Determining the $(D^0,\bar{D}^0)\rightarrow K_{S,L}K^+K^-$ strong phase difference and the impact on the CKM angle γ

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On behalf of the CLEO-c and LHCb collaborations

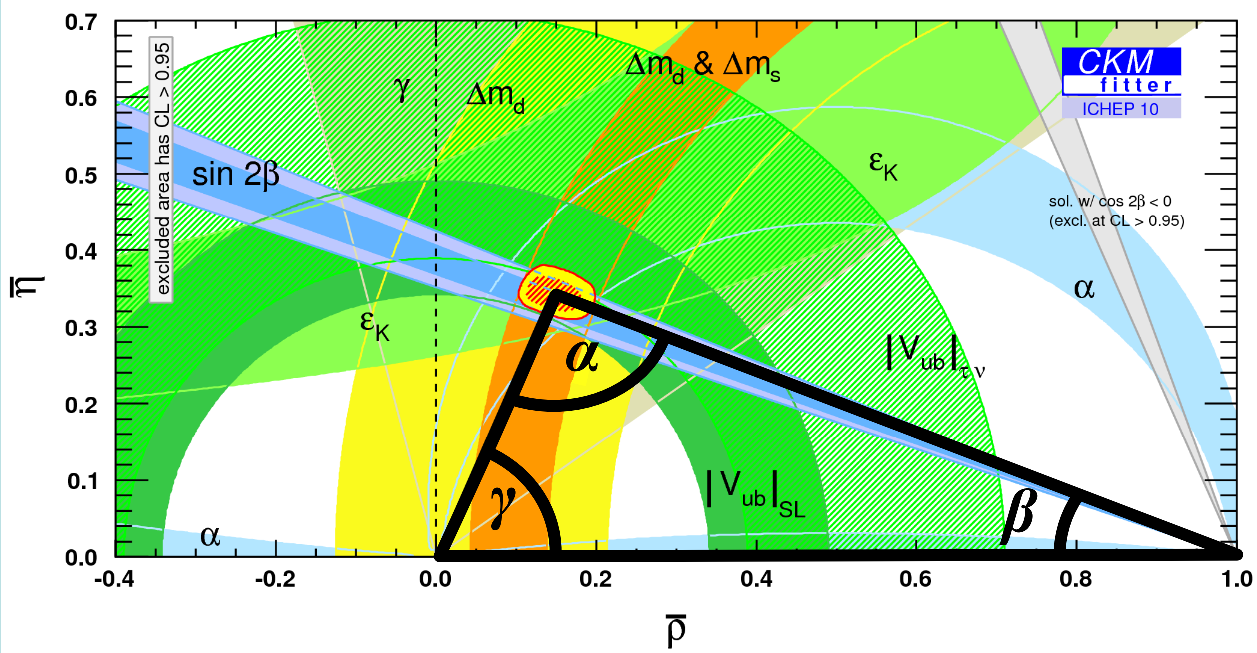
Outline

- Determining γ using $B^{\pm}\rightarrow(D^0,\overline{D}^0)K^{\pm}$
- The CLEO-c detector
- Measuring the strong phase difference between D^0 and $\overline{D}^0$ decays to $K_{S,L}K^+K^-$
- Impact on future γ measurements

Determining γ using $B^{\pm}\rightarrow(D^0,\overline{D}^0)K^{\pm}$

Unitarity triangle

- The b-d unitarity triangle of the CKM matrix



$$\alpha = (89.0^{+4.4}_{-4.2})^{\circ}$$

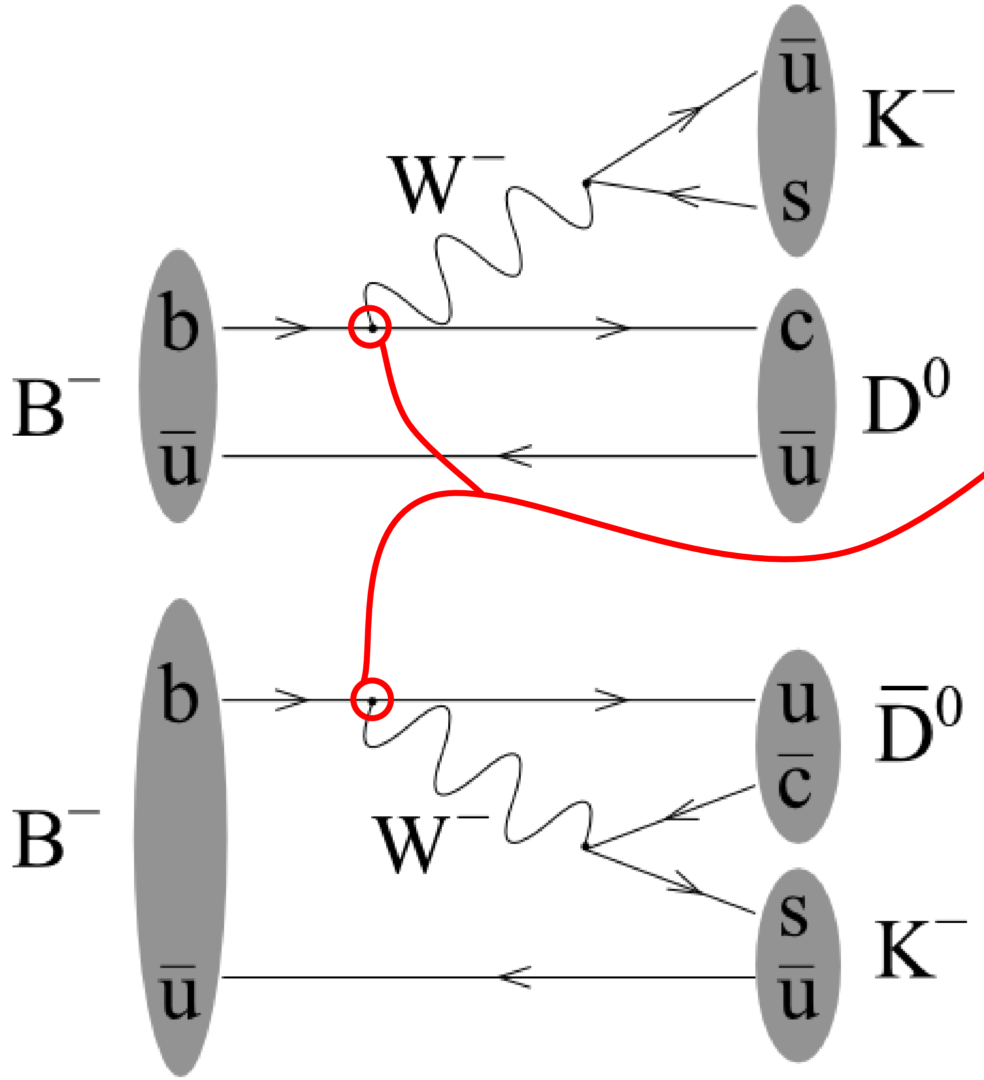
$$\beta = (21.15^{+0.90}_{-0.88})^{\circ}$$

$$\gamma = (71^{+21}_{-25})^{\circ}$$

CKMfitter: http://ckmfitter.in2p3.fr

- Results shown are direct angle measurements

Determining γ from $B^{\pm}\rightarrow(D^0,\bar{D}^0)K^{\pm}$



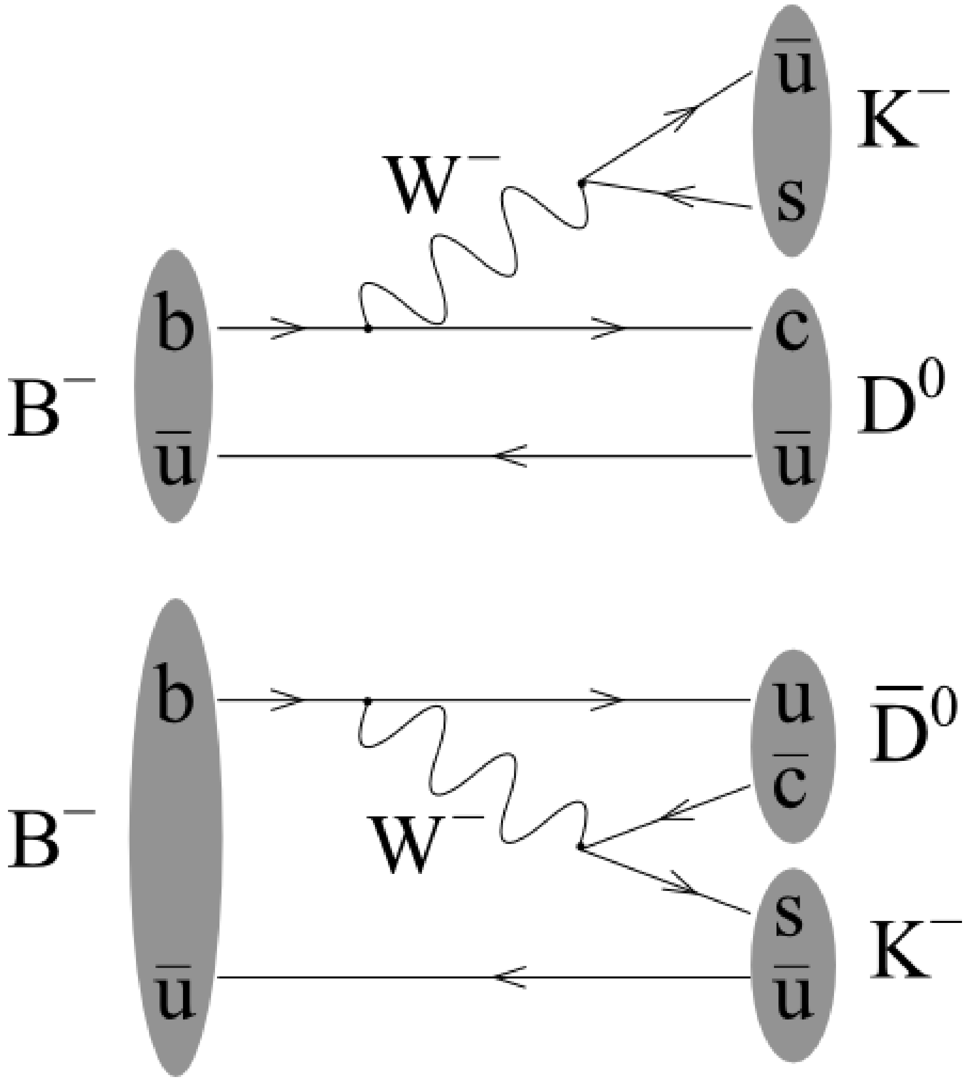
$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Amplitude ratio between $b \rightarrow \bar{u}cs$ and $b \rightarrow u\bar{c}s$ transitions:

$$r_B e^{i(\delta_B - \gamma)} \equiv \frac{\mathcal{A}(B^- \rightarrow \bar{D}^0 K^-)}{\mathcal{A}(B^- \rightarrow D^0 K^-)}$$

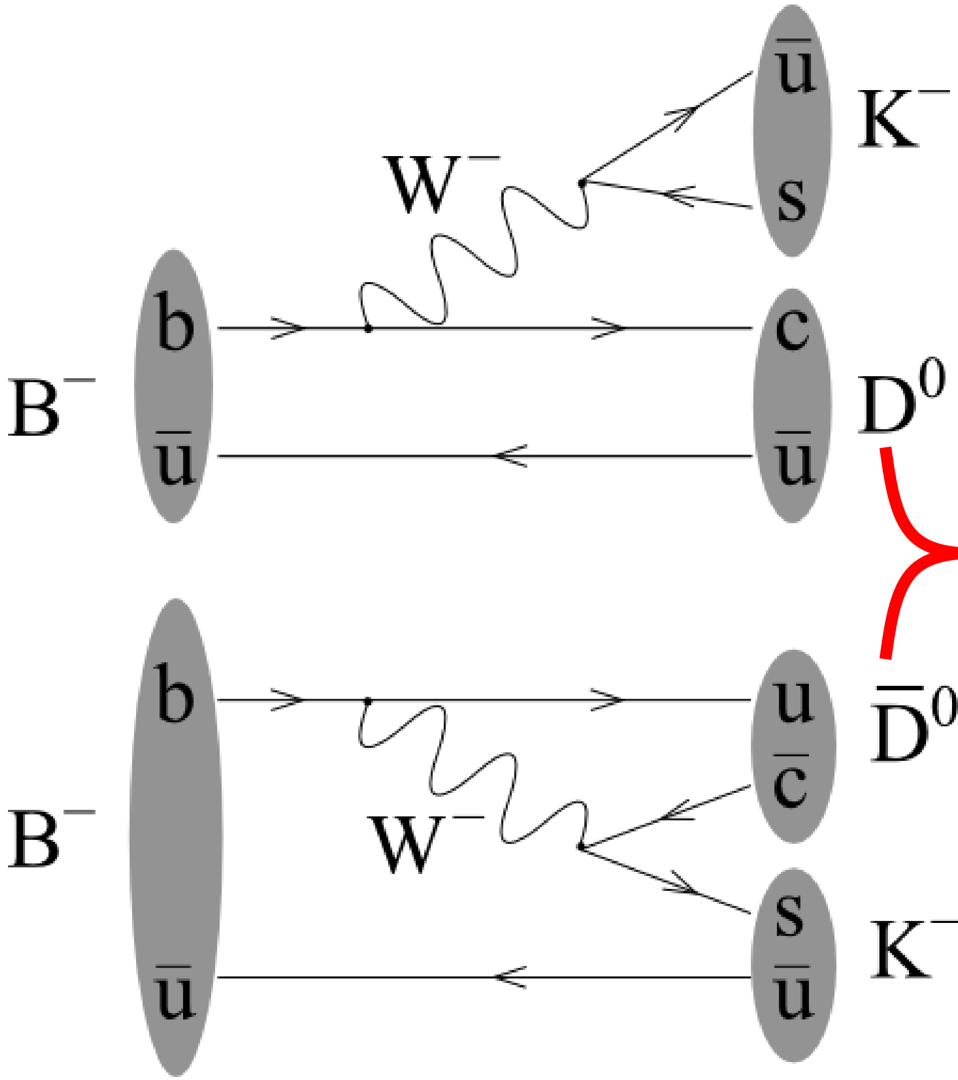
CKM and colour suppression: $r_B \sim 0.1$

Determining γ from $B^{\pm}\rightarrow(D^0,\overline{D}^0)K^{\pm}$



D^0 and $\overline{D}^0$ must decay to common final state to provide interference and hence sensitivity to γ

D^0 final states



Two-body hadronic (ADS/GLW)

$K\pi$, KK, $\pi\pi$, $K_S\pi^0$, $K_S\omega$

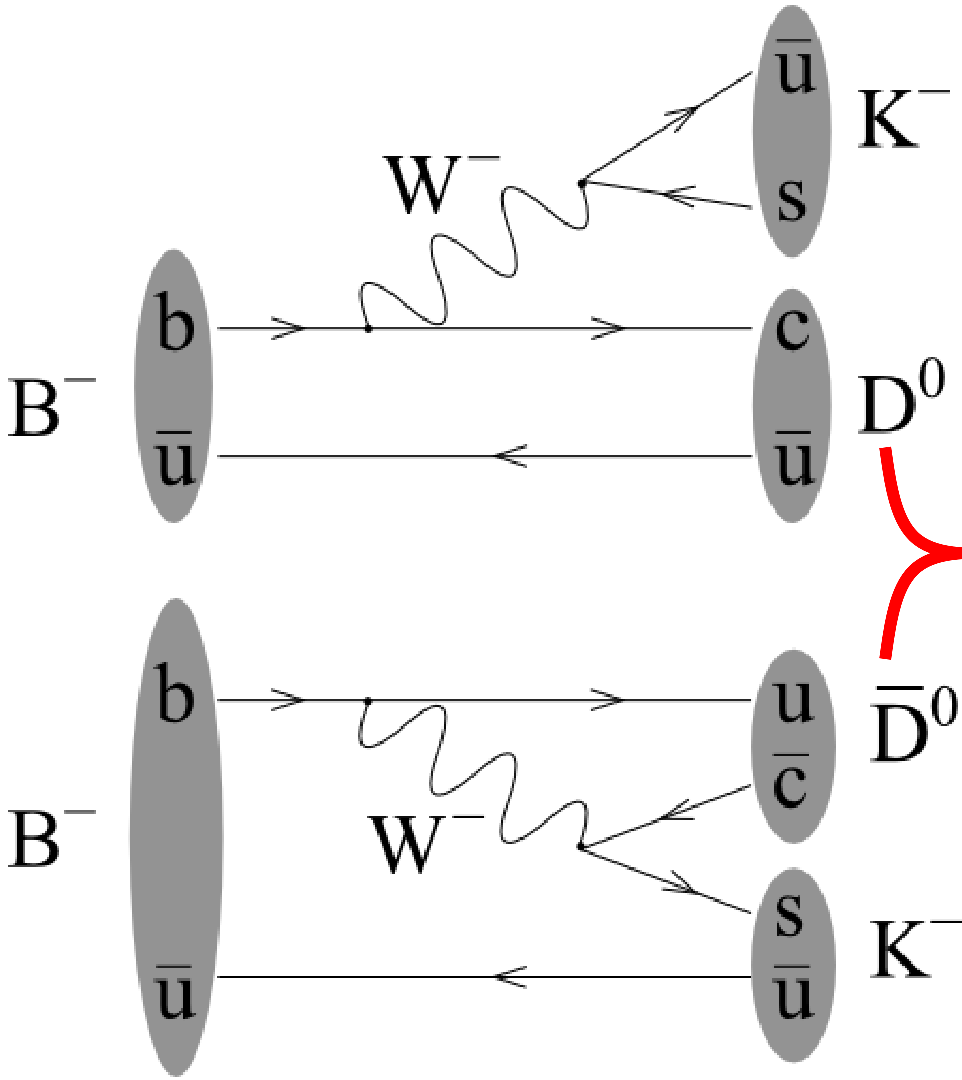
Multibody ADS

$K\pi\pi\pi$, $K\pi\pi^0$

Multibody mixed-CP eigenstate

$K_S\pi\pi$, K_SKK

Importance of charm physics



D^0 decay parameters must be precisely determined: charm physics input is vital

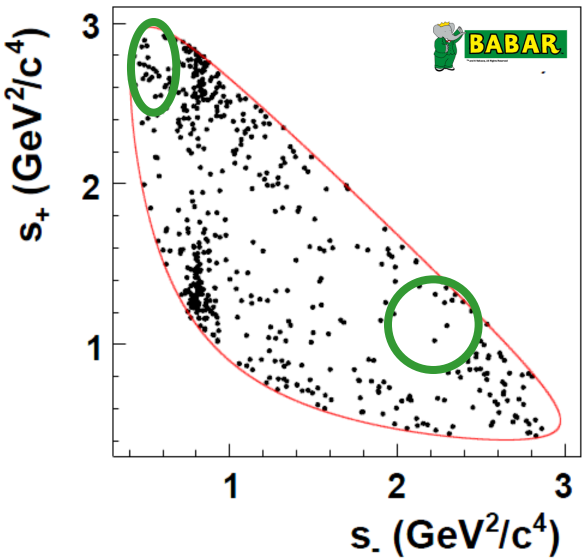
Multibody mixed-CP eigenstate

$K_S\pi\pi$, K_SKK

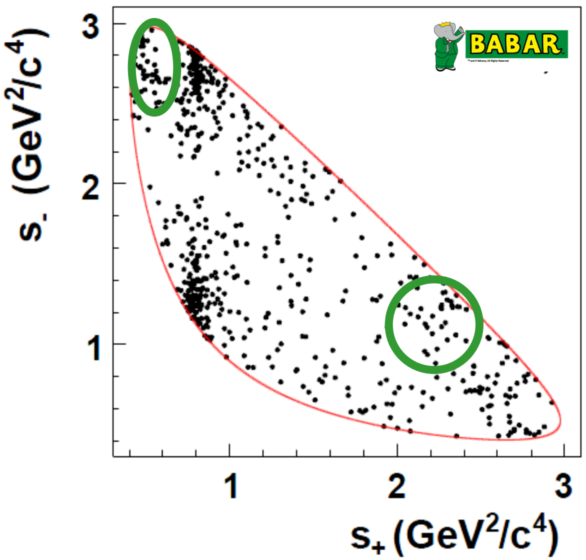
Dalitz analysis of $B^{\pm}\rightarrow(K_S hh)_D K^{\pm}$

$B^{\pm}\rightarrow(K_Shh)_DK^{\pm}$

- Three body final state – analyse K_Shh Dalitz plot
- CP violation is manifested as an asymmetry in event distributions across the plot



$B^-\rightarrow D(K_S\pi\pi)K^-$



$B^+\rightarrow D(K_S\pi\pi)K^+$

Phys. Rev D **78**, 034023 (2008)

Modelling B decays

- Define the Dalitz plot coordinates (x, y):

$$x \equiv m^2_{K^0_S h^+} \qquad y \equiv m^2_{K^0_S h^-}$$

- Define the $D^0 \rightarrow K_S hh$ decay amplitude:

$$f_{D^0}(x,y) \equiv A_{xy} e^{i\delta_{xy}} = \mathcal{A}(\mathrm{D}^0 \rightarrow \mathrm{K}^0_\mathrm{S}\mathrm{h}^+\mathrm{h}^-)(x,y)$$

- Then the B^- decay amplitude is:

$$\mathcal{A}(\mathrm{B}^- \rightarrow (\mathrm{K}^0_\mathrm{S}\mathrm{h}^+\mathrm{h}^-)_\mathrm{D}\mathrm{K}^-) \propto f_{D^0}(x,y) + r_B e^{i(\delta_B - \gamma)} f_{D^0}(y,x)$$

γ dependence

Modelling B decays

- The corresponding decay rate is:

$$\Gamma(\mathrm{B}^- \to (\mathrm{K^0_S h^+ h^-})_\mathrm{D}\mathrm{K}^-) \propto A_{xy}^2 + r_B^2 A_{yx}^2 + 2 r_B A_{xy} A_{yx}[\cos(\delta_B - \gamma)\cdot\cos(\Delta\delta_D) - \sin(\delta_B-\gamma)\cdot\sin(\Delta\delta_D)]$$

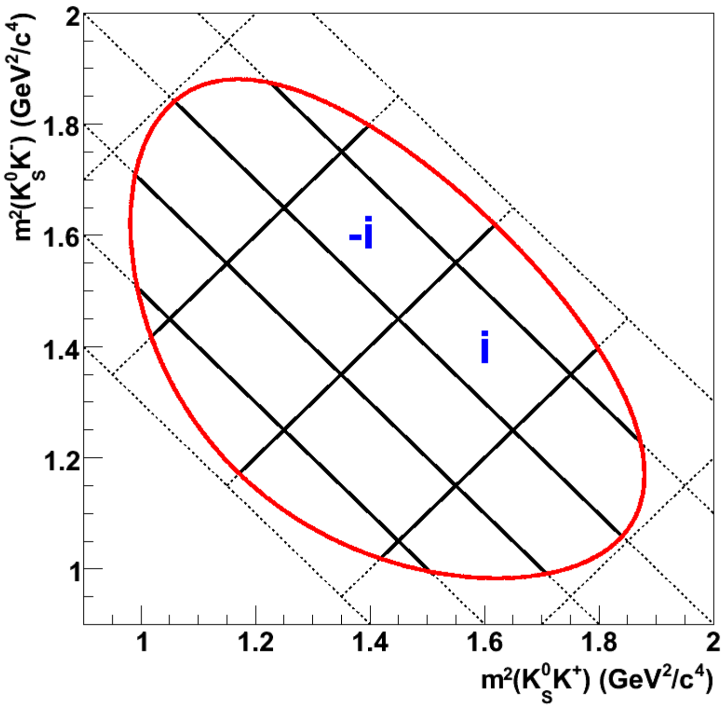
$$\Delta\delta_D \equiv \delta_{xy} - \delta_{yx}$$

- Strong phase difference
- To measure this rate, can:
  - Determine all parameters from $B^{\pm}$ decays
  - Fit a model to a flavour-tagged D^0 decay sample (unbinned)
  - Determine D^0 decay parameters in bins across Dalitz plane
- An example of how charm physics input is important

Binning the Dalitz plot

Phys. Rev. D **68**, 054018 (2003)

- Instead of using a model of the D^0 decays, divide the Dalitz plot into bins and measure yields in each bin



- Number of events in i^{th} bin, N_i, depends on weighted average cosine (c_i) and sine (s_i) of strong phase difference $\Delta\delta_D$
- Example: rectangular partitioning of $K_S KK$ Dalitz plot

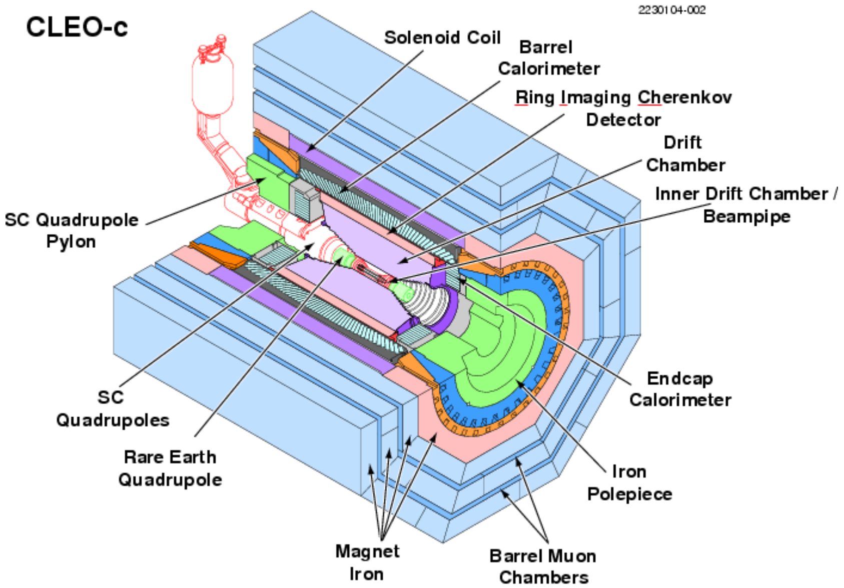
- No model error but increased statistical error
- Measure at CLEO-c using quantum correlated events

CLEO-c analysis of $D^0 \rightarrow K_S hh$

Phys. Rev. D **82**, 112006 (2010)

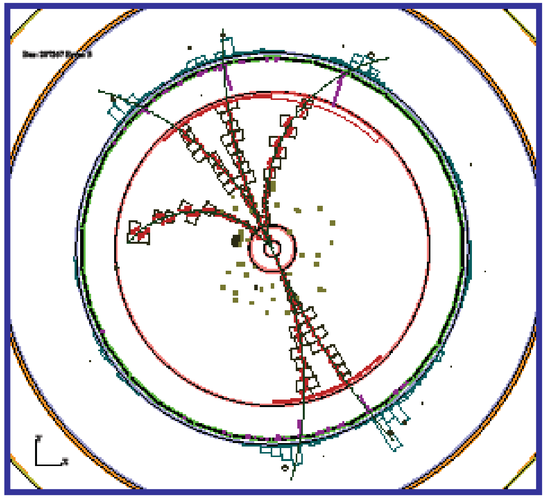
Brief overview of CLEO-c

- Symmetric general-purpose detector located at Cornell Electron Storage Ring (CESR)



- e^+e^- collider
- 93% coverage
- Excellent tracking and PID
- 818pb^{-1} @ $E_{CoM} = 3.77\text{GeV}$
  - $\psi(3770)$ resonance

Brief overview of CLEO-c



- Threshold decay at ψ(3770):
  - Very clean environment
  - High reconstruction efficiency
  - Can reconstruct 'missing' particles (K_L, ν)
- ψ(3770) decays to quantum-correlated $D\overline{D}$ pair
- Determine quantum numbers (i.e. CP) of one D: have complete knowledge of quantum numbers of the other
- CP(ψ(3770)) = −1
- CP tagging

D^0(CP+) ← ψ(3770) → $\overline{D}^0$(CP-)

CLEO-c $K_S hh$ event selections

- Selected $K_S hh$ tagged with:
  - CP eigenstates (e.g. KK, ππ, $K_S\pi^0$)
  - Flavour states (e.g. Kπ, Kππ, Keν)
  - Mixed-CP eigenstates ($K_S hh$)

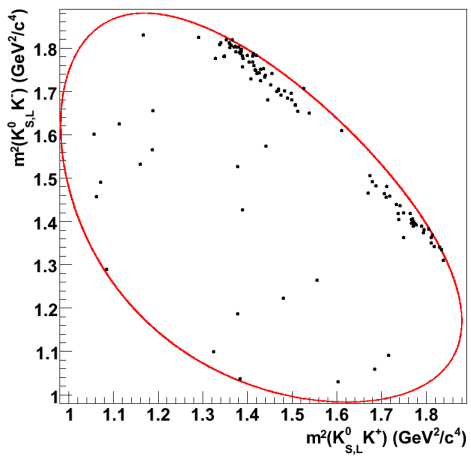
	$K_S KK$	$K_S\pi\pi$
CP eigenstates	96	789
Flavour states	864	7634
Mixed-CP eigenstates	200	473

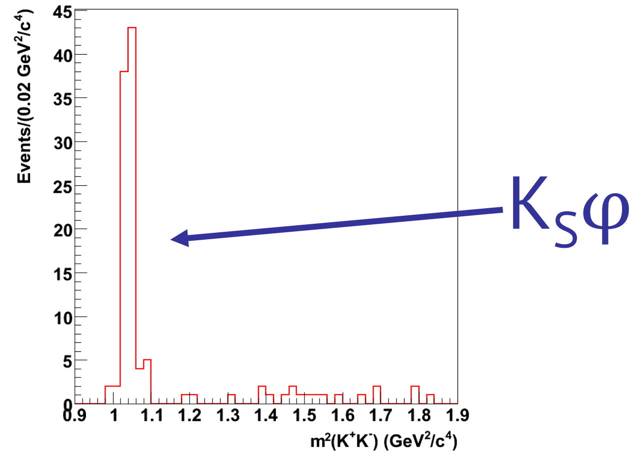
- $BR(K_S\pi\pi)/BR(K_S KK) \sim 6.3$
- In addition to $K_S hh$, also select $K_L hh$
  - Excellent detector & clean environment enables this
  - $CP(K_L hh) \sim -CP(K_S hh)$
  - More than doubles the dataset

Quantum correlations at CLEO-c

- Quantum correlations result in visible differences between different Dalitz plots
- Very striking difference seen in CP-tagged K_SKK

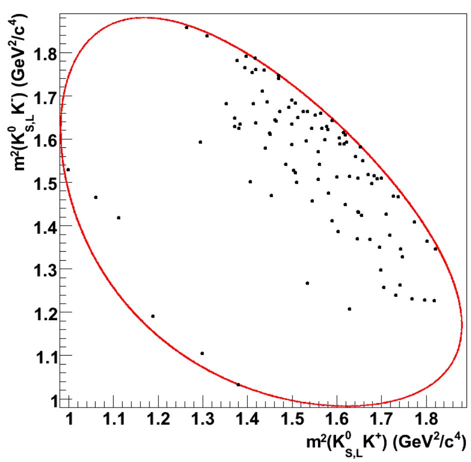
K_SKK vs CP+
K_LKK vs CP-

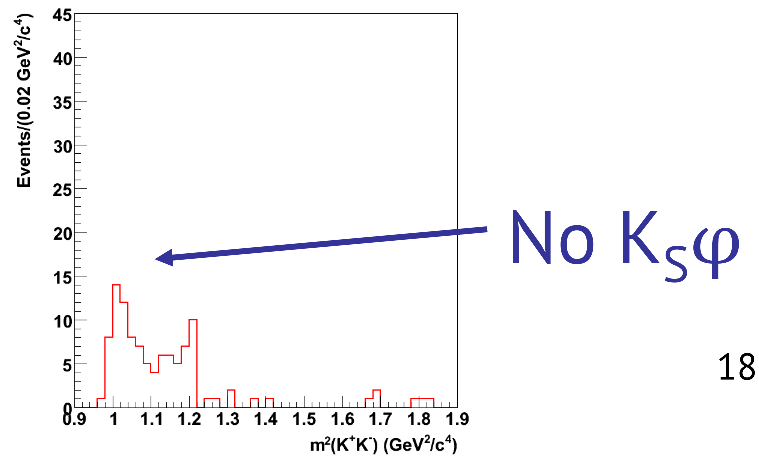




Phys. Rev. D **82**, 112006 (2010)

K_SKK vs CP-
K_LKK vs CP+





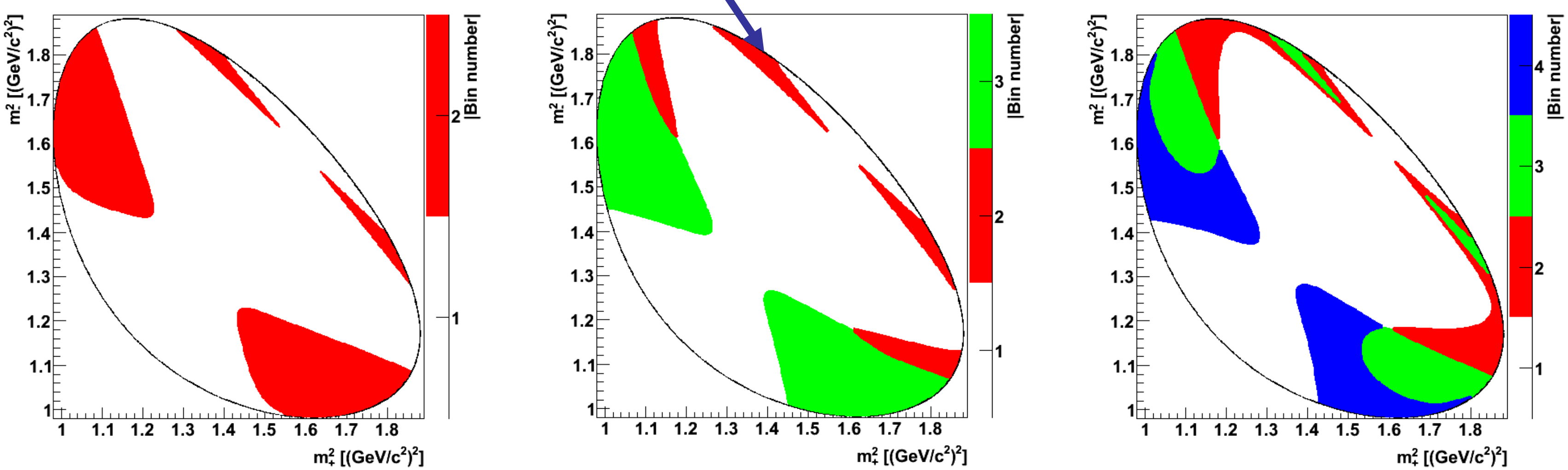
Binning the Dalitz plane

- The Dalitz plane can be binned in any way desired
- Binning in regions of similar strong phase difference (predicted by the model) provides improved statistical precision Eur. Phys. J. C **47**, 347 (2006)
- Studied several binnings for both $K_S\pi\pi$ and K_SKK

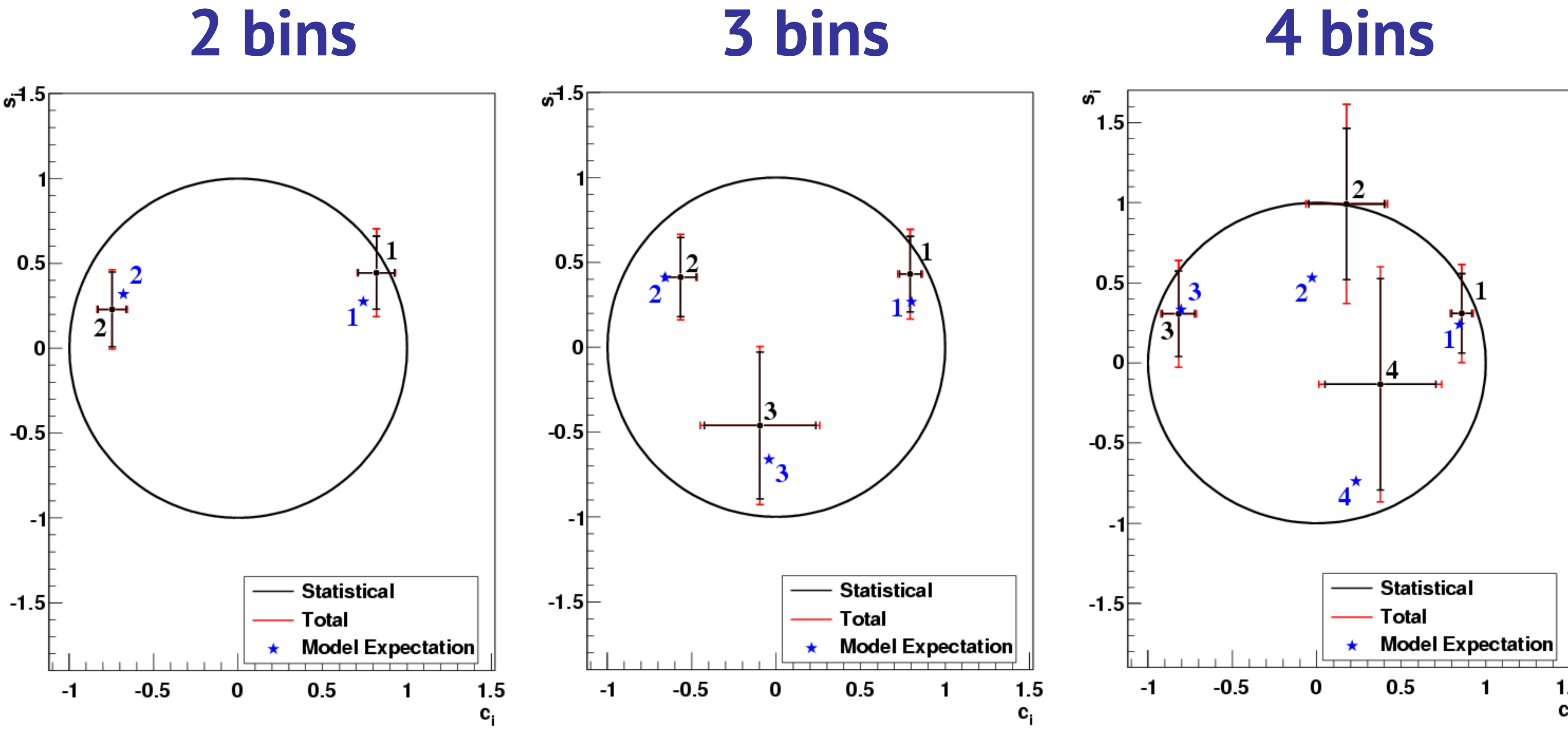
Binning the $K_S KK$ Dalitz plane

- $K_S KK$ binnings considered: 2, 3 and 4 bins
  - Relatively small number of events limits number of bins
  - Studying several binnings provides future flexibility

$K_S \varphi$ resonance



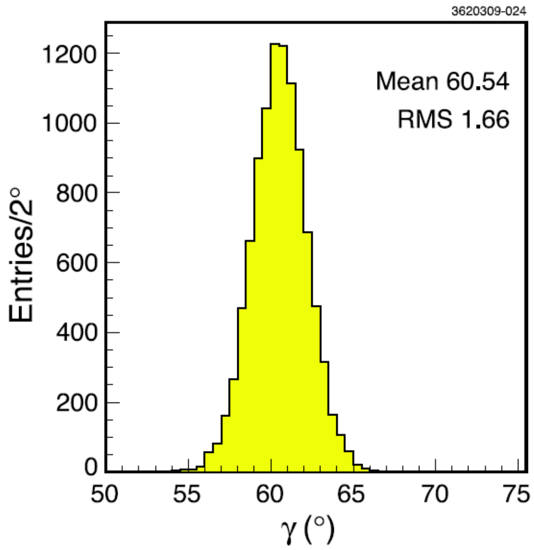
$K_S KK$ (c_i, s_i) results



- Good agreement between fit values and model
- Main systematic uncertainty from background estimation

Consequences for γ measurement

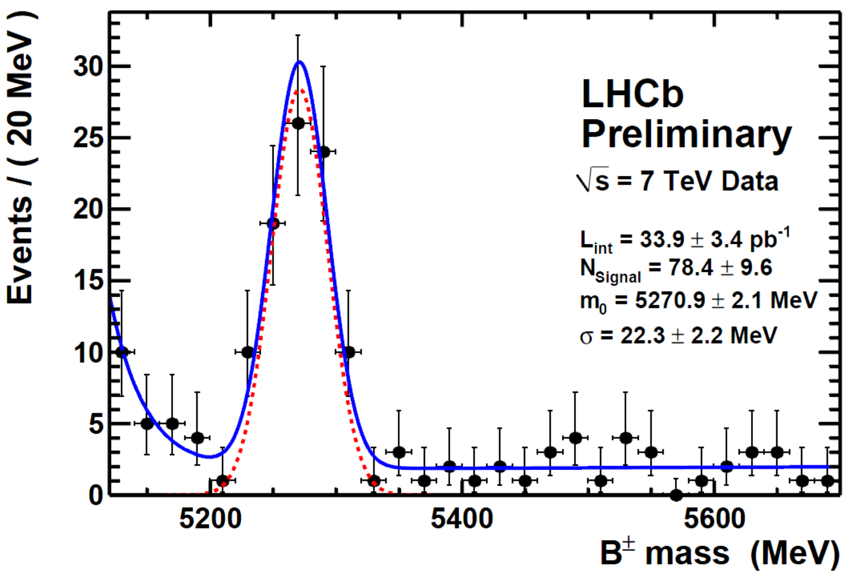
- Toy MC experiments: generate 5M B→DK events and determine impact of (c_i, s_i) on γ precision for different binnings



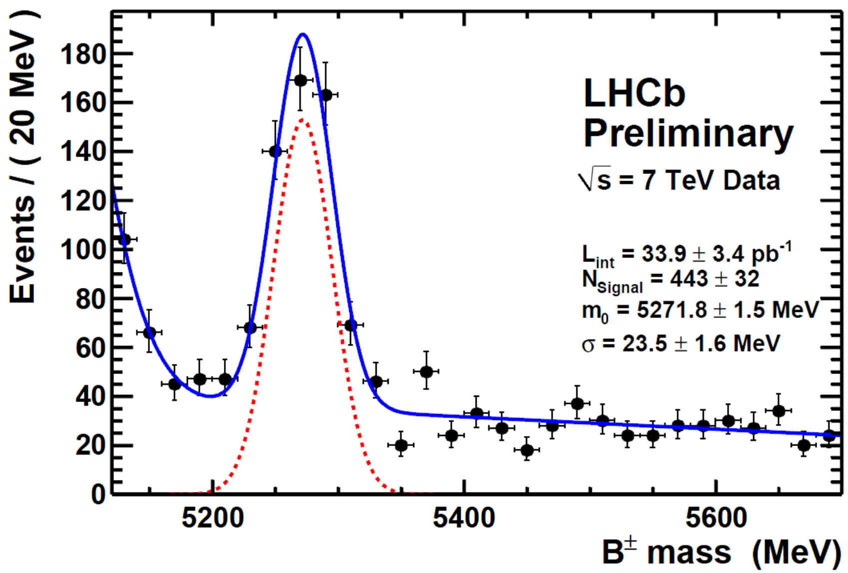
- Error on γ due to CLEO-c statistical uncertainty:
  - K_SKK: **3.2–3.9°**
  - $K_S\pi\pi$: **1.7–3.9°**
- Compare to 3–9° model uncertainty from B-factories
- BES-III will be able to reduce this even further

LHCb selection of B→D($K_S$hh)h

- LHCb has observed B→D($K_S$hh)π in 34pb^{-1}
- This is a control mode for B→DK



B→D(K_SKK)π



B→D(K_Sππ)π

- Excellent prospects for B→D($K_S$hh)K measurements

Conclusions

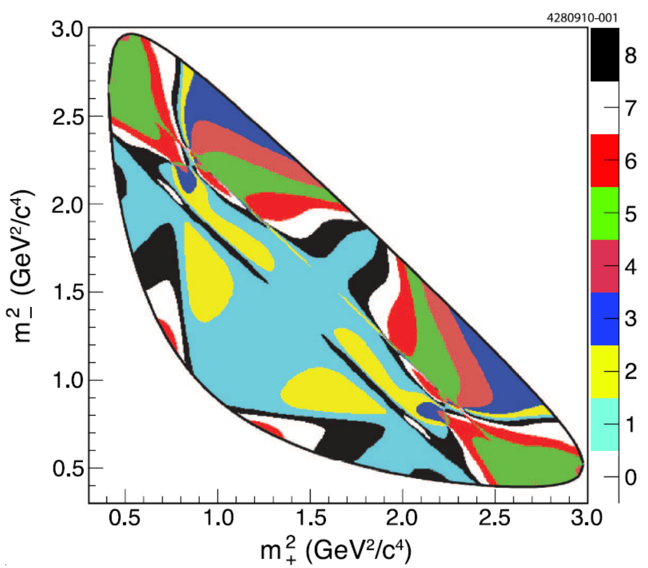
- $B \rightarrow DK$ is a very promising way to determine γ
- Input from charm physics is very important in order to precisely determine D^0 decay parameters
- Recent model-independent CLEO-c analysis of $D^0 \rightarrow K_S hh$ strong phase difference, including first measurement for $K_S KK$ final state
- Projected consequences for γ measurement: 1.7-3.9° for $K_S \pi\pi$, 3.2-3.9° for $K_S KK$
- LHCb has selected $B \rightarrow D(K_S hh)h$ events: very promising

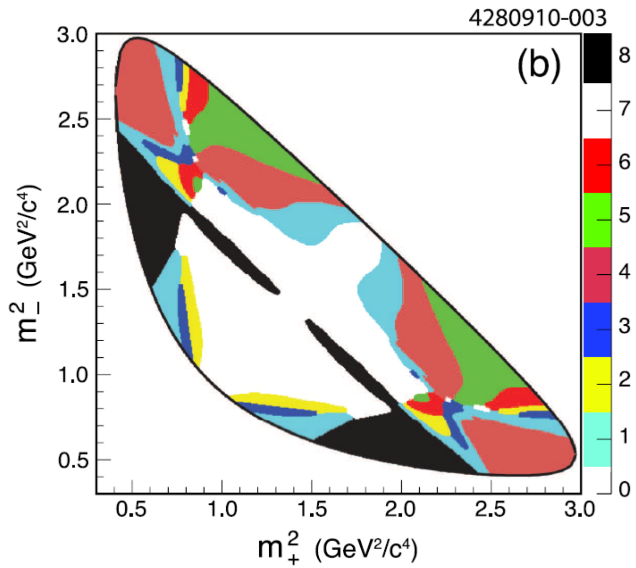
Backups

Binning the $K_S\pi\pi$ Dalitz plane

- Also updated $K_S\pi\pi$ analysis (previously studied in 2008) by considering several different binnings
- Compare and contrast models from BaBar and Belle
- Also optimised binning by considering senstivity given finite B-statistics Eur. Phys. J. C **55**, 51-56 (2008)
- Optimised binning for LHCb background expectation

Equal strong phase difference using BaBar model

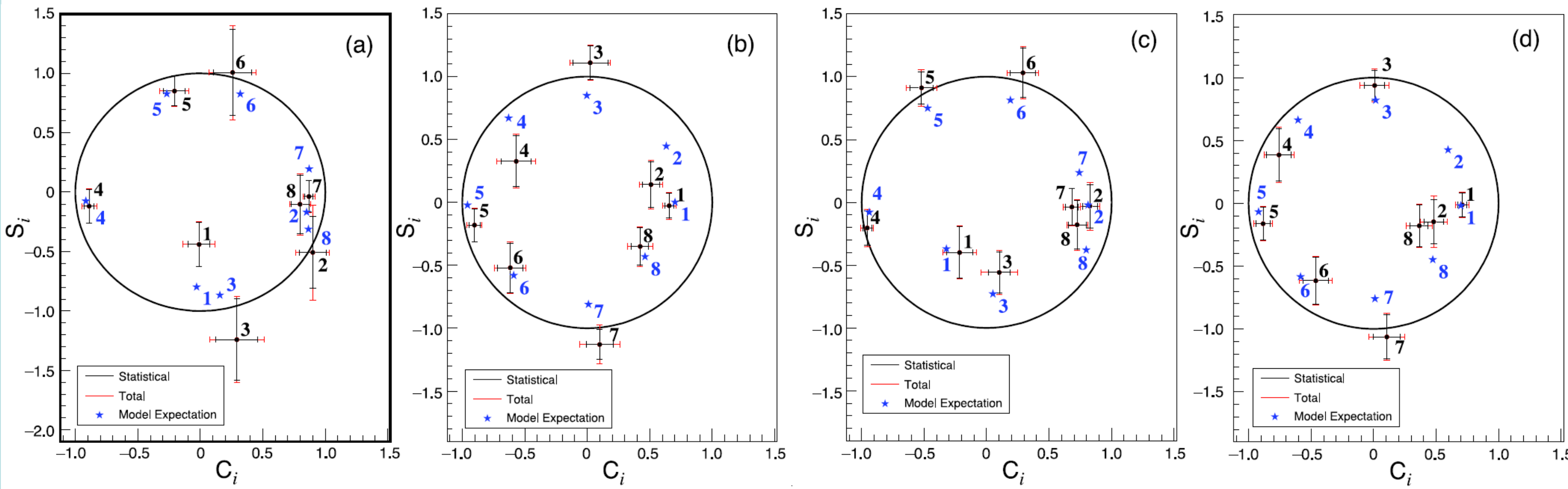




Optimised for finite B statistics

$K_S\pi\pi$ results

- Results for different binnings



BaBar model, optimised for B-stats

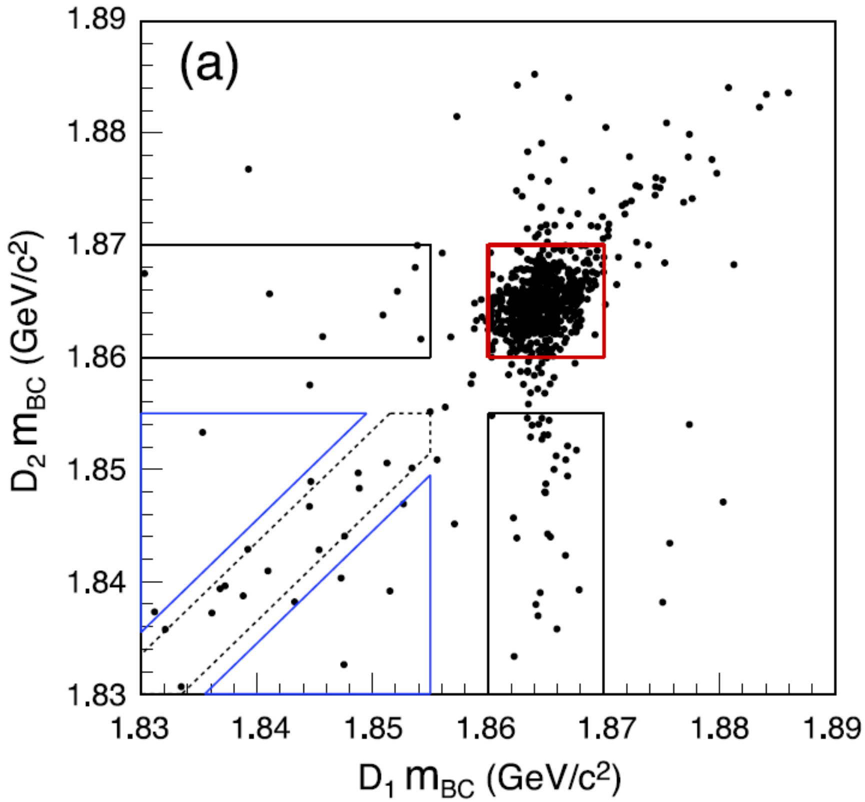
BaBar model, equal $\Delta\delta_D$

BaBar model, optimised for backgound

Belle model, equal $\Delta\delta_D$

CLEO-c event selections

- $K_S KK$ vs flavour tags ($K\pi$, $K3\pi$, $K\pi\pi^0$, $Ke\nu$)



Data

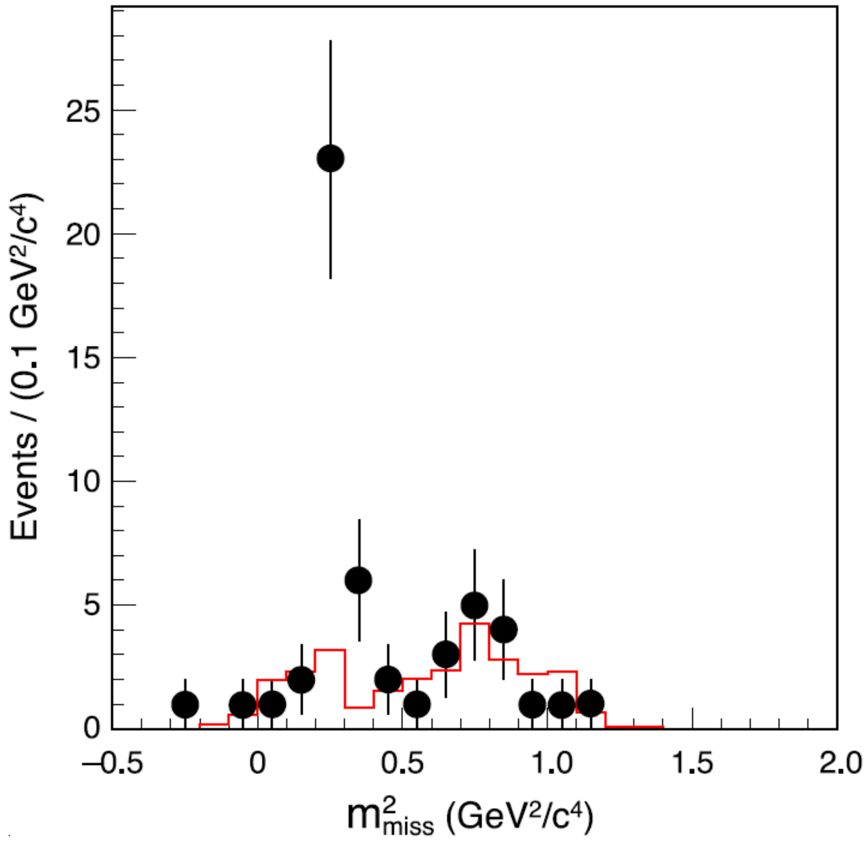
Signal region

Sidebands

- m_{BC} = beam constrained mass = sqrt($E^2 - p_D^2$)

CLEO-c event selections

- $K_L KK$ vs CP tags



Data

Background

- m^2_{miss} = squared missing mass

CLEO-c $K_S hh$ event yields

Mode	ST yield	DT yields			
		$K_S^0\pi^+\pi^-$	$K_L^0\pi^+\pi^-$	$K_S^0K^+K^-$	$K_L^0K^+K^-$
Flavor tags					
$K^-\pi^+$	144563 ± 403	1444	2857	168	302
$K^-\pi^+\pi^0$	258938 ± 581	2759	5133	330	585
$K^-\pi^+\pi^+\pi^-$	220831 ± 541	2240	4100	248	287
$K^-e^+\nu$		1191		100	
CP-even tags					
K^+K^-	13349 ± 128	124	357	12	32
$\pi^+\pi^-$	6177 ± 114	61	184	4	13
$K_S^0\pi^0\pi^0$	6838 ± 134	56		7	14
$K_L^0\pi^0$		237		17	
$K_L^0\eta(\gamma\gamma)$				4	
$K_L^0\eta(\pi^+\pi^-\pi^0)$				1	
$K_L^0\omega$				4	
$K_L^0\eta'$				1	
CP-odd tags					
$K_S^0\pi^0$	19753 ± 153	189	288	18	43
$K_S^0\eta(\gamma\gamma)$	2886 ± 71	39	43	4	6
$K_S^0\eta(\pi^+\pi^-\pi^0)$				2	1
$K_S^0\omega$	8830 ± 110	83		14	10
$K_S^0\eta'$				3	4
$K_L^0\pi^0\pi^0$				5	
$K_S^0\pi^+\pi^-$		473	1201	56	126
$K_L^0\pi^+\pi^-$				140	
$K_S^0K^+K^-$				4	9

Dalitz plot yields

- Number of events in i^{th} bin, N_i, depends on weighted average cosine and sine of strong phase difference as well as amplitude^2 in that bin

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

$$T_i \equiv \int_i |f_{D^0}(x,y)|^2 \, \mathrm{d}x \, \mathrm{d}y$$

$$c_i \equiv \frac{1}{\sqrt{T_i T_{-i}}} \int_i |f_{D^0}(x,y)||f_{D^0}(y,x)| \cos(\Delta\delta_D(x,y)) \, \mathrm{d}x \, \mathrm{d}y$$

$$s_i \equiv \frac{1}{\sqrt{T_i T_{-i}}} \int_i |f_{D^0}(x,y)||f_{D^0}(y,x)| \sin(\Delta\delta_D(x,y)) \, \mathrm{d}x \, \mathrm{d}y$$

Determining (c_i, s_i)

- c_i is determined using CP-tagged $K_S$hh

Double CP tag yield

Single CP tag yield

Double flavour tag yield

Single flavour tag yield

$$\frac{M_i^{\pm}}{S_{\mp}} = \frac{K_i \pm 2c_i\sqrt{K_iK_{-i}} + K_{-i}}{2S_f}$$

- c_i and s_i are determined using $K_S$hh tagged with K_Sh'h'

Double $K_{S,L}$hh tag yield

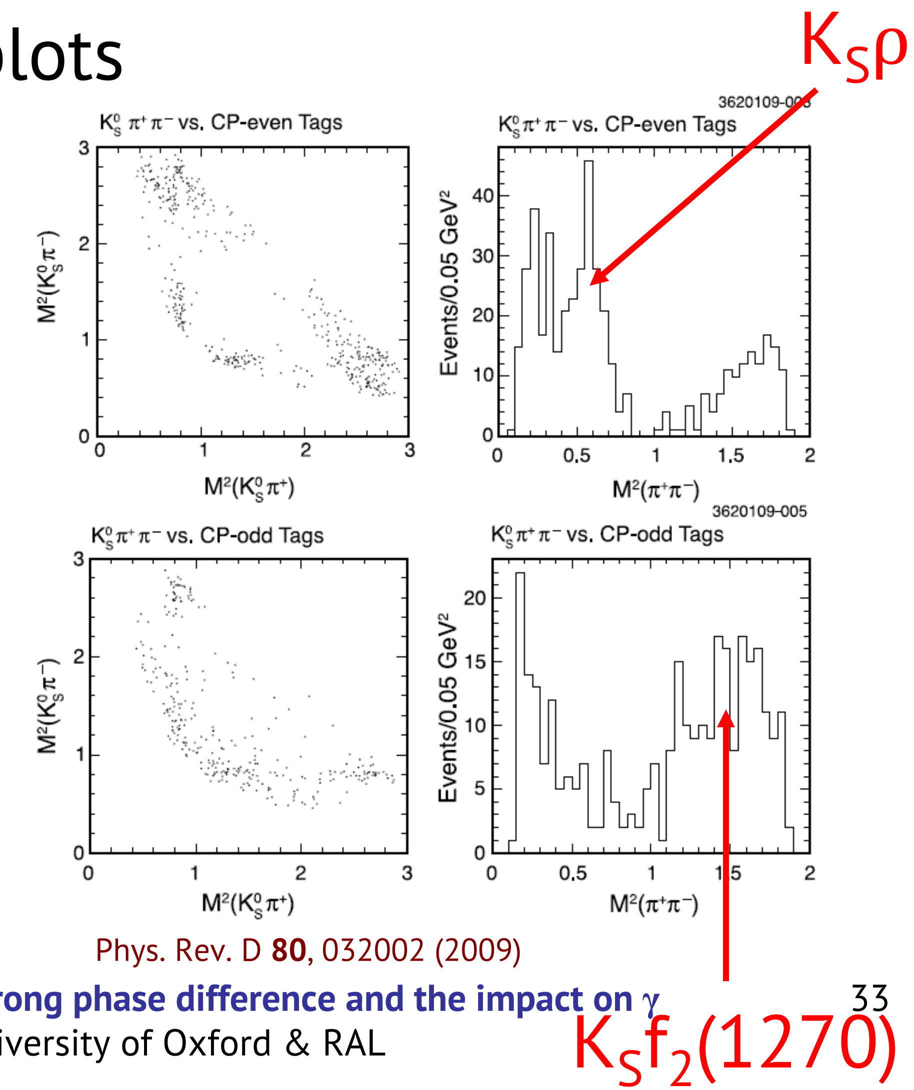
Double flavour tag yield

$$M_{ij} = \frac{N_{D,\overline{D}}}{2S_f^2}\left(K_iK_{-j} + K_{-i}K_j - 2\sqrt{K_iK_{-j}K_{-i}K_j}(c_ic_j + s_is_j)\right)$$

Single flavour tag yield

Quantum correlations at CLEO-c

- Quantum correlations result in visible differences between different Dalitz plots
- Decays to $K_S\pi\pi$ proceed via different intermediate resonances of specific CP depending on opposite-side final state (tag)



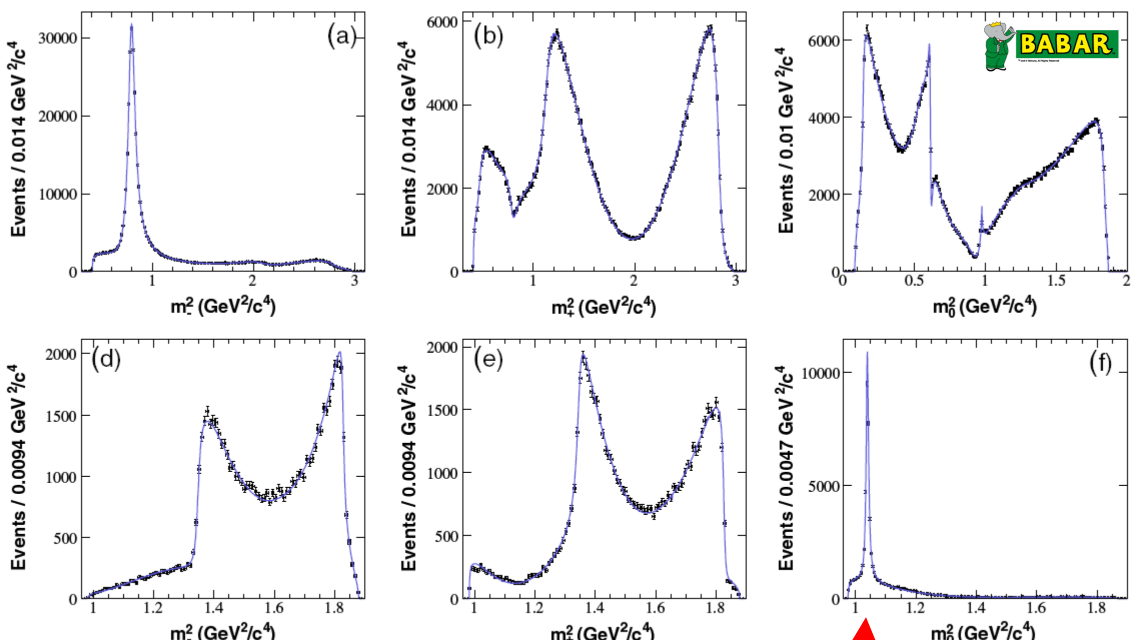
Phys. Rev. D **80**, 032002 (2009)

$D^0 \to K_S KK$ systematic errors

Uncertainty	c_1	c_2	c_3	s_1	s_2	s_3
(Pseudo-)flavor statistics	0.005	0.007	0.055	0.015	0.013	0.039
Momentum resolution	0.002	0.004	0.012	0.018	0.025	0.032
Mode-to-mode normalization	0.004	0.008	0.017	0.001	0.010	0.004
Multiple-candidate selection	0.004	0.003	0.015	0.004	0.008	0.002
DCS correction	0.001	0.001	0.003	0.002	0.005	0.002
$K^0_{S,L}\pi^+\pi^-$ $(c_i^{(\prime)}, s_i^{(\prime)})$	0.006	0.011	0.036	0.132	0.063	0.135
Fitter assumptions	0.008	0.001	0.013	0.013	0.003	0.043
MC statistics for determining $\mathbf{U}$	0.005	0.007	0.057	0.024	0.051	0.048
Parameterization of non-K^0_L final state background	0.001	0.001	0.006	0.000	0.008	0.003
Parameterization of K^0_L final state background	0.034	0.020	0.061	0.038	0.015	0.071
Background Dalitz space distribution	0.006	0.015	0.062	0.005	0.029	0.022
Assumed background $\mathcal{B}$	0.004	0.014	0.032	0.001	0.007	0.009
Total systematic	0.038	0.034	0.131	0.142	0.094	0.175
Statistical plus $K^0_L K^+K^-$ model	0.063	0.092	0.329	0.222	0.234	0.432
$K^0_L K^+K^-$ model alone	0.000	0.000	0.136	0.007	0.000	0.039
Total	0.073	0.098	0.354	0.264	0.252	0.466

Modelling B decays

- B-factories use unbinned model approach
- Use high-statistics sample of $D^{*\pm} \rightarrow D^0 \pi^\pm$
  - Pion acts as a tag to determine D^0 flavour



$D^0 \rightarrow K_S \pi\pi$

$D^0 \rightarrow K_S KK$

$K_S\varphi$ resonance

Phys. Rev D **78**, 034023 (2008)

B-factory γ measurements

- BaBar (468M $B\bar{B}$, both $K_S\pi\pi$ and K_SKK)

$$\gamma = 68^\circ \pm 14^\circ(\text{stat}) \pm 4^\circ(\text{syst}) \pm 3^\circ(\text{model})$$

Phys. Rev. Lett. **105**, 121801 (2010)

- Belle (657M $B\bar{B}$, $K_S\pi\pi$)

$$\gamma = 78.4^{\circ}{}^{+10.8^\circ}_{-11.6^\circ}(\text{stat}) \pm 3.6^\circ(\text{syst}) \pm 8.9^\circ(\text{model})$$

Phys. Rev. D **81**, 112002 (2010)

- The model error will be a limiting factor in future γ determination

CKM matrix

- Quantifies weak mixing between quark generations

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

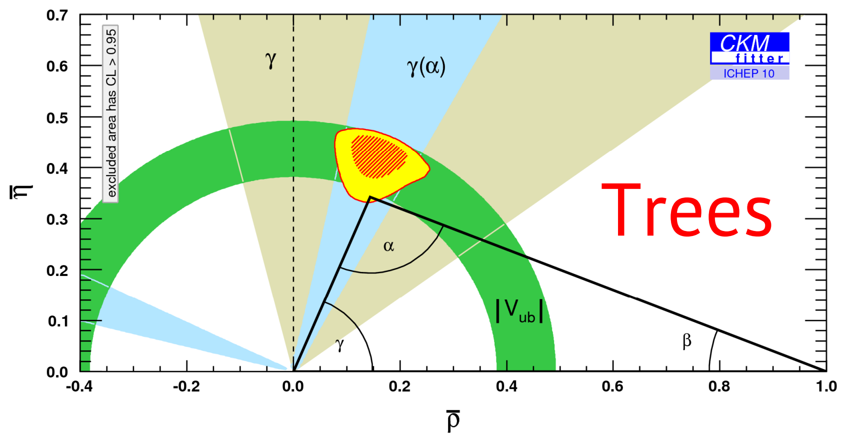
- Unitary: $V_{\mathrm{CKM}}^{\dagger} V_{\mathrm{CKM}} = \mathbb{I}$
- Six relations such as the following:

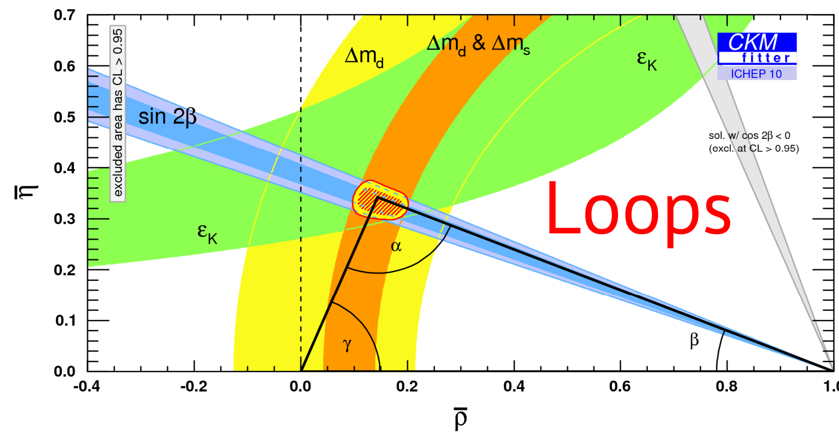
$$\boxed{\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0}$$

- Each represents a triangle in the complex plane

Trees vs loops

- Tension between the values of γ obtained from tree-level and loop-level measurements will be a strong indication of new physics

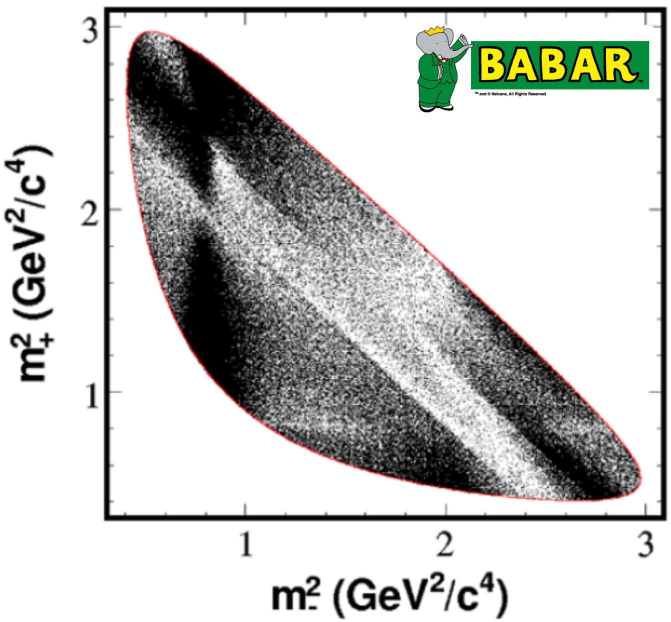




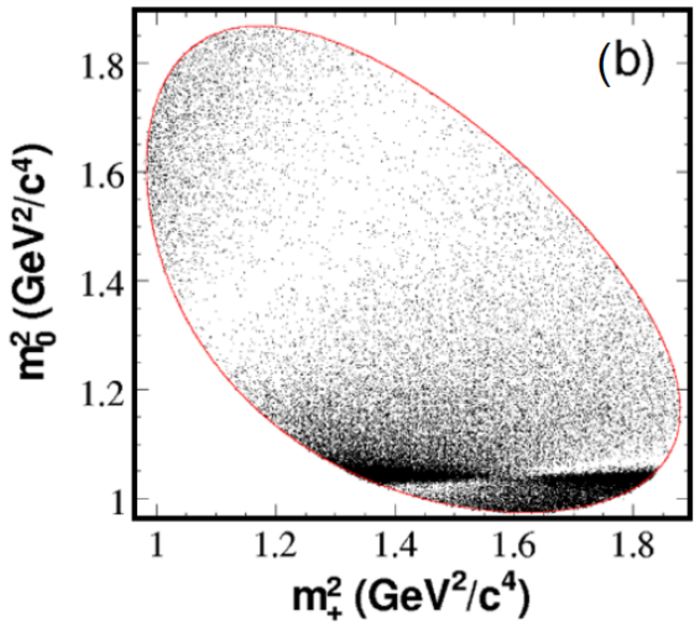
- In this talk concentrate on tree-level determinations, in particular time-independent measurements in the $B^{\pm} \rightarrow D^0 K^{\pm}$ system

Dalitz plots

- Representation of the structure of a decay in terms of (invariant mass)^2 of pairs of the final state particles
- Reveals interference and intermediate resonances



$K_S\pi\pi$



K_SKK

DCS contribution to $K_L hh$

- $K_{S,L}hh$ contain both CF and DCS decay amplitudes
- Amplitudes are related:
- $A(K_L hh) = A(K_S hh) - \text{sqrt}(2) \cdot A(K^0 hh)$
- Correction term ~ $\tan^2 \theta_c$ ~ 1/20
- Estimated using decay model
  - different resonances behave differently under CP transformation
- Small systematic error to account for this