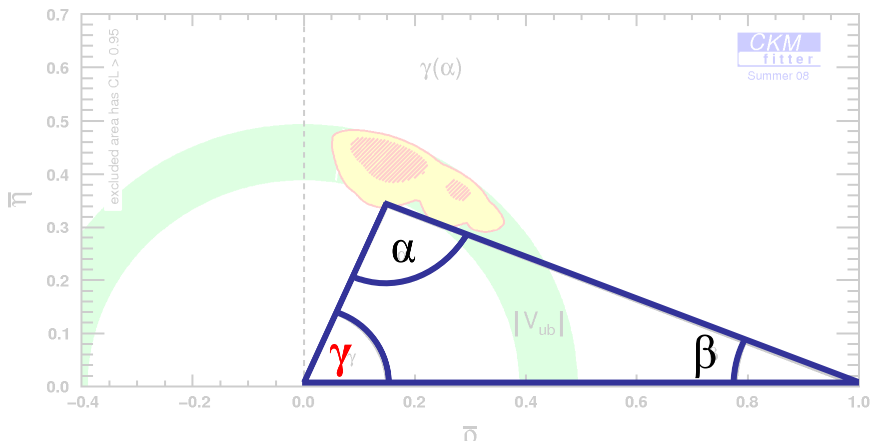

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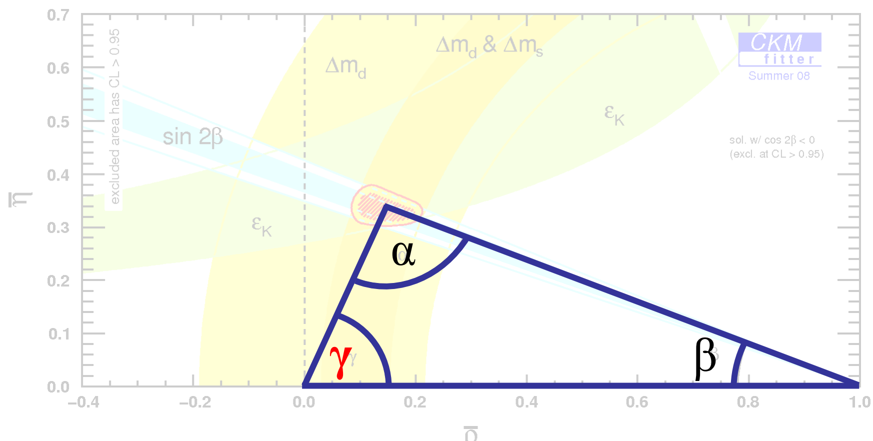

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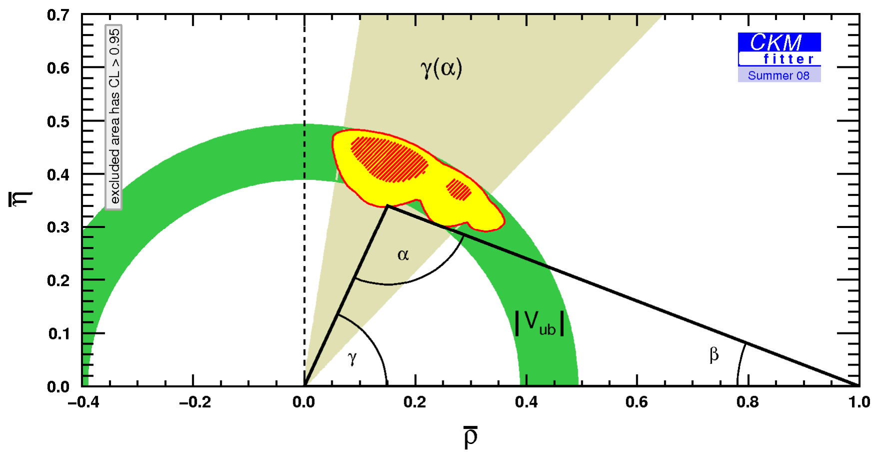

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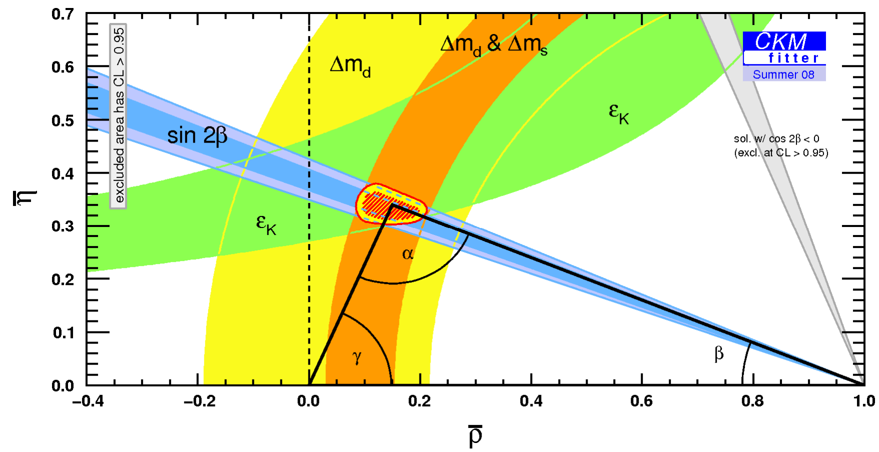


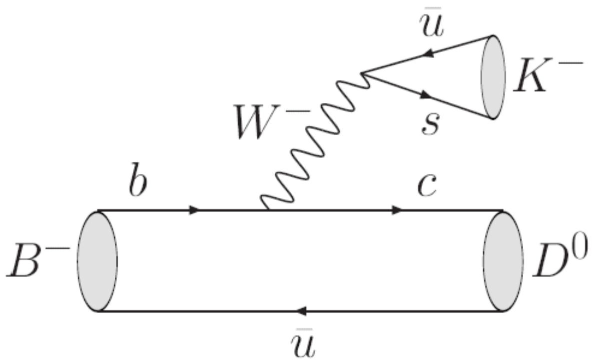
Loop measurements

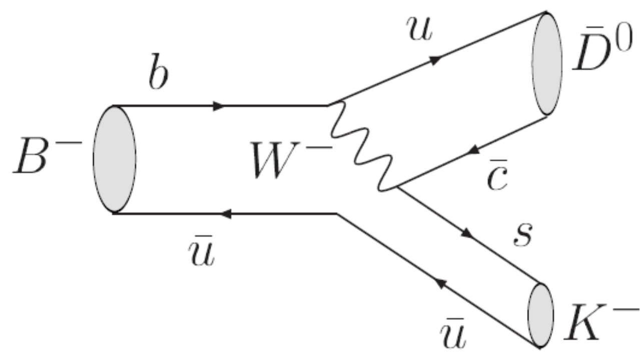
[CKMfitter, 2009]

- Goal: reduce uncertainty on γ
- Measurement may indicate **new physics**
  - If loops and trees disagree

$B^{\pm} \rightarrow (D^0/\overline{D}^0)K^{\pm}$

- Promising set of decays to precisely measure γ





$$A(B^- \rightarrow D^0 K^-) = A_B$$

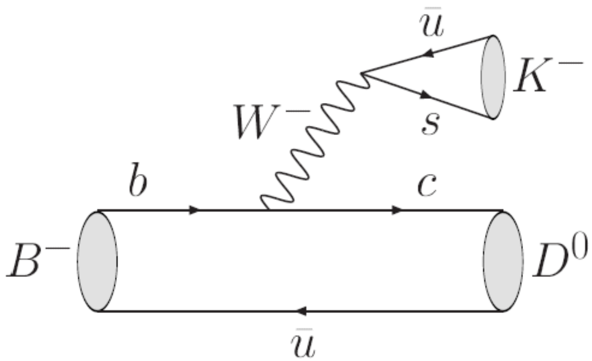
$$A(B^- \rightarrow \overline{D}^0 K^-) = A_B r_B e^{i(\delta_B - \gamma)}$$

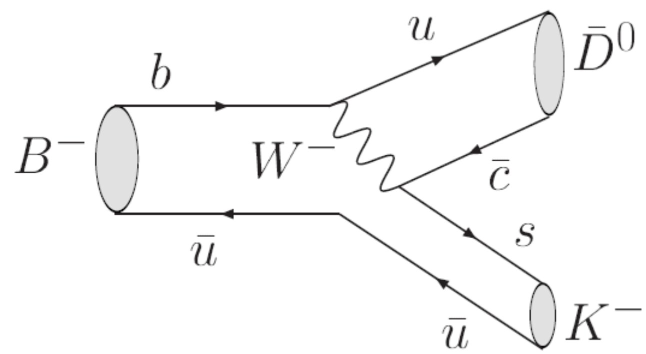
$$r_B \equiv \left| \frac{A(B^- \rightarrow \overline{D}^0 K^-)}{A(B^- \rightarrow D^0 K^-)} \right| \sim 0.1$$

Relative strong phase

$B^{\pm}\to(D^0/\bar{D}^0)K^{\pm}$

- Promising set of decays to precisely measure γ





$$A(B^-\to D^0K^-) = A_B \qquad A(B^-\to\bar{D}^0K^-) = A_B r_B e^{i(\delta_B-\gamma)}$$

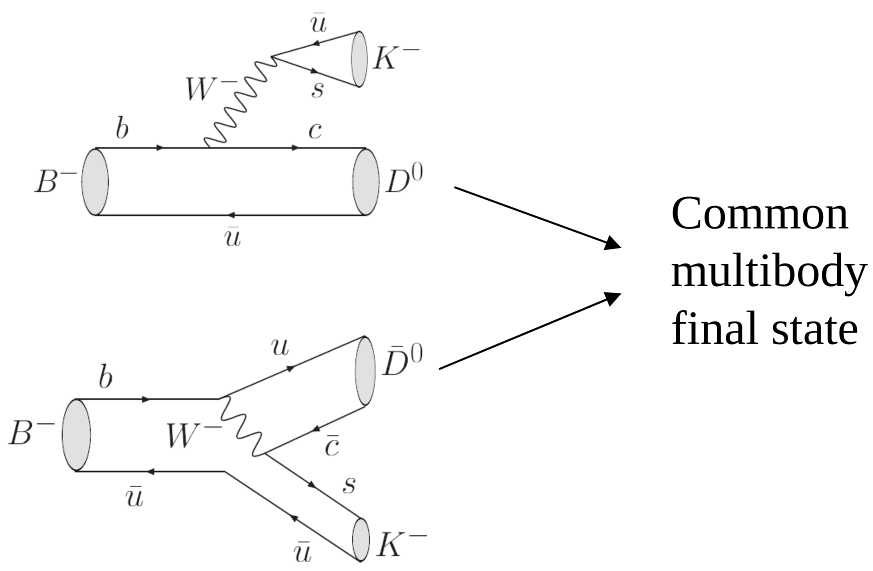
- $D^0/\bar{D}^0$ must decay to same final state → **interference**

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

Relative strong phase

D^0-Meson Decays

- Very important to understand decays of the $D^0/\bar{D}^0$ in detail
- When the $D^0/\bar{D}^0$ decay to a **multibody** final state, can use **Dalitz** analysis



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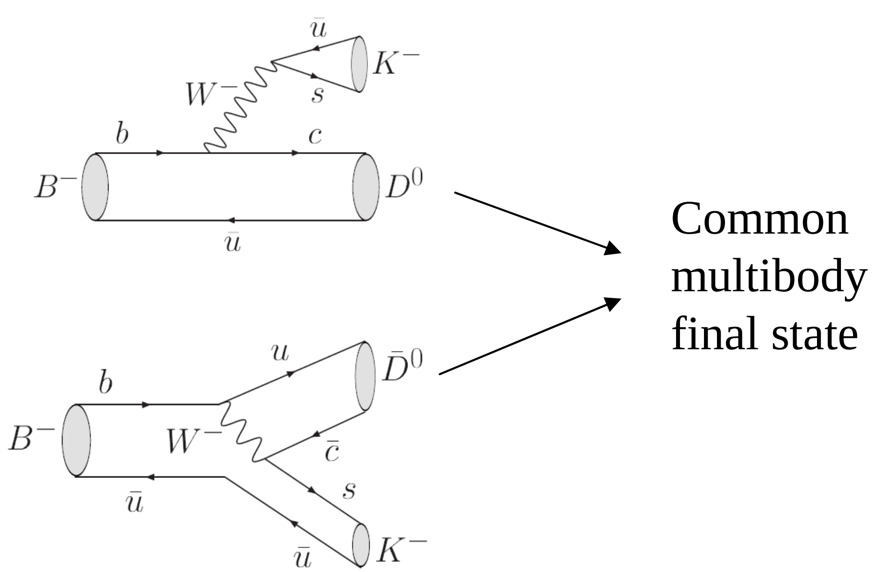
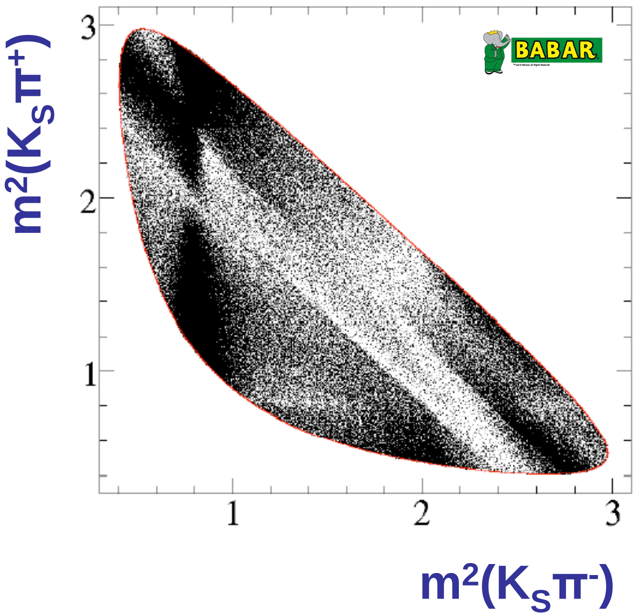


- Examples: $K_S\pi\pi$, K_SKK
- (Denoted K_Shh)

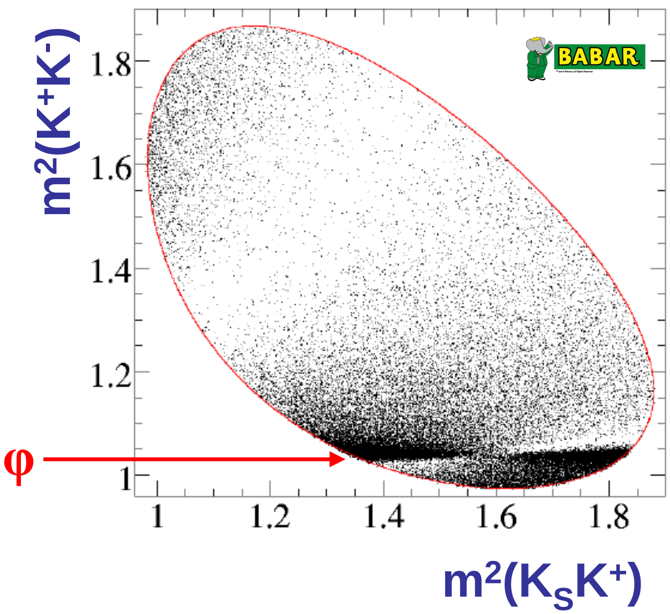
Dalitz Plot Analysis

- 3-body Dalitz plot: **invariant mass** of **one pair** of daughters vs invariant mass of **another pair**
- Example: from BaBar [Phys. Rev. D 78, 034023 (2008)]
- Note interference & resonant substructures

$D^0 \to K_S \pi\pi$



$D^0 \to K_S KK$



Dalitz Plot Analysis

- B-factory Dalitz analysis of $D^0 \to K_S \pi\pi$: [Phys. Rev. D 78, 034023 (2008)]
- BaBar: $\gamma = 63^\circ(^{+30}_{-28})^\circ \text{ (stat)} \pm 8^\circ \text{ (syst)} \pm 7^\circ \text{ (model)}$
- Belle: $\gamma = 76^\circ(^{+12}_{-13})^\circ \text{ (stat)} \pm 4^\circ \text{ (syst)} \pm 9^\circ \text{ (model)}$

[arxiv:0803.3375]

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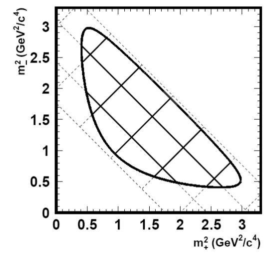
- Belle: $\gamma = 76^\circ(^{+12}_{-13})^\circ \text{ (stat)} \pm 4^\circ \text{ (syst)} \pm 9^\circ \text{ (model)}$ [arxiv:0803.3375]
- Possible to remove **model error** by dividing Dalitz plane into **bins** and **counting** events in each bin [Phys. Rev. D 68, 054018 (2003)]
  - CLEO-c data are **vital** for this method
  - Details in backup slides



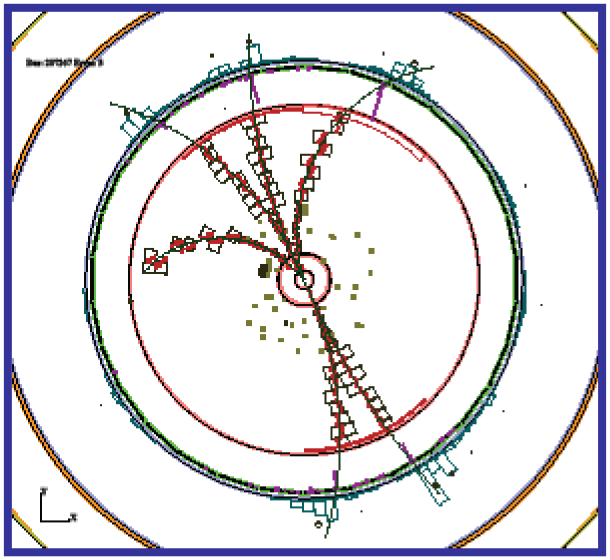
- Best choice of binning is in regions of similar **strong phase difference** (backups)

[Eur. Phys. J. C 47, 347-353 (2006)]

The Importance of CLEO-c

Introduction to CLEO-c

- Located at **C**ornell **E**lectron **S**torage **R**ing (CESR)
- $e^+e^- \rightarrow \Psi(3770) \rightarrow D^0\bar{D}^0$ pair
  - $(818 \pm 8)\ pb^{-1}$
  - **quantum correlated** with overall CP -1
  - knowledge of quantum numbers of one D yields complete knowledge of those of other D
- **Clean** environment
  - Lack of background
  - Example: $D^0 \rightarrow K_S\pi\pi$ vs $\bar{D}^0 \rightarrow K^+\pi^-$



Importance of CLEO-c

- Good quality $D^0 \rightarrow K_S hh$ decays, needed for Dalitz analysis, are abundant at CLEO-c
- Need final states of a **definite CP**
- Can get such states at CLEO-c:
  - Reconstruct one D-meson's decay to a known CP eigenstate (such as K^+K^-, which has CP **+1**)
  - This is known as a **tag**
  - Due to entanglement, know the other D must be in a state of **opposite CP** (since $CP(D^0\bar{D}^0) = $ **-1**)
  - Reconstruct $D \rightarrow K_S hh$, knowing that this particular final state is of CP **-1**
  - The equivalent can be done with CP -1 tags

Importance of CLEO-c (2)

- As well as $D^0 \rightarrow K_S hh$, $D^0 \rightarrow \mathbf{K_L} hh$ decays also useful
  - Opposite CP, same general principle
  - Increase in statistics, more constraints on γ
- Study of $D^0 \rightarrow \mathbf{K_{(S,L)}\pi\pi}$ completed [J. Rademacker, CKM2008]
- This analysis replaces model error of 7-9° with CLEO-c statistical error of **1-2°** [CLEO-c preliminary]
- Without information from CLEO-c, uncertainty on LHCb ($K_S\pi\pi$, $10 fb^{-1}$) data predicted to be ~**8.5°**; with CLEO-c data, uncertainty ~**6°** *
- A good improvement!

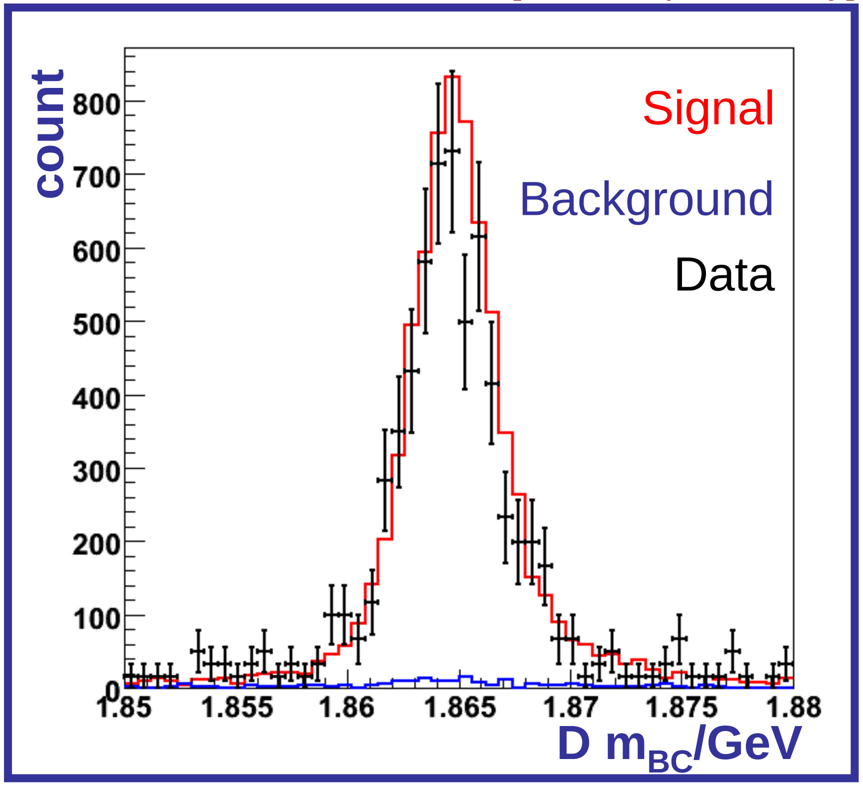
*For $r_B = 0.1$

Preliminary results from $D^0 \rightarrow K_S KK$ at CLEO-c

Analysis of $D^0 \to K_{(S,L)}KK$

- Analogous to $D^0 \to K_{(S,L)}\pi\pi$ study
- Looked at ~30 **tag** modes
- ~550 CP-tagged events in $818 pb^{-1}$
- MC/data overlay for K_SKK vs $K\pi\pi^0$ →
- Clean environment

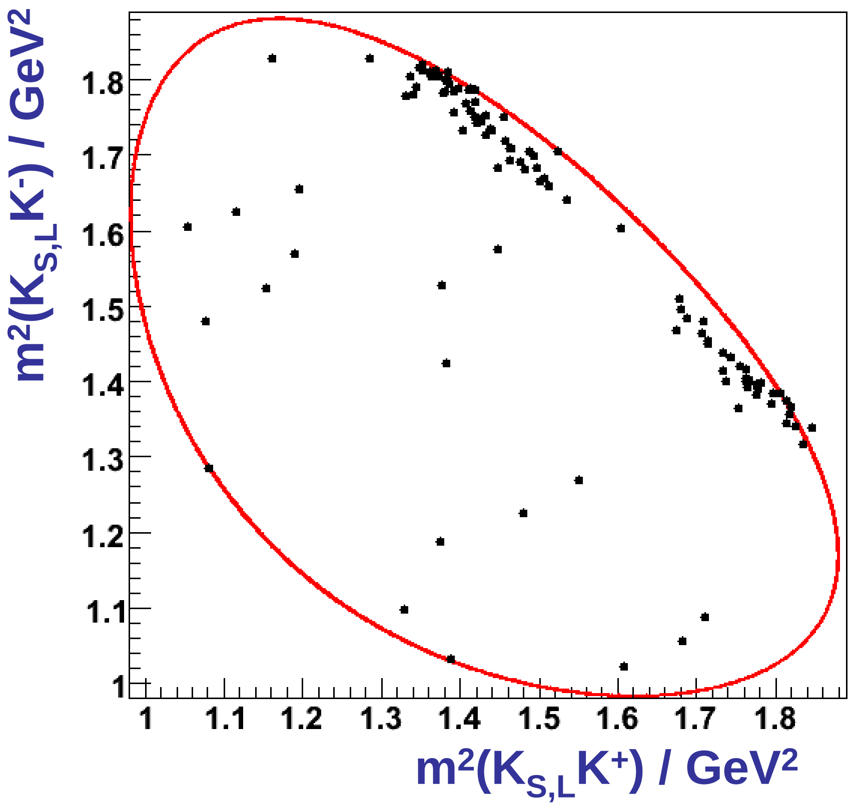
[CLEO-c preliminary]

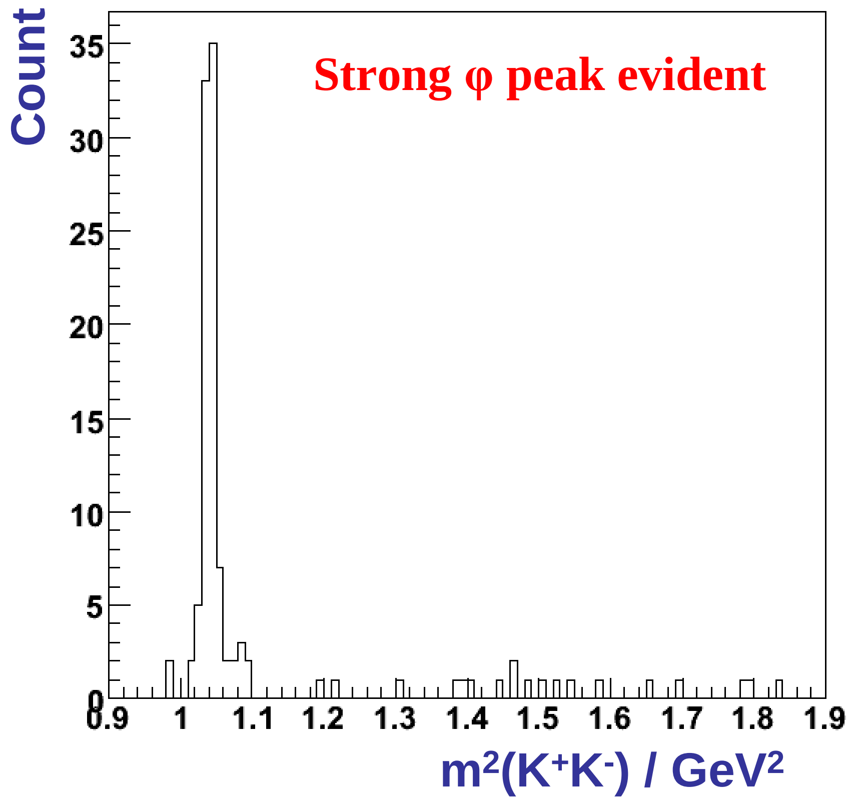


$$m_{BC} = \sqrt{(E^2_{Beam} - \mathbf{p}^2_D)}$$

$K_{(S,L)}KK$ Dalitz Plots [CLEO-c preliminary]

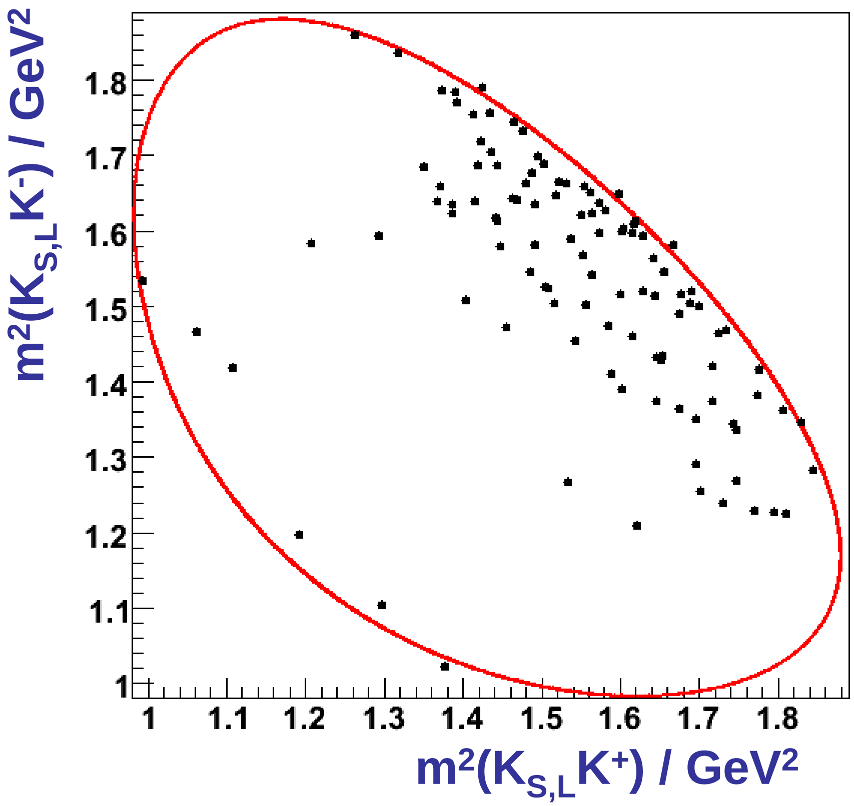
- K_SKK vs CP **+1** tags & K_LKK vs CP **-1** tags

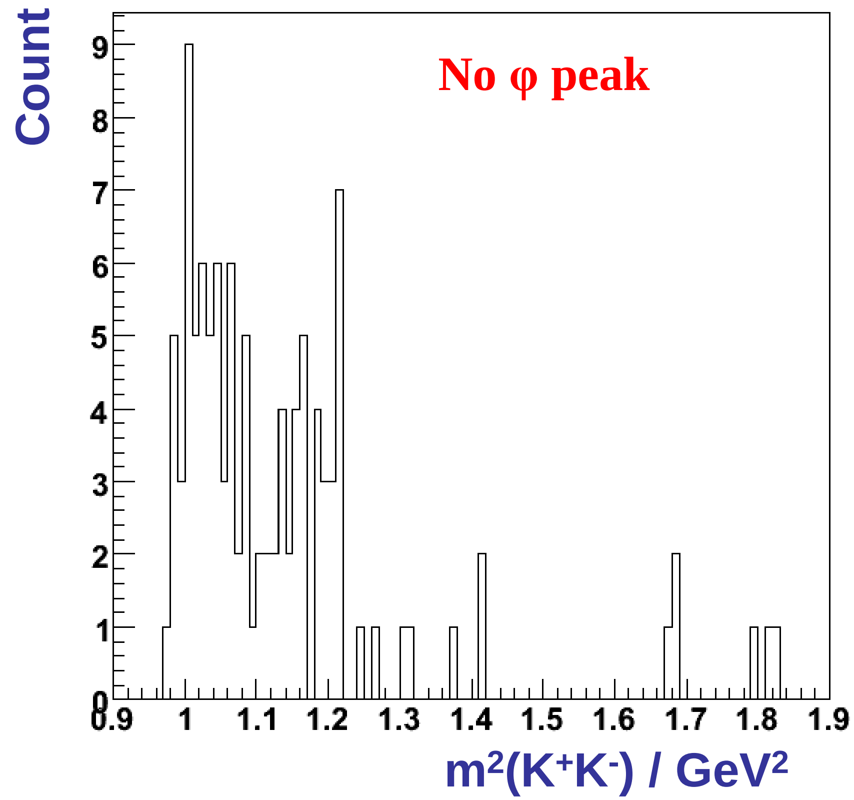




$K_{(S,L)}KK$ Dalitz Plots [CLEO-c preliminary]

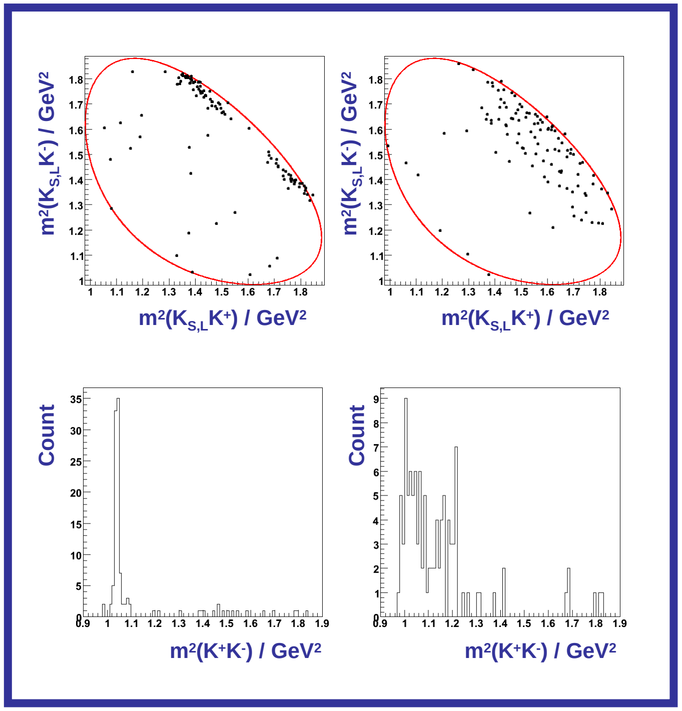
- K_SKK vs CP **-1** tags & K_LKK vs CP **+1** tags





$K_{(S,L)}KK$ Analysis Status

- Striking difference between the Dalitz plots
  - Have access to good CP-tagged data, needed for model independent determination of γ
- Next steps: extract strong phase information from binned Dalitz plot and calculate impact on precision of LHCb γ
- Optimistic that a significant improvement will be achieved



Summary

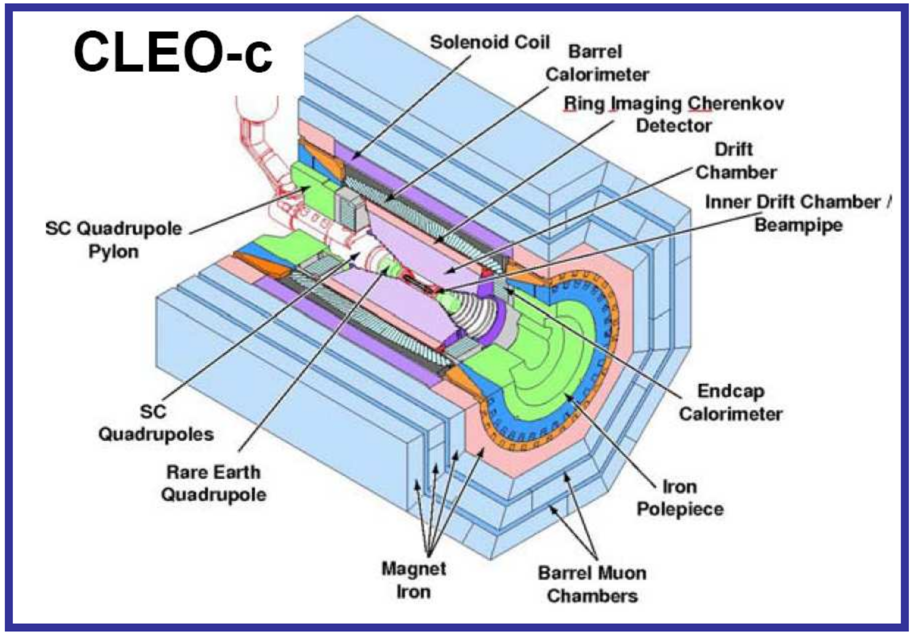
- γ currently least constrained of CKM angles
- General class of decays $B^{\pm} \rightarrow D^0 K^{\pm}$ useful to reduce uncertainty on γ
- **CLEO-c** provides invaluable way to probe D^0-meson decays and allows a **model-independent** extraction of γ from a binned Dalitz analysis
- Enhances prospects of LHCb & future high statistics experiments
- $D^0 \rightarrow K_S \pi\pi$ analysis reduces LHCb error on γ to ~6.5°
- $D^0 \rightarrow K_S KK$ analysis ongoing - preliminary results promising

Backups

The CLEO-c Detector

The CLEO-c Detector

- Solenoidal detector
- Tracking system
  - Momentum, dE/dx
- RICH
  - PID
- CsI Calorimeter
  - showers



Calculating γ using $B^{\pm} \rightarrow D^0 K^{\pm}$

CP Violation & γ

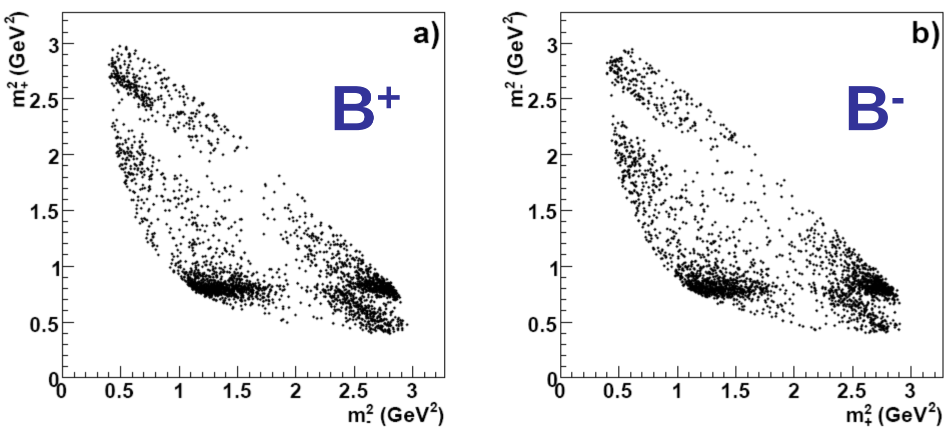
- Compare decay rate for $B^+ \to D^0K^+$ to $B^- \to D^0K^-$

$$A(B^- \to D^0K^-) = A_B$$
$$A(B^- \to \overline{D}^0K^-) = A_B r_B e^{i(\delta_B - \gamma)}$$
$$A(B^+ \to D^0K^+) = A_B r_B e^{i(\delta_B + \gamma)}$$
$$A(B^+ \to \overline{D}^0K^+) = A_B$$

NB

- CP violation
- Difference manifested in Dalitz plots

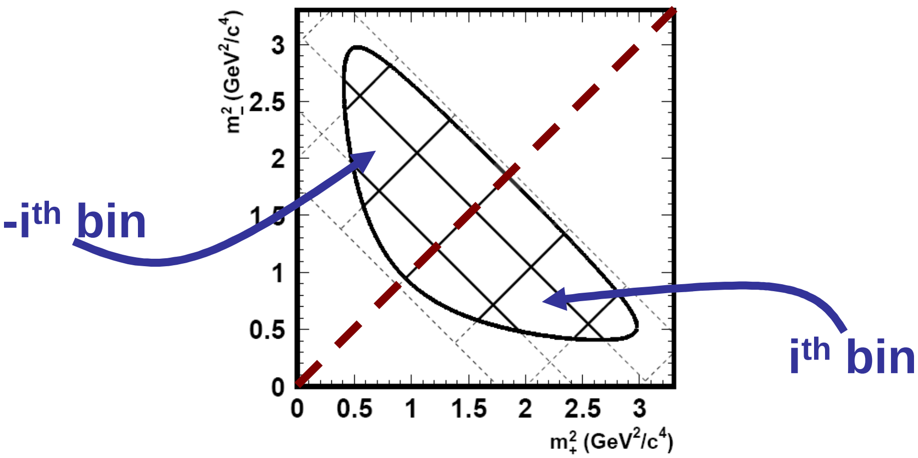
[LHCb public note 2007-048]



Extracting γ from $B^{\pm} \rightarrow D^0(K_S hh)K^{\pm}$

- Number of events in i^{th} bin of **$B^{\pm} \rightarrow D^0 K^{\pm}$** Dalitz plot:

$$N_i(\mathrm{B}^{\pm} \to (\mathrm{K^0_S h^+ h^-})_\mathrm{D} \mathrm{K}^{\pm}) = a_B \left\{ T_i + r_B^2 T_{-i} + 2 r_B \sqrt{T_i T_{-i}} [\cos(\delta_B \pm \gamma) c_i + \sin(\delta_B \pm \gamma) s_i] \right\}$$



a_B = normalisation

$T_{\pm i}$ measured in flavour decays

r_B = colour suppression factor ~ 0.1

δ_B = strong phase of B decay

c_i, s_i = weighted average of $\cos(\Delta\delta_D)$, $\sin(\Delta\delta_D)$ over a bin

- Dalitz plot symmetrised about y=x
- Opposing bins numbered i, -i

Extracting γ from $B^{\pm}\to D^0(K_S hh)K^{\pm}$

- **c_i** and **s_i** are dependent upon number of events in each bin on the **$D\to K_S hh$** Dalitz plot (as opposed to the $B^{\pm}\to D^0K^{\pm}$ Dalitz plot)
  - A **counting** experiment: **model independent**
- $K_S hh$ vs CP tags determine c_i only:

$$M_i^{\pm} = h_{CP\pm}(K_i \pm 2c_i\sqrt{K_i K_{-i}} + K_{-i})$$

- $K_S hh$ vs $K_{(S,L)}hh$ determines c_i and s_i:

$$M_{ij} \; = \; h_{corr}(K_i K_{-j} + K_{-i}K_j - 2\sqrt{K_i K_{-j} K_{-i} K_j}(c_i c_j + s_i s_j))$$

K_i = number events in i^{th} bin of Dalitz plot

M_i = number events in i^{th} bin of **CP-tagged** Dalitz plot

M_{ij} = number of events simultaneously in i^{th} bin of D Dalitz plot and j^{th} bin of Dbar Dalitz plot

h_{CP}, h_{corr} = normalisation

Extracting γ from $B^{\pm} \to D^0(K_S hh)K^{\pm}$

- Recap:

$$N_i(\mathrm{B}^{\pm} \to (\mathrm{K}^0_\mathrm{S}\mathrm{h}^+\mathrm{h}^-)_\mathrm{D}\mathrm{K}^{\pm}) = a_B \left\{T_i + r_B^2 T_{-i} + 2r_B\sqrt{T_i T_{-i}}[\cos(\delta_B \pm \gamma)c_i + \sin(\delta_B \pm \gamma)s_i]\right\}$$

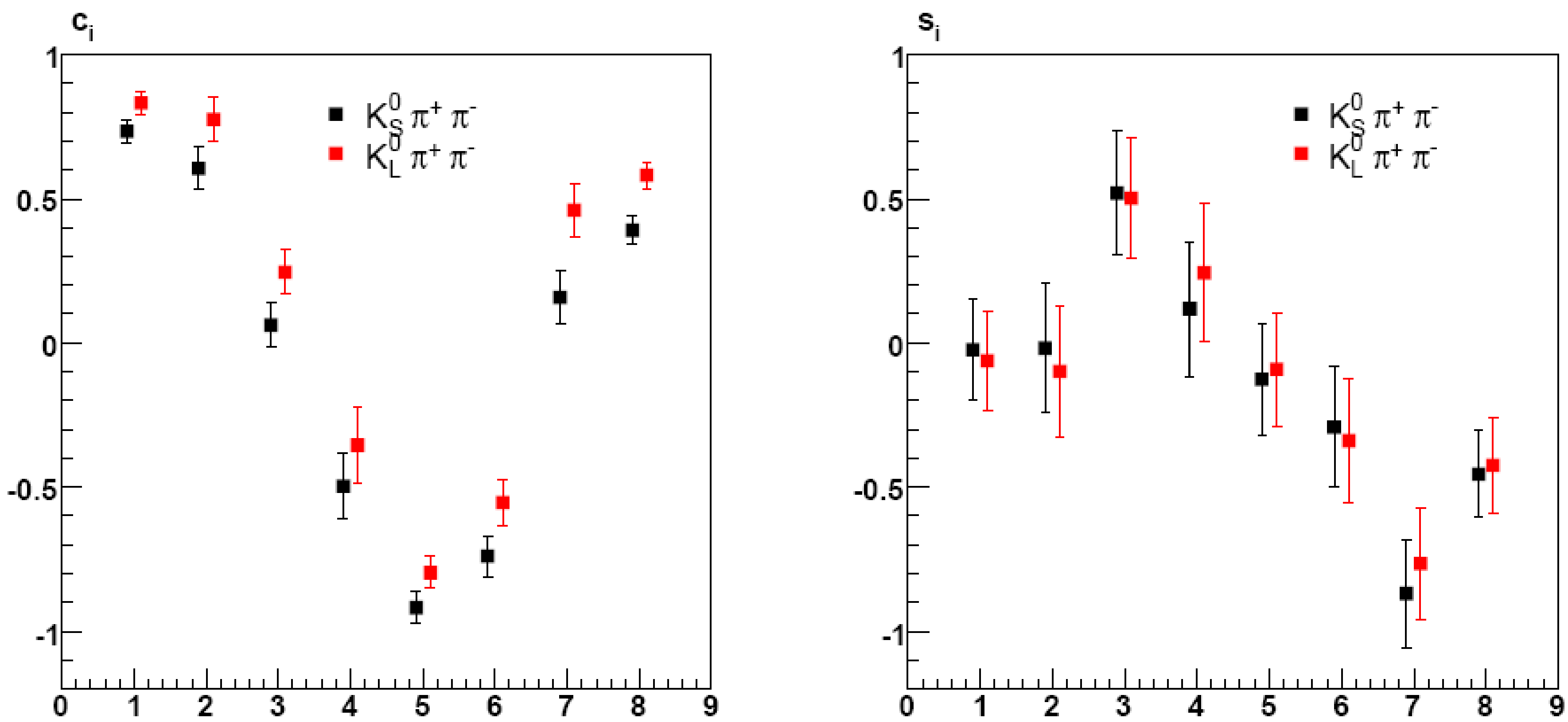
$$M_i^{\pm} = h_{CP\pm}(K_i \pm 2c_i\sqrt{K_i K_{-i}} + K_{-i})$$

$$M_{ij} = h_{corr}(K_i K_{-j} + K_{-i}K_j - 2\sqrt{K_i K_{-j} K_{-i} K_j}(c_i c_j + s_i s_j))$$

- Know c_i, s_i, T_i, N_i: all ingredients to measure γ!
- Current studies use toy MC programs to fit γ, r_B and δ_B

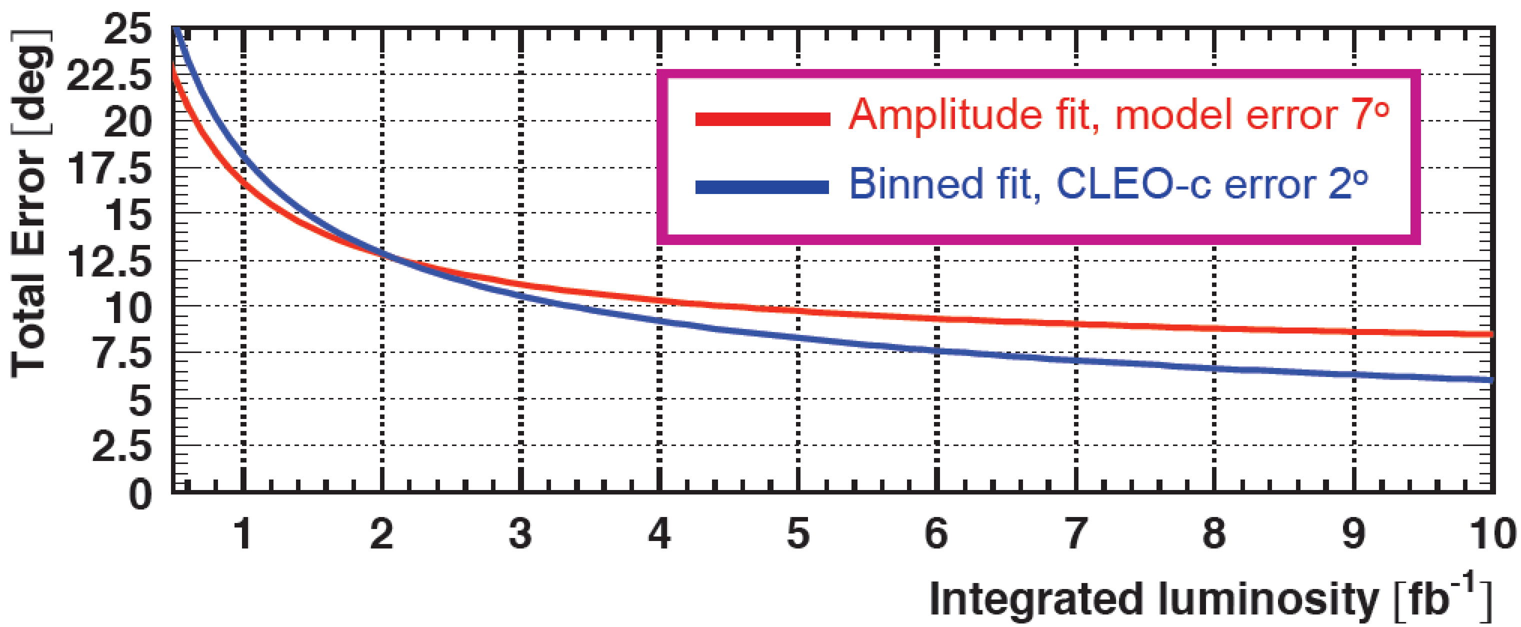
c_i & s_i for $D \rightarrow K_S\pi\pi$

- ~3300 events used
- Coefficients extracted from fit: [CLEO-c preliminary]



Impact on LHCb γ

- Impact of CLEO-c data on γ measured from $B^{\pm}\to D(K_S\pi\pi)K^{\pm}$ at LHCb:



[J. Rademacker, CKM2008]

Strong Phase Difference

Strong Phase, δ_D

- Formalism for $D \to K_S hh$ ($h = \pi, K$)
- $D^0/\overline{D}^0$ decay via resonances, so **strong phase δ_D** can in principle be different at every point of the Dalitz plot
- Key point is the D^0 & $\overline{D}^0$ **interfere**

$$A(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-) = A_D \underbrace{r_D} e^{i\delta_D}$$

$$A(\overline{\mathrm{D}}^0 \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-) = A_D$$

$$r_D \equiv \left| \frac{A(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-)}{A(\overline{\mathrm{D}}^0 \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-)} \right|$$

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Strong Phase Difference, $\Delta\delta_D$

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$$r_D \equiv \left| \frac{A(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-)}{A(\overline{\mathrm{D}}^0 \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-)} \right|$$

$$\Delta\delta_\mathrm{D} \equiv \delta_\mathrm{D}(x,y) - \delta_{\overline{\mathrm{D}}}(x,y)$$

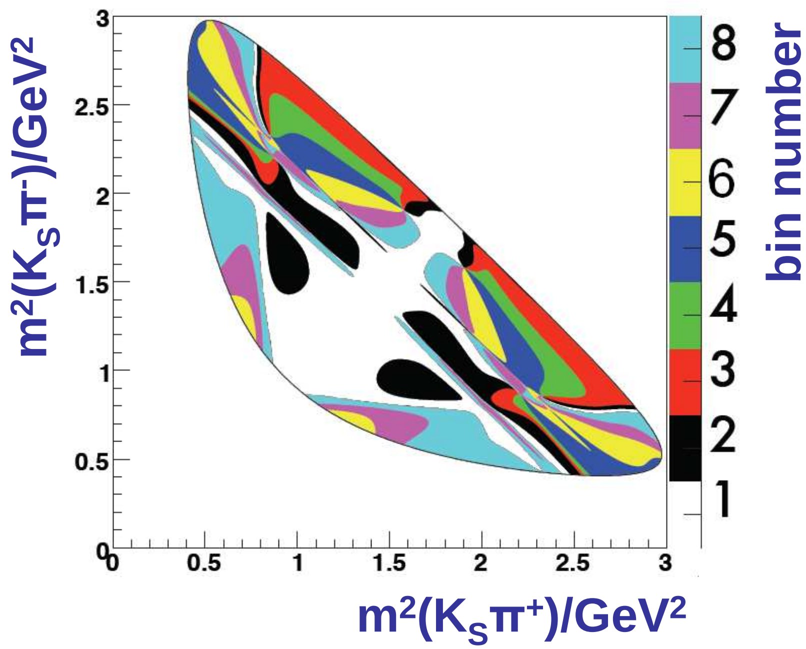
$\delta_\mathrm{D}(x,y)$: Strong phase at (x,y) on Dalitz plane for D^0 decay

$\delta_{\overline{\mathrm{D}}}(x,y)$: Equivalent for $\overline{D}^0$ decay

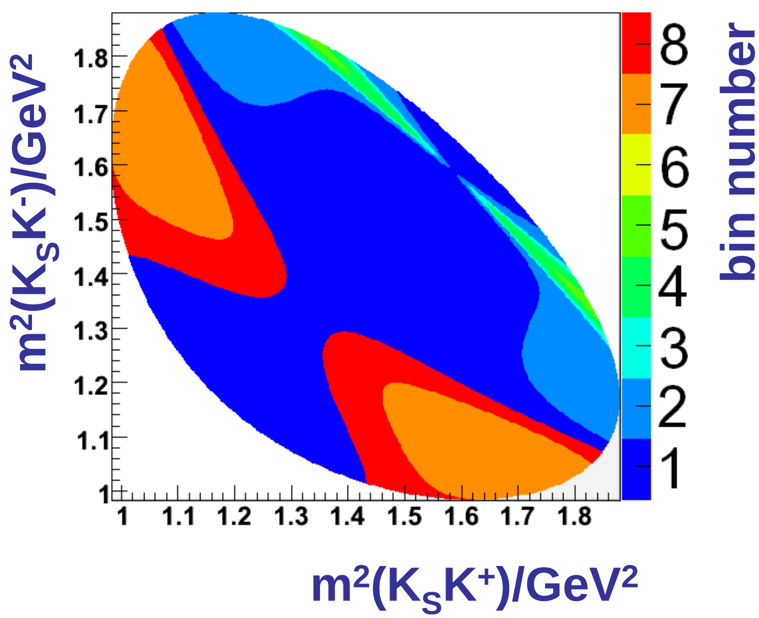
Strong Phase Difference, $\Delta\delta_D$

- **Optimal** binning (to minimise uncertainty) is regions of similar strong phase difference
[Eur. Phys. J. C 47, 347-353 (2006)]

$K_S\pi\pi$



K_SKK



Coherence Factor

ADS Method

- B→D(X)K, where X = a **non-CP eigenstate**
  - Kπ, Kππ^0, K3π, …
- For B→D(Kπ)K have four possible decays:

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

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

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

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

- Decays **2** & **4**, in which the final state kaons have opposite charges, have large interference
- Measure rates → handle on γ

4-body ADS; Coherence Factor

- $B \to D(K3\pi)K$ is a four-body extension to the ADS method
- Complicated because of possible resonances in $D \to K3\pi$ decay
- Each point in phase space can potentially have a different strong phase associated with it
- Similar situation for $B \to D(K\pi\pi^0)K$

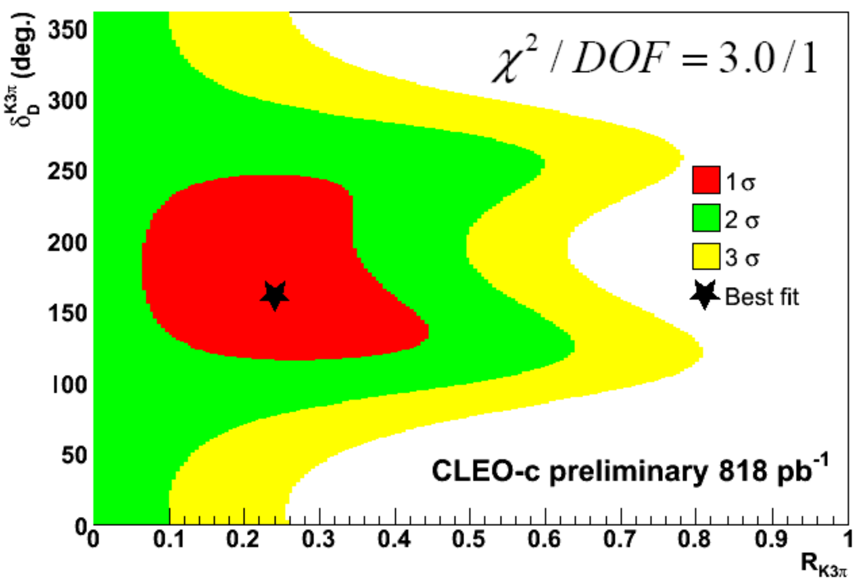
Coherence Factor

- The coherence factor $\mathbf{R_{K3\pi}}$ quantifies the amount of influence these resonances have on the determination of γ
  - 0 = incoherent – several intermediate resonances with different strong phases – no ability to determine γ directly from this rate. Still provides an excellent determination of r_B
  - 1 = coherent – one intermediate resonance

$$\Gamma(\mathrm{B}^- \rightarrow (\mathrm{K}^+ 3\pi)_{\mathrm{D}} \mathrm{K}^-) \propto r_B^2 + (r_D^{K3\pi})^2 + 2 R_{K3\pi} r_B r_D^{K3\pi} \cdot \cos(\delta_B + \delta_D^{K3\pi} - \gamma)$$

K3π Results

- Likelihood scan over $R_{K3\pi}$, $\delta_{K3\pi}$



Incoherent

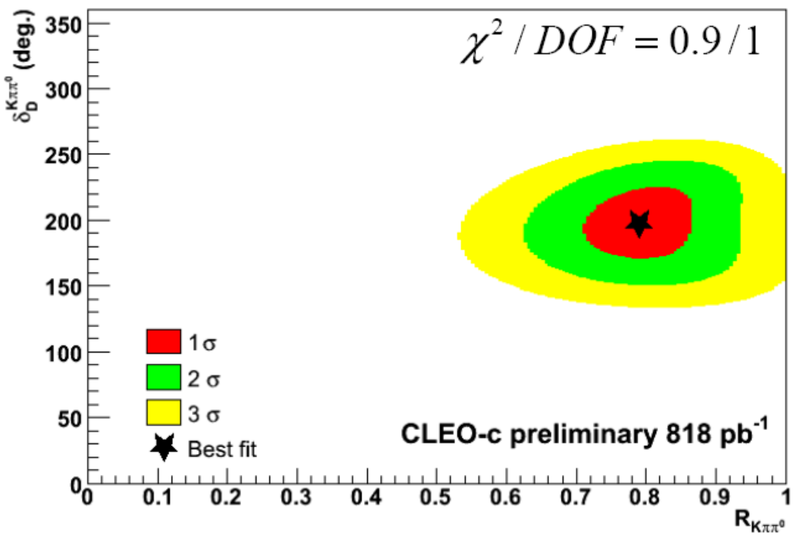
$$R_{K3\pi} = 0.24^{+0.21}_{-0.17} \quad [R_{K3\pi} < 0.57 \text{ at } 95\% \text{ c.l.}]$$

$$\delta_D^{K3\pi} = \left(161^{+85}_{+48}\right)^\circ \quad [\text{No } 95\% \text{ c.l. constraint}]$$

[J. Libby, CKM2008]

$K\pi\pi^0$ Results

- Likelihood scan over $R_{K\pi\pi0}$, $\delta_{K\pi\pi0}$



Coherent

$$R_{K\pi\pi^0} = 0.79 \pm 0.08$$

$$\delta_D^{K\pi\pi^0} = \left(197^{+28}_{-27}\right)^\circ$$

[J. Libby, CKM2008]