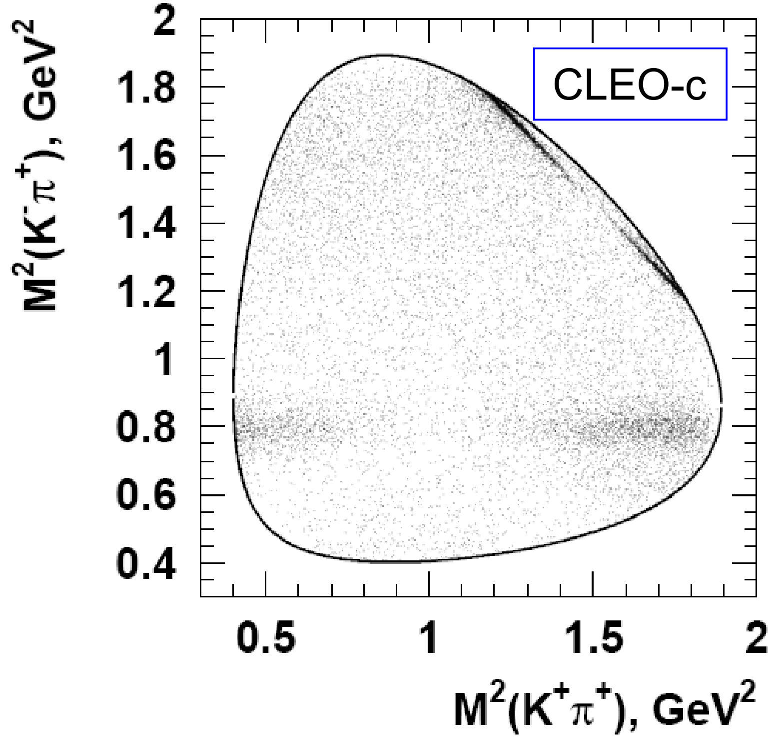
Dalitz Decays in Charm

Jonas Rademacker on behalf of the CLEO-c collaboration

Dalitz Plots

- Kinematics of 3-body decay D→A,B,C fully described by 2 parameters.
- Usually chose $m^2_{AB} \equiv (p_A + p_B)^2$ and $m^2_{BC} \equiv (p_B + p_C)^2$.
  - Lorentz invariant
  - Phase-space is flat in these parameters.

$D^+ \to K^+K^-\pi^+$



Plot from P. Naik's presentation at HADRON 07 on behalf of CLEO-c

- Decay rates:

$$\frac{d\Gamma(m^2_{ab}, m^2_{bc})}{dm^2_{ab}\, dm^2_{bc}} = \left|a_1 e^{i\delta_1} + a_2 e^{i\delta_2} + a_3 e^{i\delta_3} + \ldots\right|^2 \frac{d\Phi(m^2_{ab}, m^2_{bc})}{dm^2_{ab}\, dm^2_{bc}}$$

Dalitz analyses can...

- Main strength of Dalitz analyses: Access to complex amplitudes, incl phases.
- Use for...
  - Understanding properties the light meson resonances.
  - Understand charm itself - mixing, CPV
  - Measure properties (phases) of B-meson decays to charm (CPV)

$K^*\ \rho\ a_1\ f(980)...$

$\sigma(?)\ \kappa(?)...$

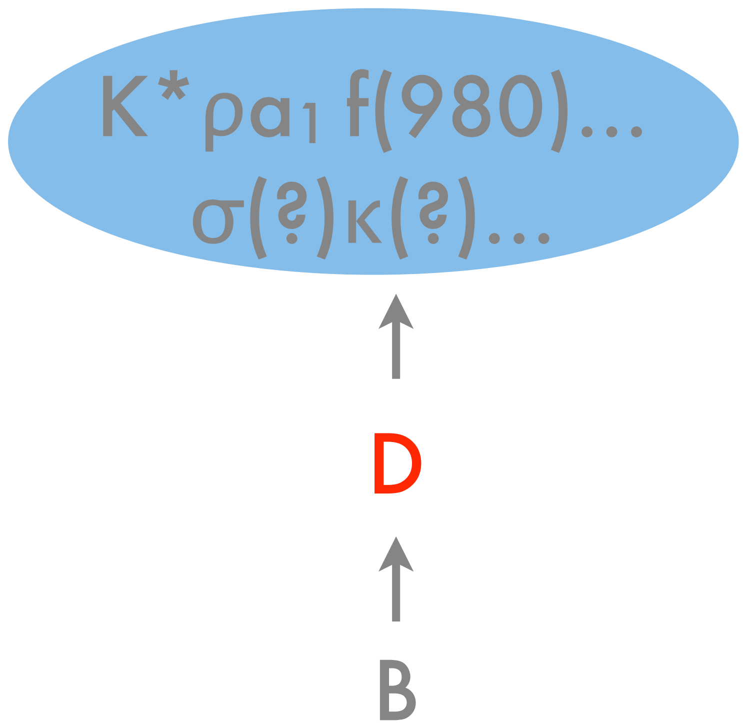
↑

D

↑

B

Charm Dalitz for the resonances

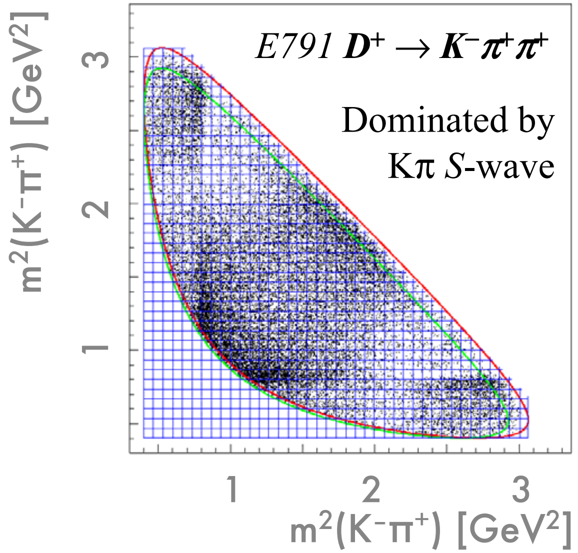


"Isobar" Model

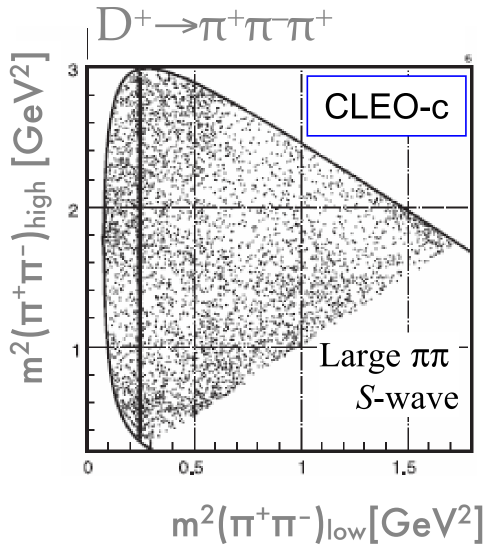
- Each resonance = Breit Wigner lineshape (or similar) times factors accounting for spin.
- Popular amongst experimentalists, but less so amongst theorists: violates unitarity. But not much as long as resonances are reasonably narrow, don't overlap too much.
- General consensus: Isobar OK for P, D wave, but problematic for S-wave.
- Alternatives exist, e.g. K-matrix formalism, which respects unitarity.

S-wave

- S-wave resonances $\sigma \to \pi^+\pi^-$, $\varkappa \to K^+\pi^-$ are the real?
  - needed in isobar fits to $D^+ \to \pi^+\pi^-\pi^+$, $D^0 \to K_s\pi^+\pi^-$, $D^+ \to K^-\pi^+\pi^+$
  - unclear if compatible with LASS scattering data
  - not required in $D^0 \to K^-\pi^+\pi^0$, $D^0 \to \pi^+\pi^-\pi^0$ isobar fits
- K-matrix Models don't explicitly require σ, $\varkappa$.



Phys. Rev. Lett 89, 121801 (2002)

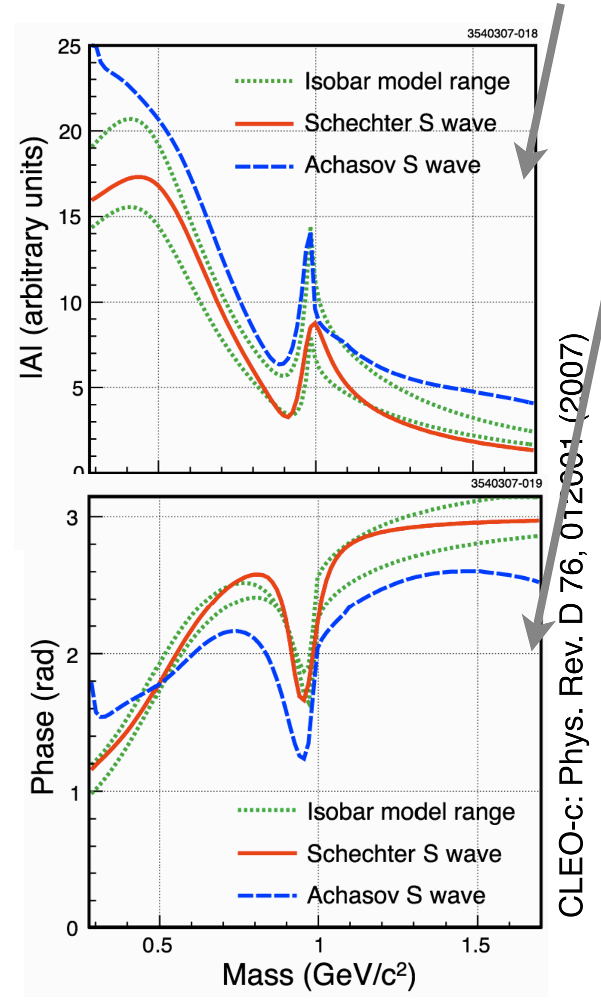


P. Naik on behalf of CLEO at HADRON 07

CLEO-c's $D^+ \to \pi^+\pi^+\pi^-$ 3-model fit

- Previously on this channel: E791's isobar fit, FOCUS pioneered K-matrix.
- CLEO-c: Isobar (two types: Flatté and complex-pole for $f_0(980)$ and σ) and two models that respect unitarity & chirality [CLEO-c: Phys. Rev. D 76, 012001 (2007)]
  - Schechter [see CLEO paper and Int J. Mod. Phys. A20, 6149 (2005)]
  - Achasov [see CLEO paper and N. N. Achasov and G. N. Shestakov, Phys. Rev. D 67, 114018 (2003), and many more -click here.]
- All fit data well. Results compatible with prev experiments and each other.

$A(\text{S-wave } \pi\pi) = |A| e^{i\delta}$



E791: Phys. Rev. Lett. 86, 770 (2001); FOCUS: Phys. Lett. B 585, 200 (2004); CLEO-c: Phys. Rev. D 76, 012001 (2007)

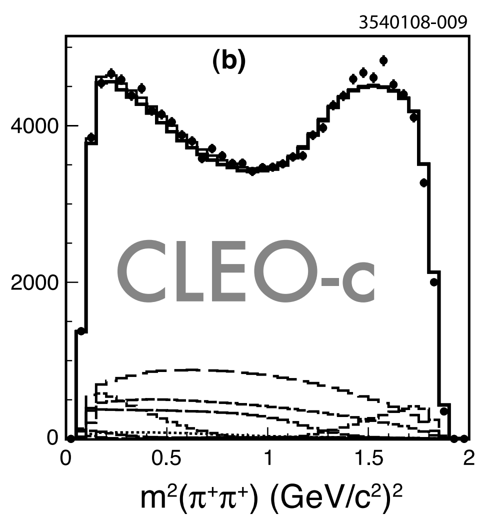
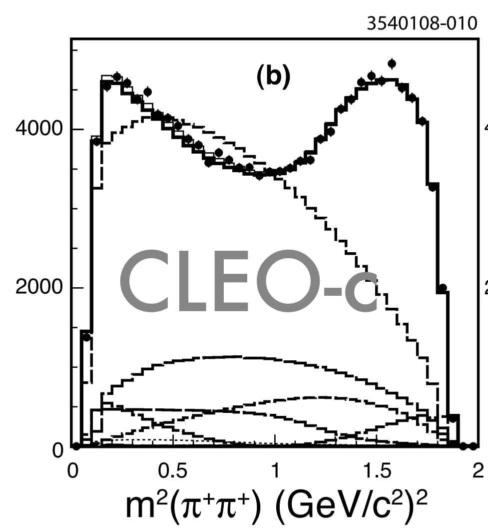
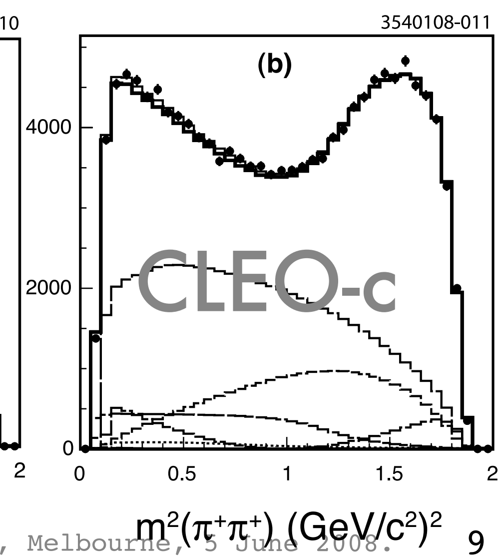
$D^+ \to K^- \pi^+ \pi^+$

- Large $K\pi$ S-wave component, large B.R.
- History
  - 2002, highest-statistics result (15k evts), isobar model fit by E791* (result not in PDG - model used not compatible with PDG prescription).
  - In 2006, E791** re-analysed their data, describing the S-wave contribution in a model-independent way.
  - CLEO-c repeated this analysis in 2008*** (140k evts)
  - FOCUS use K-matrix approach (2007)**** (54k evts)

*Phys. Rev. Lett 89, 121801 (2002); **Phys. Rev. D73, 032004 (2006);
***arXiv:0802.4214 (submitted to PRD); ****arXiv:0705.2248 [hep-ex], to appear in Phys. Lett. B

$D^+ \to K^-\pi^+\pi^+$ Isobar and Model Independent Fit at CLEO-c

- Quasi Model Independent: Replace S-wave Breit Wigners + non-resonant component with binned complex amplitude (26 bins).
- New compared to E791: Add I=2 $\pi\pi$ S-wave - both, to isobar and to quasi-model independent fit. Crucial element in both fits.

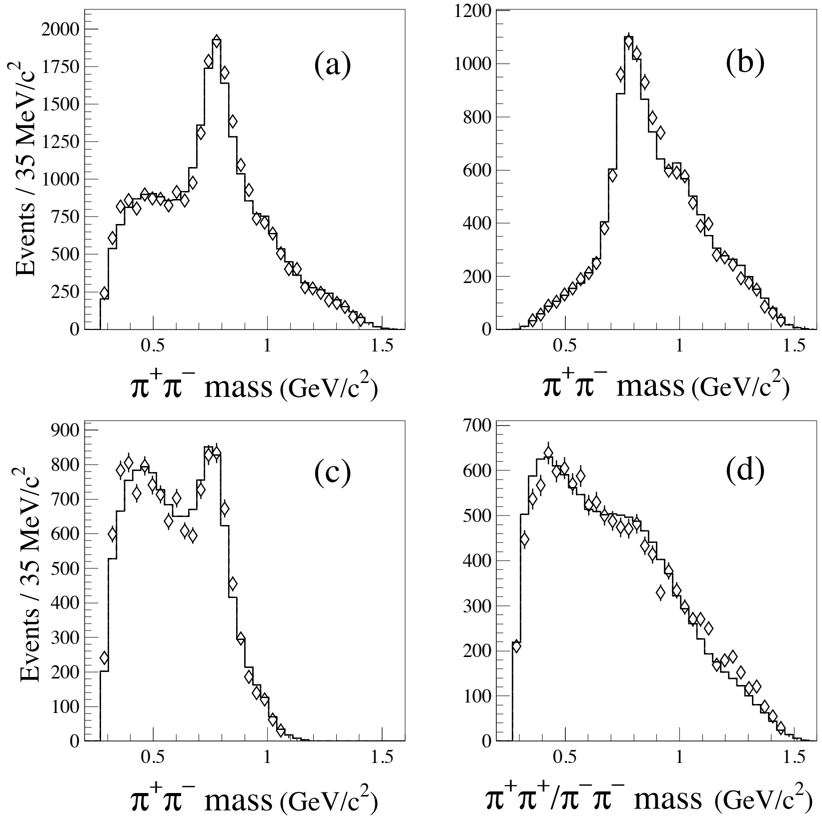
Model:	isobar (E791 model)	isobar with I=2 ππ S-wave	binned Kπ S-wave incl binned I=2 ππ S-wave
χ^2-prob	$<10^{-6}$	13%	32%
Fit pro-jection (ππ)			

arXiv:0802.4214 (submitted to PRD)

4-body "Dalitz" $D \to \pi^+\pi^+\pi^-\pi^-$

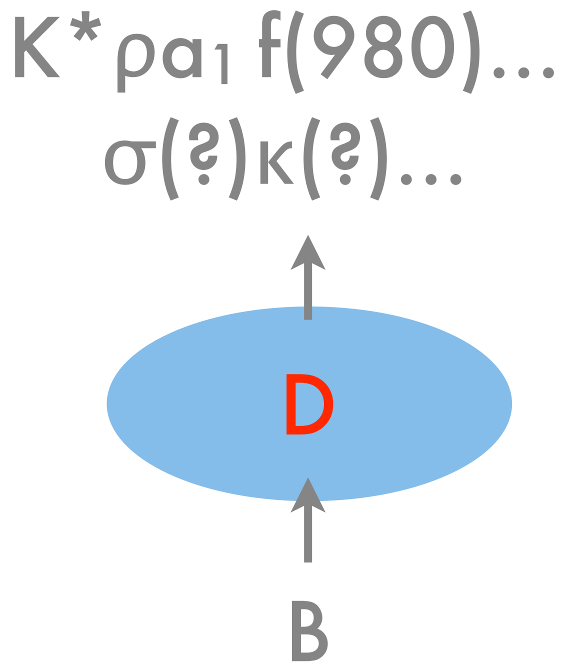
- Similar formalism, now with 5 variables rather than 2.
- $D \to a_1(1260)\pi$ is the dominant channel, followed by $\rho\rho$.
- Found dominant decay of a_1 is $\sigma\pi$ (isobar analysis)
- Many more results in paper, (incl $\rho\rho$ polarisation)
- 4-body amplitude in D also important for B physics.

FOCUS (Jan. 2007)



Phys.Rev.D75:052003,2007

Dalitz Plots for Charm mixing and CP violation



The Charm System

- D mass eigenstates: $D_{1,2}=p|D\rangle \pm q|\overline{D}\rangle$
  - $x = \frac{\Delta m}{\bar{\Gamma}}$ ~mixing frequency
  - $y = \frac{\Delta \Gamma}{2\bar{\Gamma}}$ ~lifetime difference
  - CP-violation if $|p/q| \neq 1$ or phase $\phi \neq 0$ (measured in interference between mixing and decay, like -2β in B)
- SM: x, y ~ $10^{-3} - 10^{-2}$, no CPV
- New Physics could affect charm very differently to K or B system (only mixing up-type quark).
- Most sensitive to NP: CP violation in charm.

Charm mixing

- First charm mixing evidence was found with $D \to K^+\pi^-$. Sensitive to $(x')^2$ and y', where

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

- δ = strong phase between the interfering CF $D \to K^-\pi^+$ and DCS $D \to K^+\pi^-$. (CLEO measured $\cos\delta = 0.9 \pm 0.3$). W. M. Sun at CHARM 2007 for CLEO, arXiv:0712.0498 [hep-ex]

- Same principle works with $D \to K^+\pi^-\pi^0$ Dalitz plots and measures measures x'', y''. See William Lockman for BaBar at Lepton-Photon 2007, Daegu, S. Korea and backup slides for details.

Charm mixing with time-dependent $D \to K_s \pi^+ \pi^-$ Dalitz

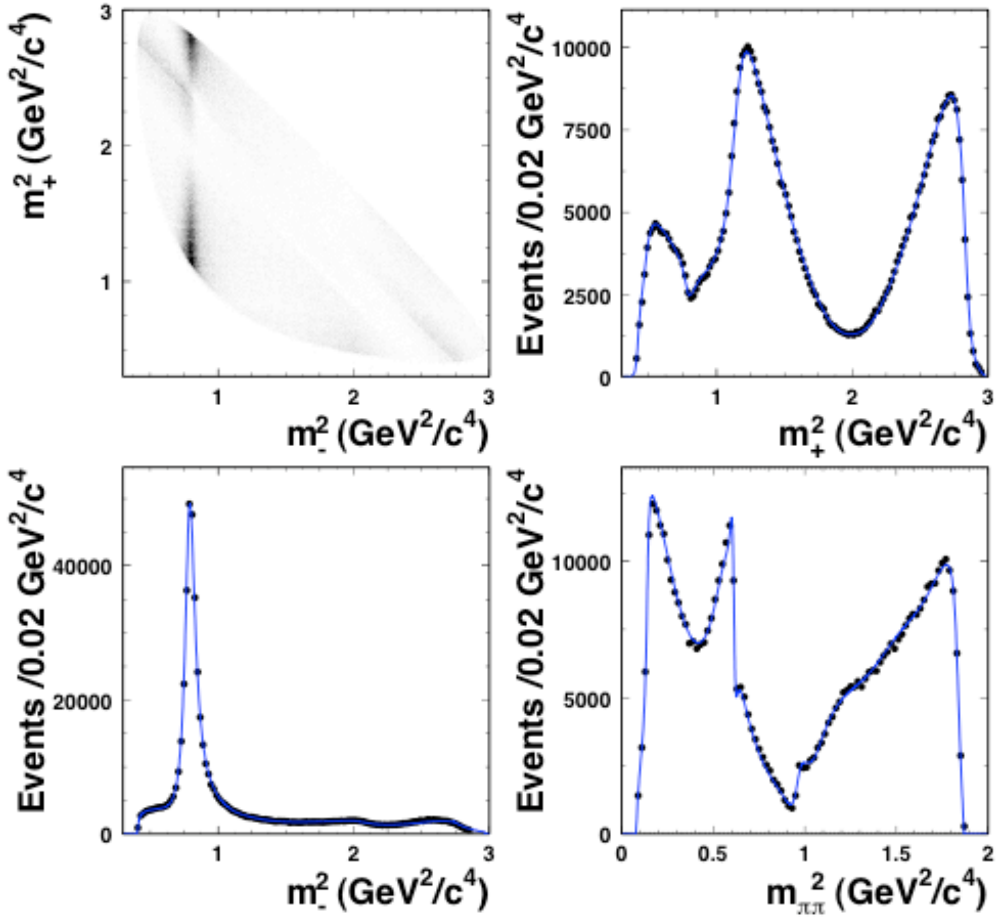
- $K_s\pi^+\pi^-$ is self-conjugate, both CF modes like $D \to K^{*-}\pi^+$ and DCS modes such as $D \to K^{*+}\pi^-$ are in the same Dalitz plot ⇒ measure their relative phase δ_i.
- Dalitz fit measures all phases that are needed.
- Extracts (x, y) directly; not (x′, y′) or (x″,y″)
- Linear dependence on x, sensitivity to the sign of x.
- Pioneered by CLEO Phys. Rev.D72:012001,2005, hep-ex/0503045

Charm mixing with time-dependent $D \to K_s \pi^+ \pi^-$ Dalitz

$D \to K_s \pi^+ \pi^-$ at BELLE

(ca ½M for 540/fb)

Phys.Rev.Lett.99:131803,2007



isobar model

Resonance	Fit fraction
$K^*(892)^-$	0.6227
$K_0^*(1430)^-$	0.0724
$K_2^*(1430)^-$	0.0133
$K^*(1410)^-$	0.0048
$K^*(1680)^-$	0.0002
$K^*(892)^+$	0.0054
$K_0^*(1430)^+$	0.0047
$K_2^*(1430)^+$	0.0013
$K^*(1410)^+$	0.0013
$K^*(1680)^+$	0.0004
$\rho(770)$	0.2111
$\omega(782)$	0.0063
$f_0(980)$	0.0452
$f_0(1370)$	0.0162
$f_2(1270)$	0.0180
$\rho(1450)$	0.0024
σ_1	0.0914
σ_2	0.0088
NR	0.0615

Charm mixing with time-dependent Dalitz Plots at BELLE

- HFAG FPCP 2008*

mix: $x = (0.89^{+0.26}_{-0.27})\%$ $y = (0.75^{+0.17}_{-0.18})\%$

CPV: $|p/q| = 0.87^{+0.18}_{-0.15}$ $\phi = -9.1^{o}{}^{+8.1^{o}}_{-7.8^{o}}$

- BELLE's $D \rightarrow K_s\pi^+\pi^-$ alone**

$x = (0.81 \pm 0.30^{+0.13}_{-0.17})\%$

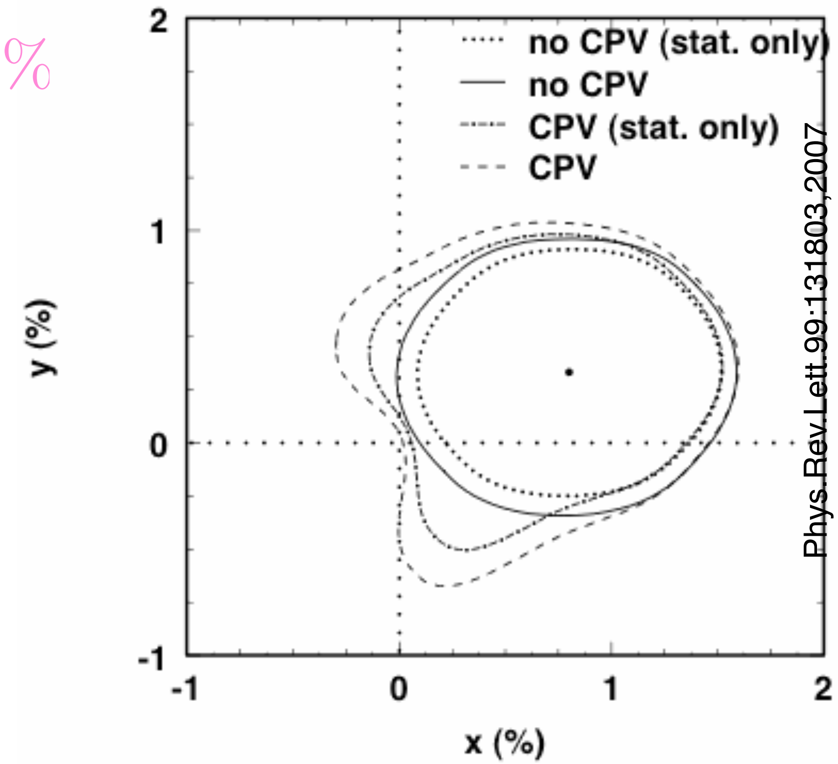
$y = (0.37 \pm 0.25^{+0.10}_{-0.15})\%$

$|p/q| = 0.86 \pm 0.30^{+0.10}_{-0.09}$

$\phi = -14^{o} \pm 18^{o} \pm 5^{o}$

- Best single result on x.

95% CL, BELLE, D→Ksππ

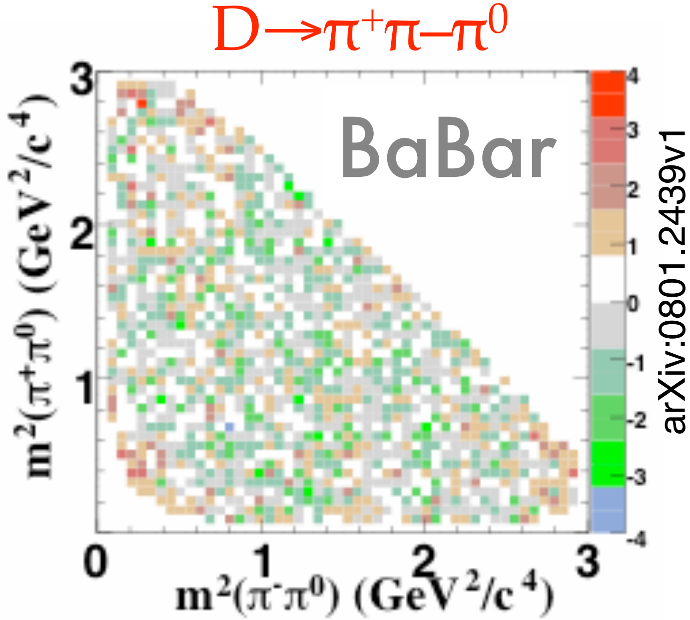


*http://www.slac.stanford.edu/xorg/hfag/charm/FPCP08/results_mix+cpv.html
**Phys.Rev.Lett.99:131803,2007

Search for CPV in SCS decays

- New physics could affect Singly Cabibbo Suppressed decays differently from Cabbibo Favoured or Doubly Cabbibo Supressed.
- Recent Dalitz studies by BaBar ($D \to \pi^+\pi^-\pi^0$, $D \to K^+K^-\pi^0$) and CLEO-c $D^+ \to K^+K^-\pi^+$. Results: CPV in SCS smaller than few%.

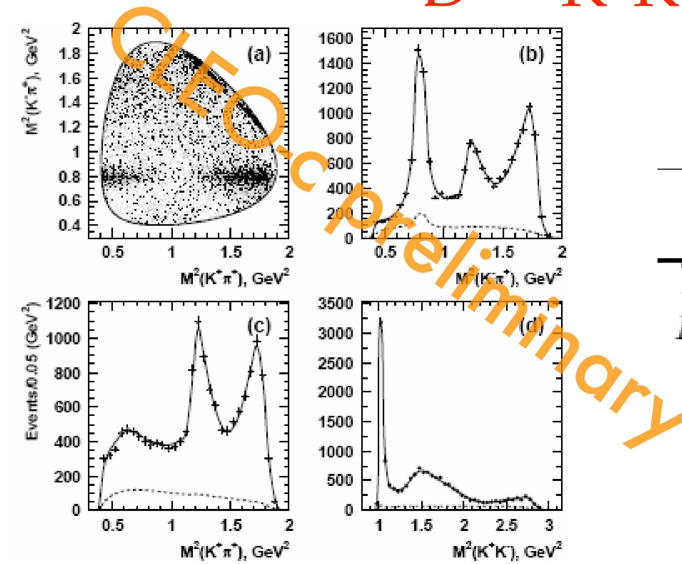
$D \to \pi^+\pi^-\pi^0$



BaBar result: arXiv:0802.4035, submitted to PRL

BELLE result (integrated decay rates, not Dalitz): arXiv:0801.2439, submitted to PRD

$D^+ \to K^+K^-\pi^+$, CLEO-c

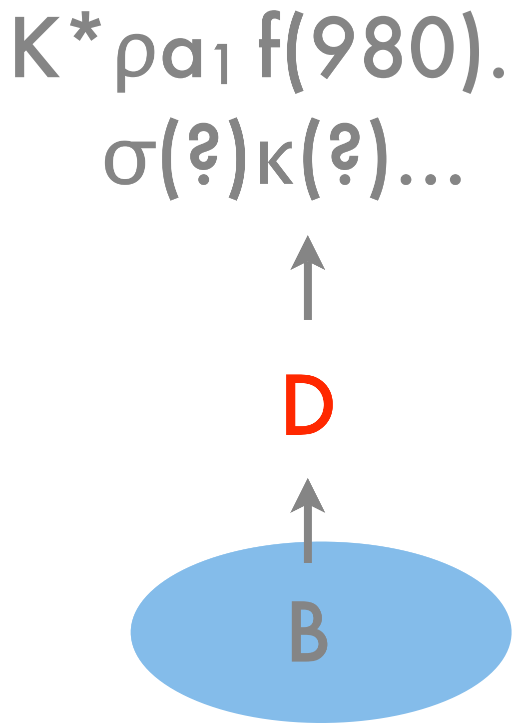


$$A_{CP} = \frac{N_{D+}/\epsilon_{D+} - N_{D-}/\epsilon_{D-}}{N_{D+}/\epsilon_{D+} + N_{D-}/\epsilon_{D-}}$$

Component	A_{CP}(fraction) (%)
$\overline{K}^*(892)^0 K^+$	$0.2 \pm 2.7^{+2.3+0.7}_{-0.4-0.4}$
$K^-\pi^+(S)K^+$	$-1 \pm 5^{+1+6}_{-2-4}$
$a_0(980)\pi^+$	$-18 \pm 23^{+4+24}_{-9-6}$
$\phi(1020)\pi^+$	$-3.7 \pm 1.9^{+0.1+0.2}_{-0.2-0.3}$
$f_2(1270)\pi^+$	$5 \pm 26^{+3+22}_{-4-46}$
$a_0(1450)\pi^+$	$-20 \pm 13^{+0+16}_{-8-9}$
$\phi(1680)\pi^+$	$-6 \pm 21^{+22+7}_{-4-3}$
$\overline{K}^*_2(1430)^0 K^+$	$59 \pm 41^{+1+8}_{-28-41}$

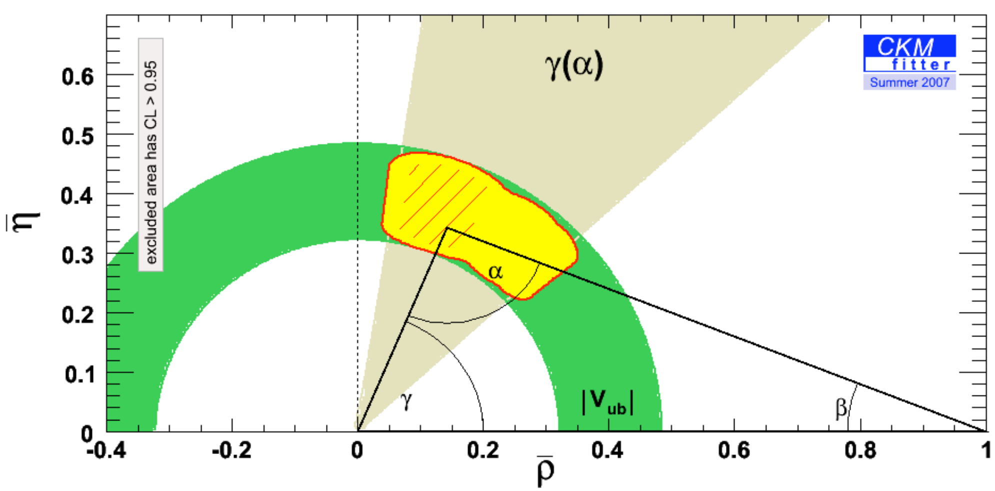
CLEO-c result: Presented at HADRON07 by P. Naik on behalf of CLEO-c

Charm Dalitz for precision B physics

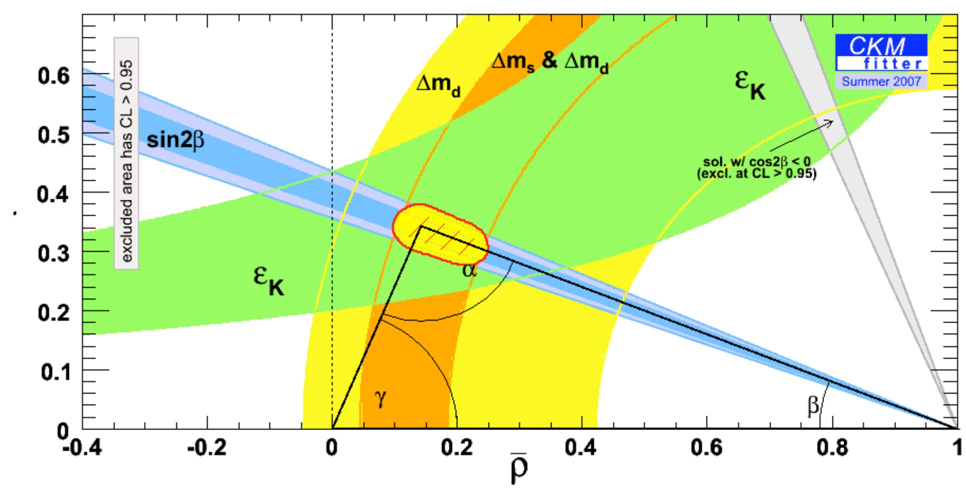


The importance of measuring Tree-level γ

Constraints from Trees

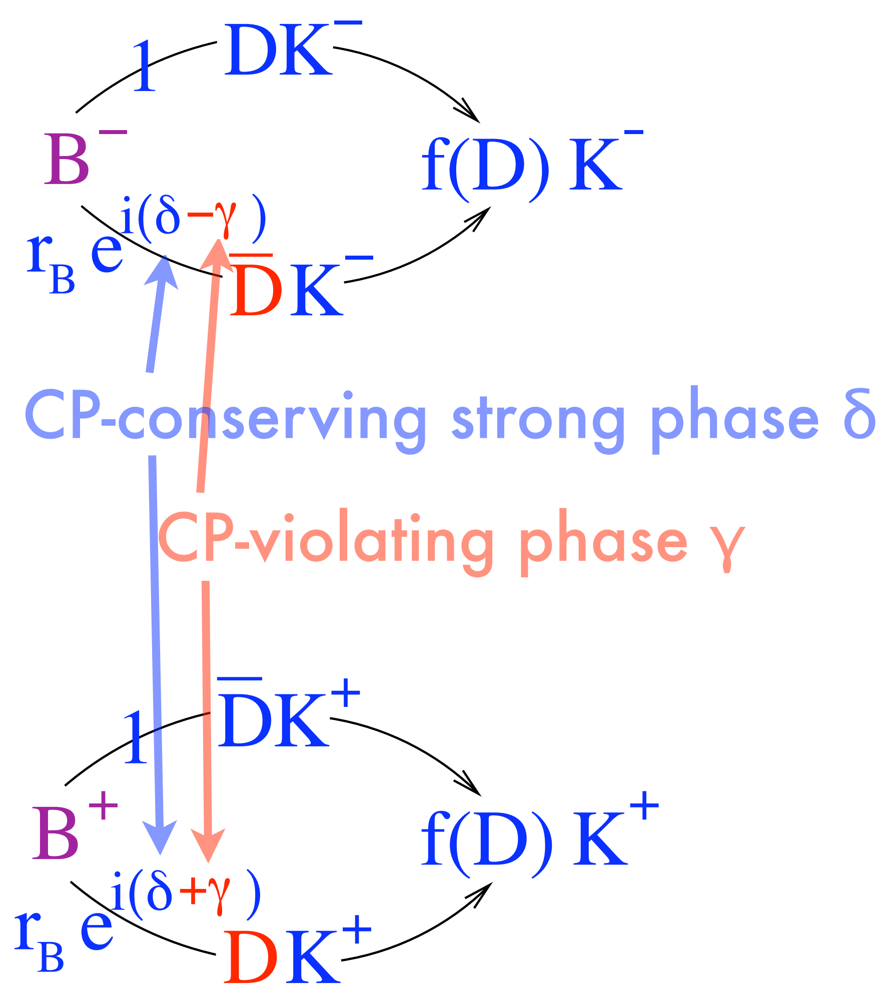


Constraints from Loops



$B^{\pm} \rightarrow DK^{\pm}$

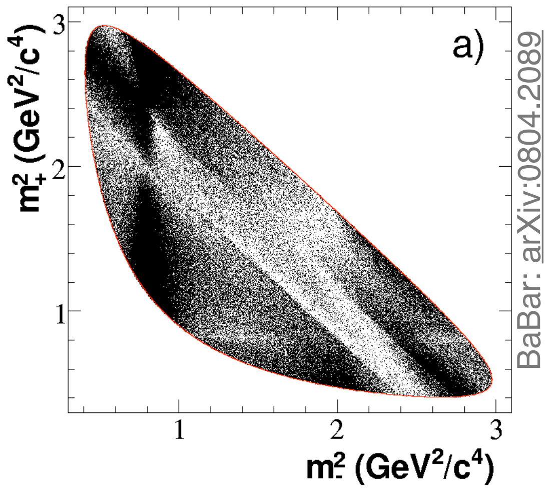
- Tree level only - no new physics
- Crucial for NP sensitivity by providing a theoretically clean reference.
- No time measurement, no tagging.



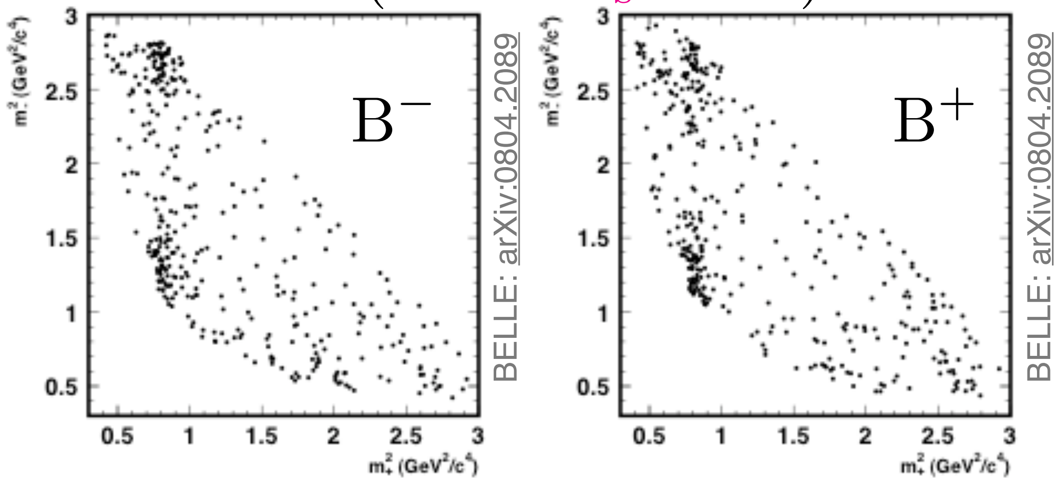
Gronau, Wyler Phys.Lett.B265:172-176,1991, (GLW)
Gronau, London Phys.Lett.B253:483-488,1991 (GLW)
Atwood, Dunietz and Soni Phys.Rev.Lett. 78 (1997) 3257-3260 (ADS)
Giri, Grossman, Soffer and Zupan Phys.Rev. D68 (2003) 054018
Belle Collaboration Phys.Rev. D70 (2004) 072003

Dalitz Plots for γ at Belle&BaBar

$D^0 \to K_s\pi^+\pi^-$



$B^\pm \to (D^0 \to K_s\pi^+\pi^-)K^\pm$



BaBar* (383M BB): $\gamma = 76^\circ \pm 22^\circ(\text{stat}) \pm 5^\circ(\text{sys}) \pm 5^\circ(\text{model})$, r_B=0.086±0.04

BELLE** (657M BB): $\gamma = 76^\circ{}^{+12^\circ}_{-13^\circ}(\text{stat}) \pm 4^\circ(\text{sys}) \pm 9^\circ(\text{model})$, r_B=0.16 ±0.04

Using B^0→D(K_sππ)K* instead of charged B (May 08): arXiv:0805.2001

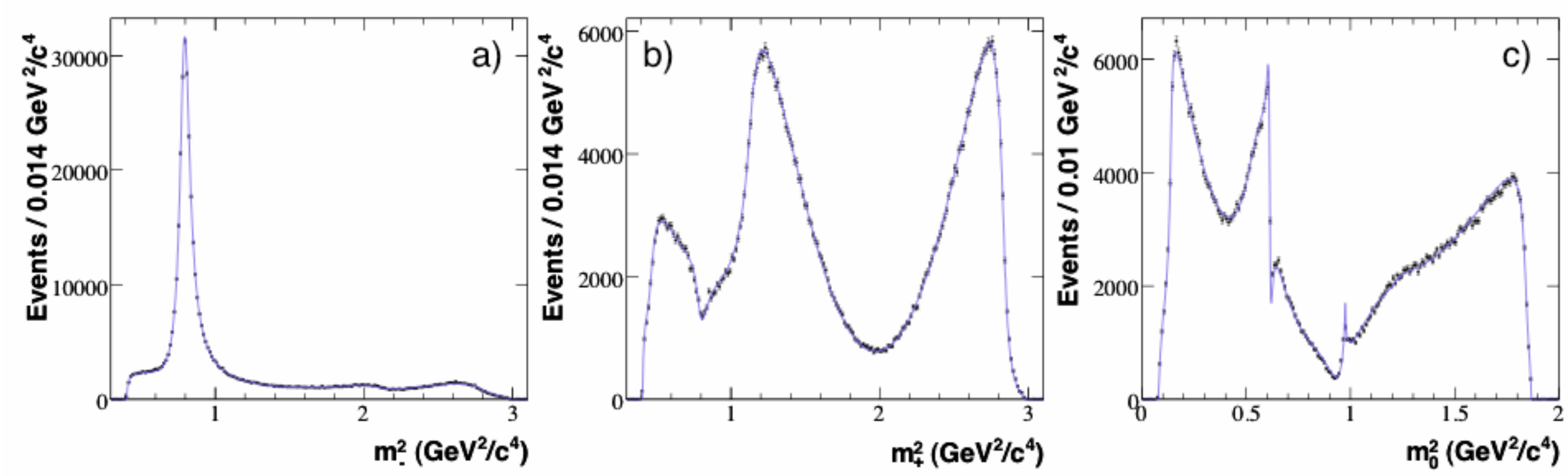
BaBar: 162°±56° or 342°±56°, r_s < 0.55 at 95%CL

*Combined result B±→DK± and B±→D*K± for Ksππ and KsKK Dalitz plot. arXiv:0804.2089; April 2008

**Combined result B±→DK± and B±→D*K± for Ksππ Dalitz plot. arXiv:0803.3375, March 2008

BaBar's improved Dalitz model

BaBar $D \to K_s \pi\pi$ fit projections



arXiv:0804.2089

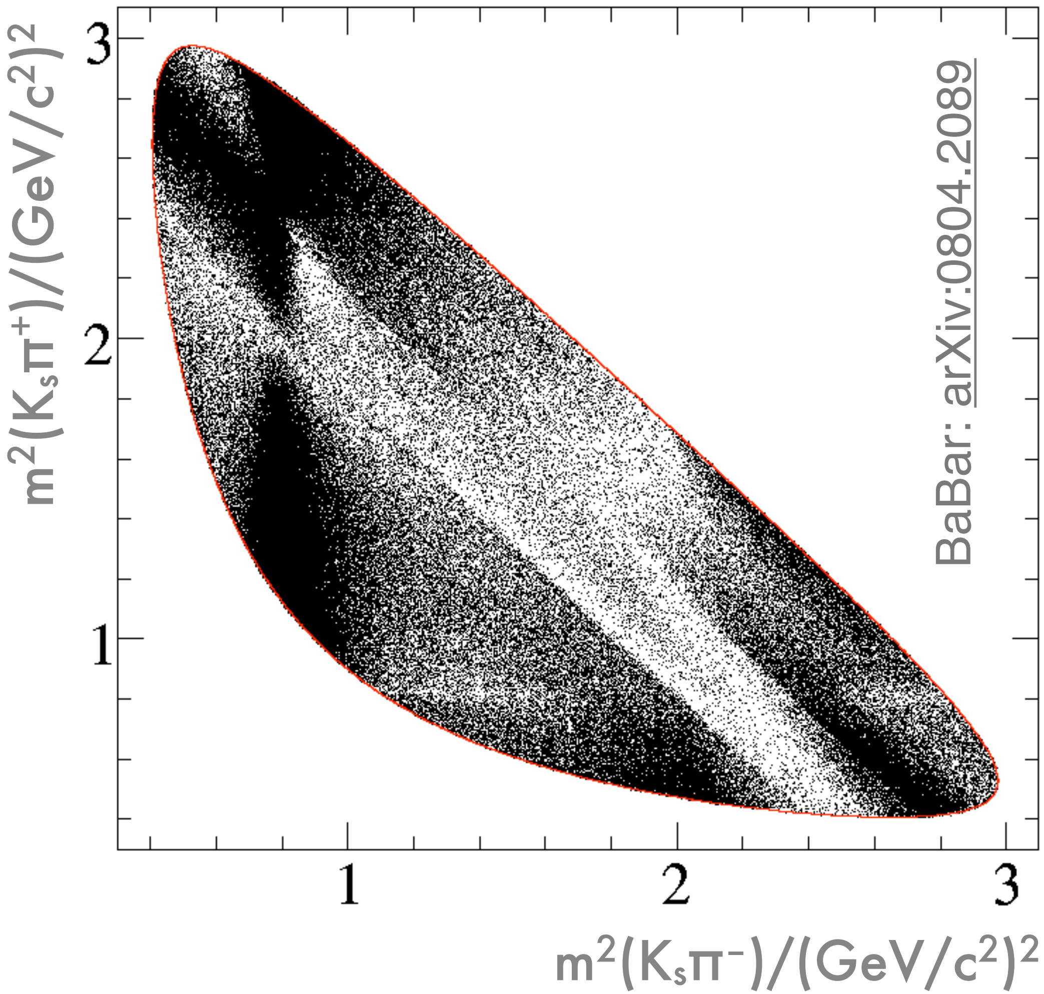
- BaBar now use K-matrix* for $\pi\pi$ S-wave (fit fraction 12%±3%) and LASS-parameterisation** for $K\pi$ S-wave.
- Isobar: $\chi^2/\text{ndof} = 1.20$; K-matrix+LASS: $\chi^2/\text{ndof} = 1.11$;

*E. P. Wigner. Phys. Rev. **70**, 15 (1946); I. J. R. Aitchison, Nucl. Phys. A **189**, 417 (1972)

Nucl. Phys. B **296, 493 (1988)

Model Dependence

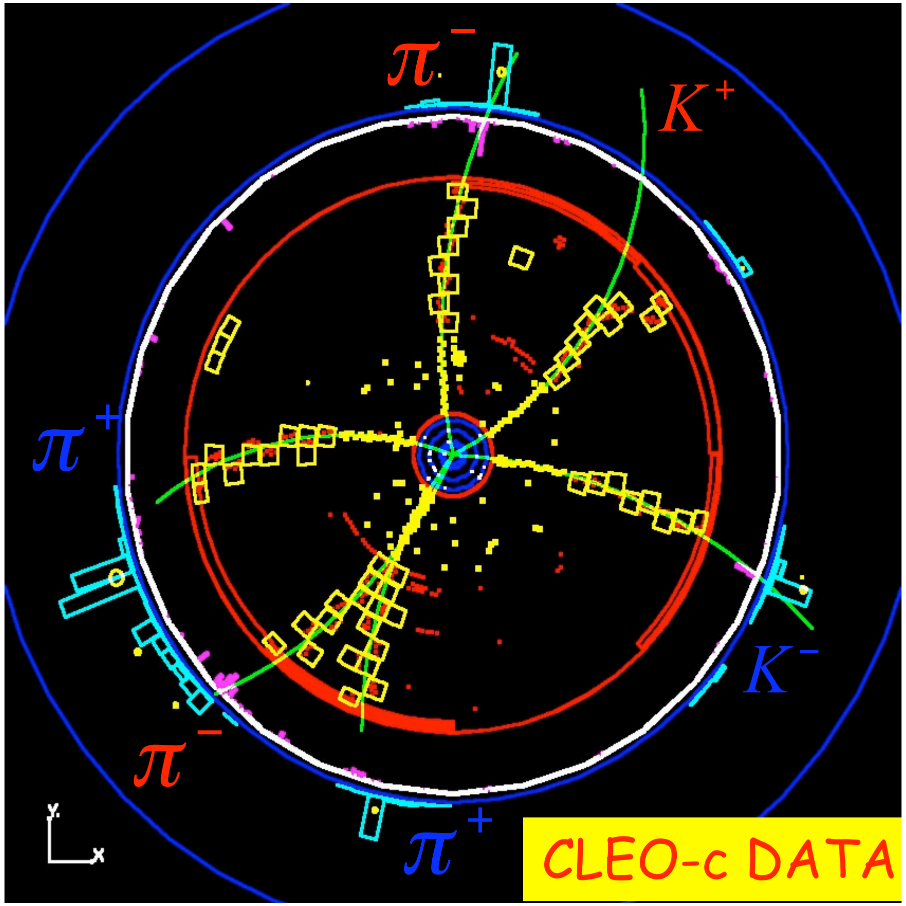
- Need D-Dalitz structure as input.
- Complex Amplitudes have 2 parameters at each point in plot.
- Measure only 1 parameter: Intensity.
- Need Model. Get model dependence. Still largest systematic in both analyses.



CLEO-c

$e^+e^- \rightarrow \psi(3770) \rightarrow D\overline{D}$

- Threshold production of correlated DD.
- Final state must be CP-odd.
- And flavour-neutral.
- That gives us access to both amplitude and phase across the Dalitz plot.



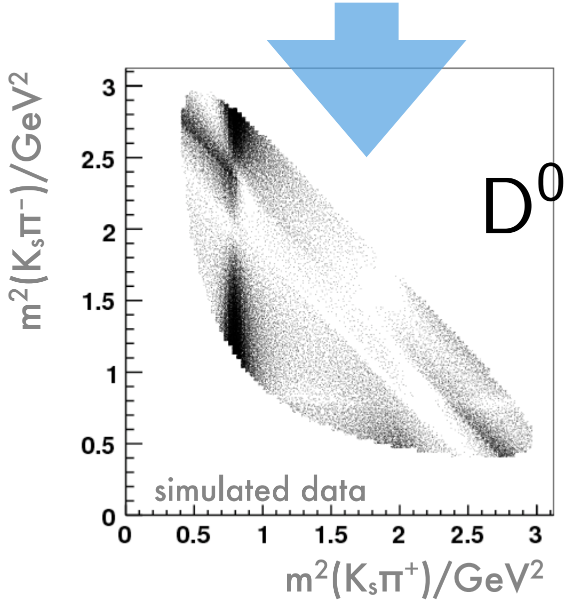
$\psi(3770) \rightarrow D^+(K^-\pi^+\pi^+)D^-(K^+\pi^-\pi^-)$

CP- tagged Decays

$\psi'' \rightarrow D_a D_b$

$D_a \rightarrow K^+ e^- \nu_e$ ($\bar{D}^0$)

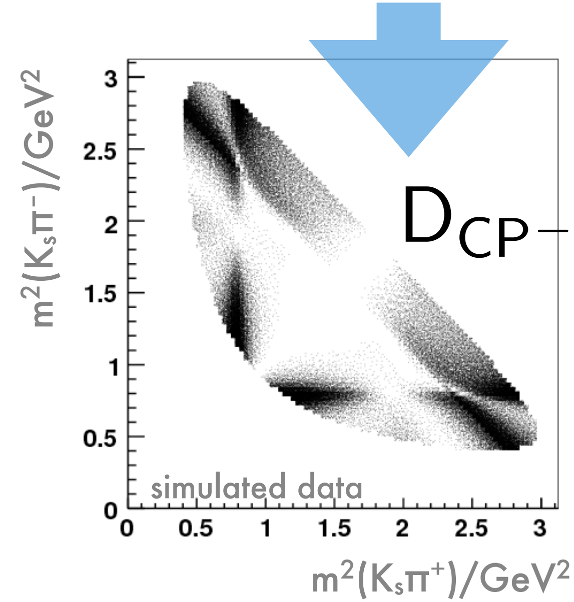
$D_b \rightarrow K_s \pi^+ \pi^-$



$\psi'' \rightarrow D_a D_b$

$D_a \rightarrow KK$ (D_{CP+})

$D_b \rightarrow K_s \pi^+ \pi^-$



Input for a model independent (binned) analysis of $B^\pm \rightarrow D(K_s\pi\pi)K^\pm$:

Giri, Grossmann, Soffer, Zupan, Phys Rev D 68, 054018 (2003).
Bondar, Poluektov hep-ph/0703267 (2007)

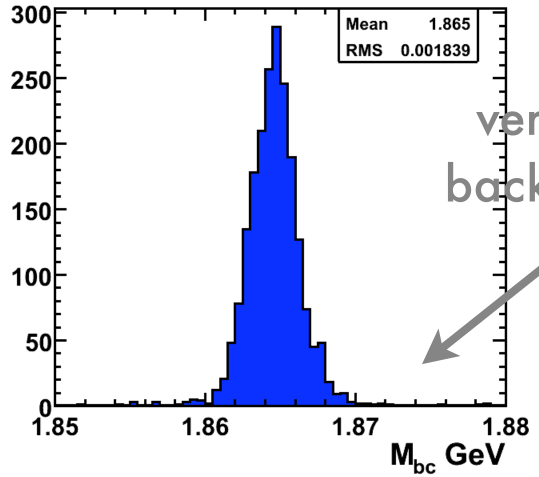
CLEO-c's impact on γ from $B^\pm \to D(K_s\pi\pi)K^\pm$

- Analysis not finalised. Based on 398/pb, expect for full 818/pb sample, using $D_a \to CP\pm$, $D_b \to K_s\pi\pi$ and $D_a \to K_s\pi\pi$, $D_b \to K_s\pi\pi$:

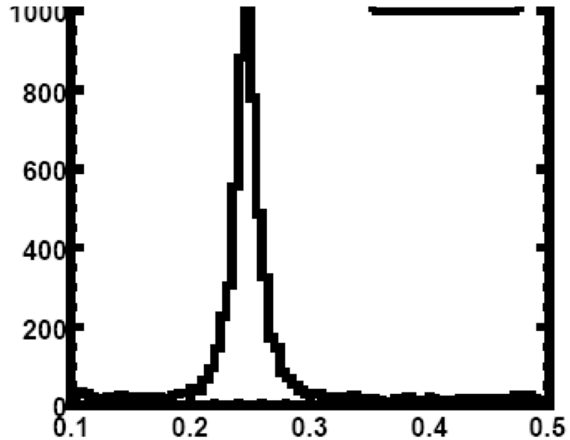
  σ(γ) from CLEO-c's input ~5° (replaces model error, 5°-9°).

- Using $D \to K_L\pi\pi$ could double statistics - currently investigating systematics.

Reconstructed $D \to K_s\pi\pi$



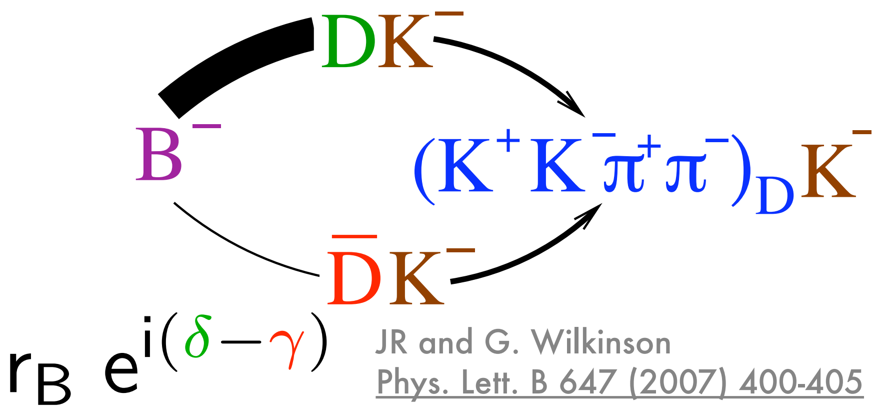
missing mass² in "reconstructed" $D \to K_L\pi\pi$



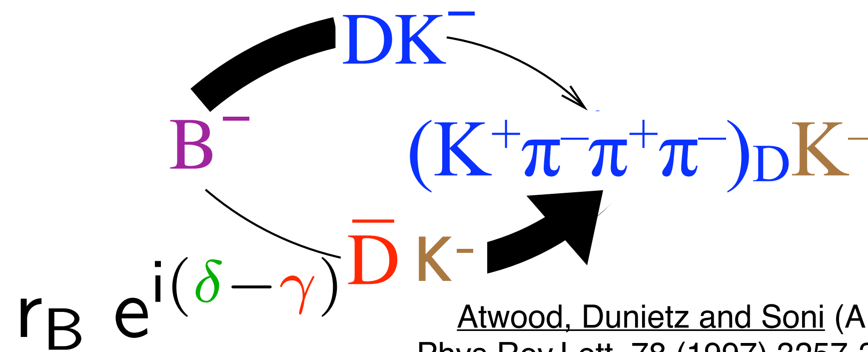
References for binned, model independent analysis of $B^\pm \to D(K_s\pi\pi)K^\pm$:

Giri, Grossmann, Soffer, Zupan, Phys Rev D 68, 054018 (2003).
Bondar, Poluektov hep-ph/0703267 (2007)

γ from 4-body Modes



JR and G. Wilkinson
Phys. Lett. B 647 (2007) 400-405



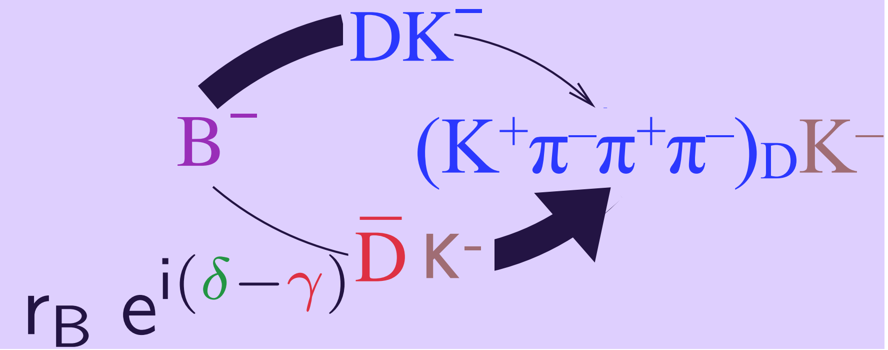
Atwood, Dunietz and Soni (ADS), Phys.Rev.Lett. 78 (1997) 3257-3260

Atwood, Soni: Phys.Rev. D68 (2003) 033003

- Same principle as for 3-body analyses.
- Four-body "Dalitz" (amplitude) analyses can be done, see for example recent FOCUS results.
- Expect similar performance from KKππ amplitude analysis as for $K_S\pi\pi$ (see Phys. Lett. B 647 (2007) 400-405 and public note LHCb-2007-098)
- Expect more from from Kπππ due to "ADS effect".

Quasi-two body treatment of:

Atwood, Soni: Phys.Rev. D68 (2003) 033003



- Treat K3π like two-body decay with and single effective strong phase δ_D.
- New parameter: Coherence factor $R < 1$.

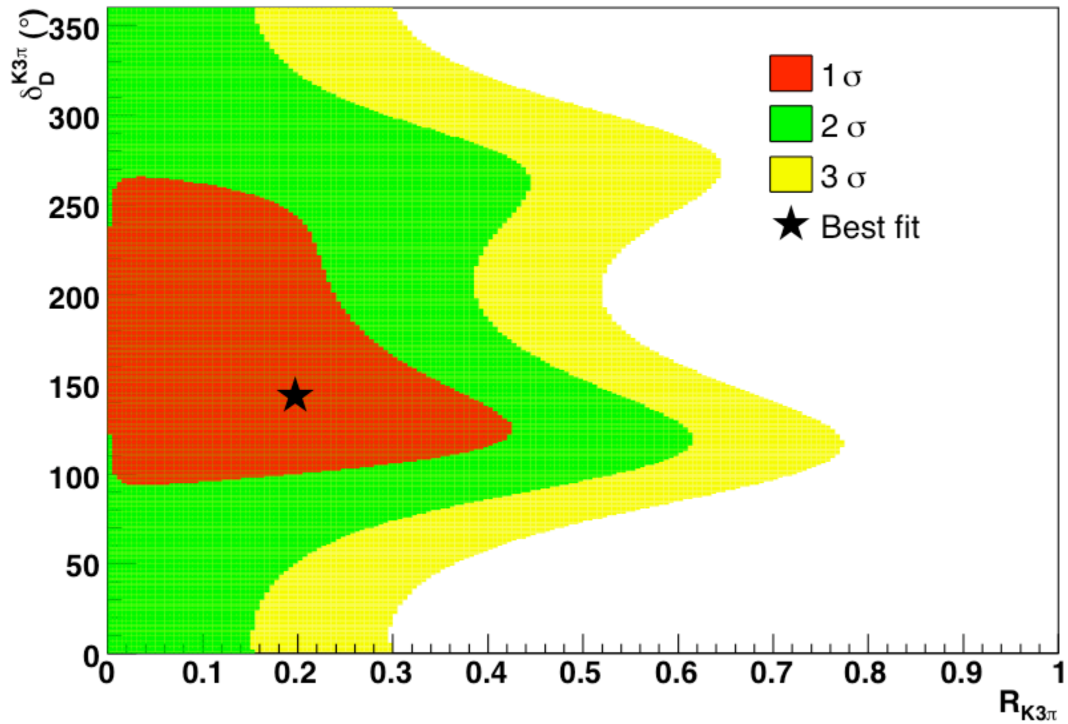
$$\Gamma(B^- \to (K^+3\pi)_D K^-) \propto r_B^2 + (r_D^{K3\pi})^2 + 2R_{K3\pi} r_B r_D^{K3\pi} \cdot \cos(\delta_B + \delta_D^{K3\pi} - \gamma)$$

- CLEO-c's coherent $\psi(3770)\to D_1D_2$ events allow measurement of R, δ_D - important input for LHCb

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. $K^\pm\pi^\mp$	$R_{K3\pi}\cos(\delta^{K\pi} - \delta^{K3\pi})$

Kπππ coherence factor

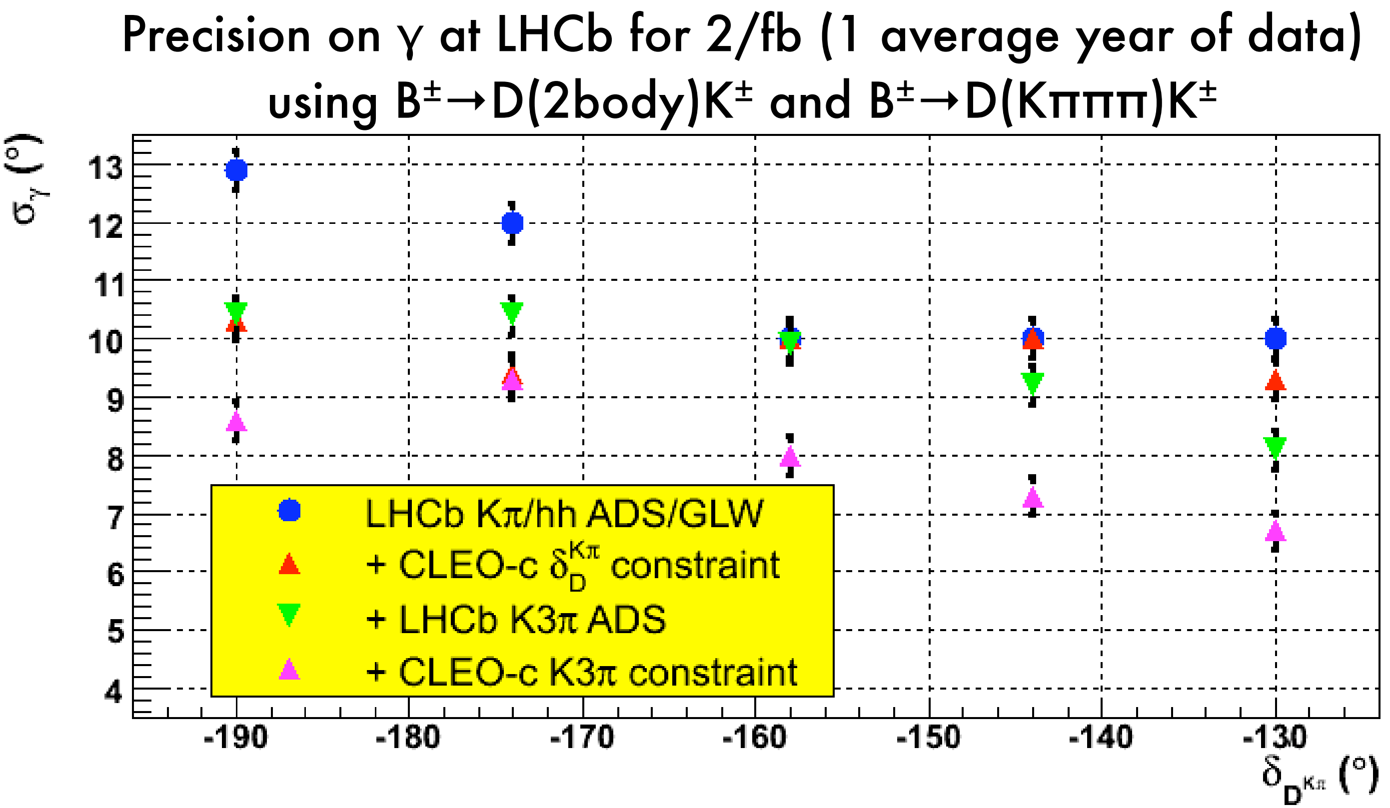
- First measurement of coherence factor.
- Low value preferred. Implies that quasi-2 body analysis of Kπππ on its own would not be terribly sensitive to γ.
- However, for combined analysis of KK, Kπ, ππ, Kπππ this still provides powerful constraints.



Andrew Powell on behalf of CLEO-c at the Lake Louise Winter Institute 2008. Proceedings: arXiv:0805.1722

Kπππ coherence factor

- Significantly increases the precision of global γ fits in combined fit with other modes (KK, ππ, Kπ).



Jim Libby on behalf of CLEO-c at the International Workshop on e+e- collisions from Phi to Psi (PHIPSI08).

- Other ADS-type modes such as $K\pi\pi^0$ under study.

Summary

- S-wave resonances not a solved problem. Progress from new high-statistics results.
- Charm mixing and especially CP violation provide unique windows to New Physics. Dalitz analyses give access to strong phases that would otherwise dilute measurements.
- $\psi(3770)$ data from CLEO-c, and in future hopefully BES III, provide essential input for γ measurements. Especially important for high-precision, high-statistics results at LHCb (start 2008) and future Super-Flavour Factory.

$K^* \rho a_1 f(980)...$
$\sigma(?) \kappa(?)...$

↑

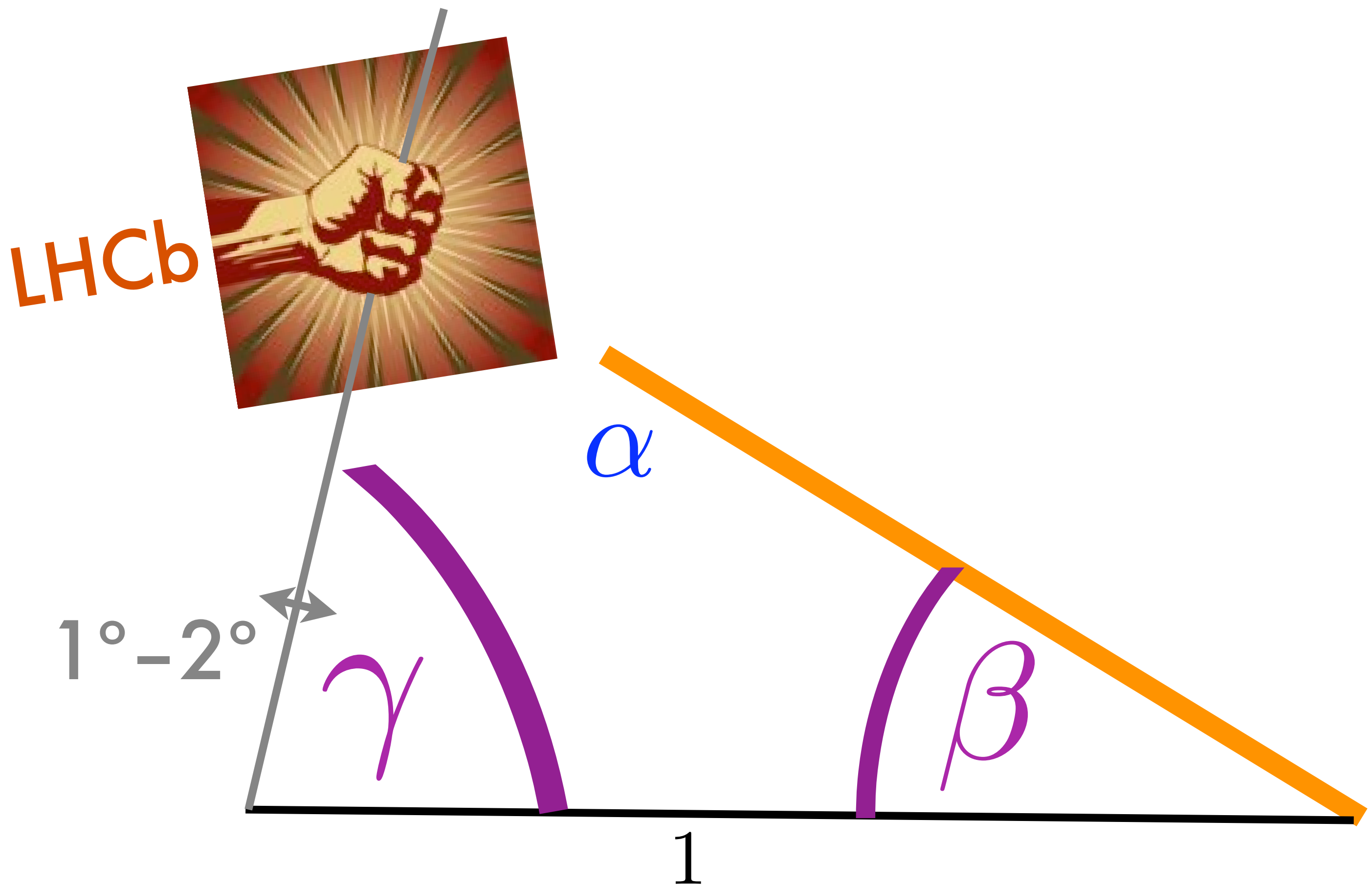
D

↑

B

Back up

SM-γ for New Physics



Focus T-matrix poles in D+->3pi

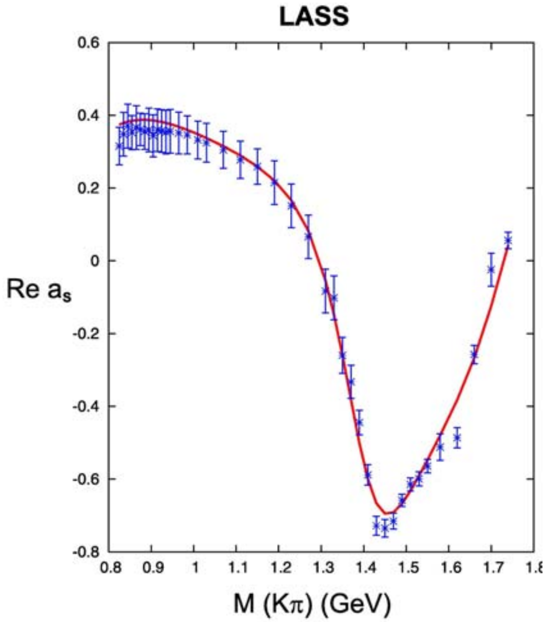
T-*matrix* pole	$(m, \Gamma/2)$ (GeV)	D^+ (relative) coupling constant
$f_0(980)$	$(1.019, 0.038)$	$1\ e^{i0}$ (fixed)
$f_0(1300)$	$(1.306, 0.170)$	$(0.67 \pm 0.03)\ e^{i(-67.9 \pm 3.0)}$
$f_0(1200-1600)$	$(1.470, 0.960)$	$(1.70 \pm 0.17)\ e^{i(-125.5 \pm 1.7)}$
$f_0(1500)$	$(1.488, 0.058)$	$(0.63 \pm 0.02)\ e^{i(-142.2 \pm 2.2)}$
$f_0(1750)$	$(1.746, 0.160)$	$(0.36 \pm 0.02)\ e^{i(-135.0 \pm 2.9)}$

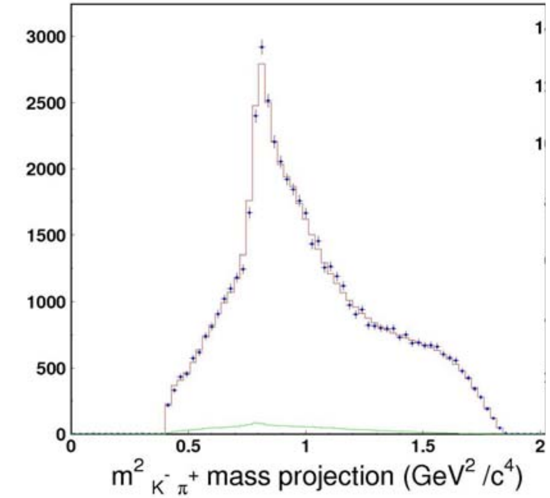
Focus Fit Fractions in D->3pi

	D_s^+
decay channel	fit fraction (%)
$(S\text{-wave})\,\pi^+$	$87.04 \pm 5.60 \pm 4.17 \pm 1.34$
$f_2(1270)\,\pi^+$	$9.74 \pm 4.49 \pm 2.63 \pm 1.32$
$\rho^0(1450)\pi^+$	$6.56 \pm 3.43 \pm 3.31 \pm 2.90$
	D^+
decay channel	fit fraction (%)
$(S\text{-wave})\,\pi^+$	$56.00 \pm 3.24 \pm 2.08 \pm 0.50$
$f_2(1270)\,\pi^+$	$11.74 \pm 1.90 \pm 0.23 \pm 0.18$
$\rho^0(770)\pi^+$	$30.82 \pm 3.14 \pm 2.29 \pm 0.17$

$D^+ \to K^-\pi^+\pi^+$ at FOCUS

- Focus use K-matrix approach, parameterised according to LASS elastic scattering lineshape. Separate fit to I=1/2 and I=3/2 Kπ.
- Consistent description for Kπ elastic scattering and resonances in charm.
- S-wave fraction 83%±1%, Fit χ^2-prob 1.2%
- Isobar fit with ϰ as x-check. Consistent with prev. experiments. Fit χ^2-prob 6.3%





The ππ S-wave in D→πππ

- Recent results by E791 [Phys. Rev. Lett 86, 770 (2001), FOCUS (Phys. Lett. B 585, 200 (2004), CLEO-c (Phys. Rev. D 76, 012001 (2007)).
- E791 uses the isobar model, FOCUS the K-matrix*, CLEO-c compares isobar, Schechter**, and Achasov*** model.

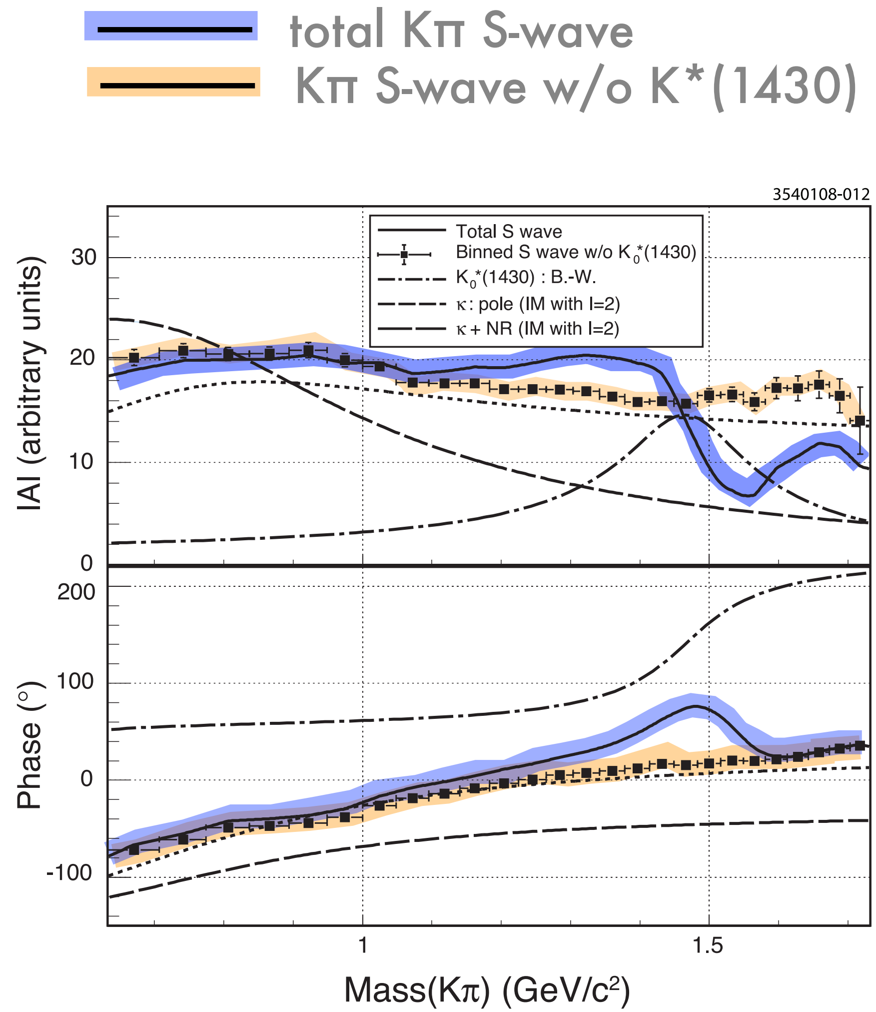
* E. P. Wigner, Phys. Rev. 70 (1946) 15.
S. U. Chung et al, Annalen Phys. 4 (1995) 404.
V. V. Anisovich and A. V. Sarantsev, Eur. Phys. J. A16 (2003) 229

** Int J. Mod. Phys. A20, 6149 (2005)

***private communications with the authors of the CLEO paper, and many papers - click here.

$D^+ \to K^- \pi^+ \pi^+$ Isobar and Model Independent Fit at CLEO-c

- For same parameterisation, results compatible between E791* and CLEO-c** both models.
- Crucial to achieve agreement with CLEO-c's data: Add I=2 ππ S-wave.
- Significantly improves fit for both models. Better fit quality for binned S-wave.



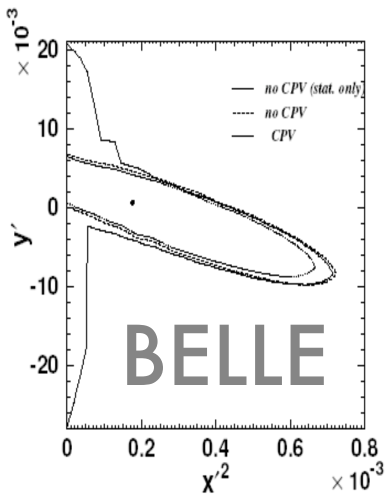
*Phys. Rev. Lett 89, 121801 (2002); Phys. Rev. D73, 032004 (2006); **arXiv:0802.4214 (submitted to PRD)

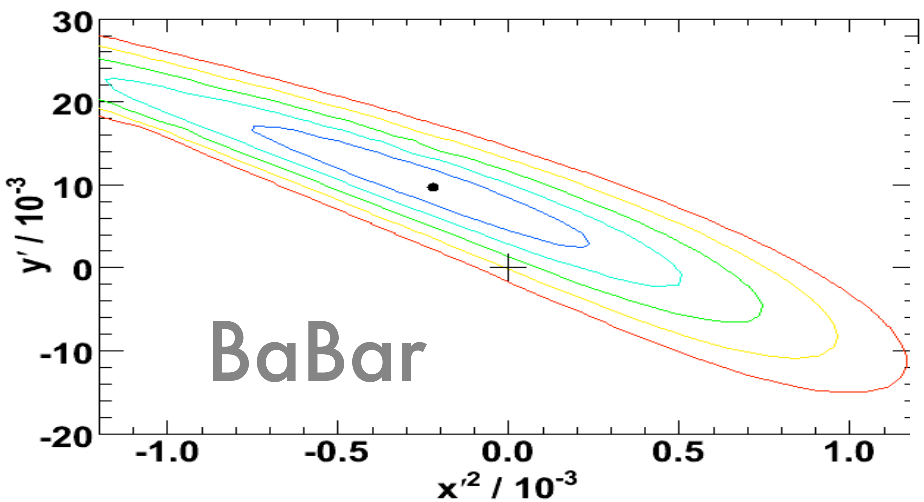
BELLE Kspipi Dalitz for mix

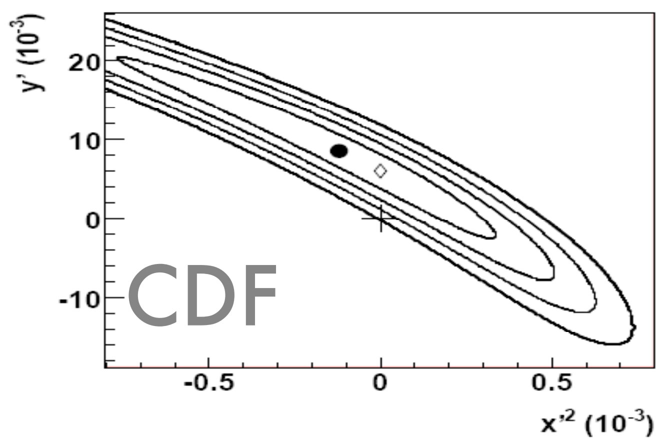
Resonance	Amplitude	Phase (°)	Fit fraction
$K^*(892)^-$	1.629 ± 0.006	134.3 ± 0.3	0.6227
$K_0^*(1430)^-$	2.12 ± 0.02	-0.9 ± 0.8	0.0724
$K_2^*(1430)^-$	0.87 ± 0.02	-47.3 ± 1.2	0.0133
$K^*(1410)^-$	0.65 ± 0.03	111 ± 4	0.0048
$K^*(1680)^-$	0.60 ± 0.25	147 ± 29	0.0002
$K^*(892)^+$	0.152 ± 0.003	-37.5 ± 1.3	0.0054
$K_0^*(1430)^+$	0.541 ± 0.019	91.8 ± 2.1	0.0047
$K_2^*(1430)^+$	0.276 ± 0.013	-106 ± 3	0.0013
$K^*(1410)^+$	0.33 ± 0.02	-102 ± 4	0.0013
$K^*(1680)^+$	0.73 ± 0.16	103 ± 11	0.0004
$\rho(770)$	1 (fixed)	0 (fixed)	0.2111
$\omega(782)$	0.0380 ± 0.0007	115.1 ± 1.1	0.0063
$f_0(980)$	0.380 ± 0.004	-147.1 ± 1.1	0.0452
$f_0(1370)$	1.46 ± 0.05	98.6 ± 1.8	0.0162
$f_2(1270)$	1.43 ± 0.02	-13.6 ± 1.2	0.0180
$\rho(1450)$	0.72 ± 0.04	41 ± 7	0.0024
σ_1	1.39 ± 0.02	-146.6 ± 0.9	0.0914
σ_2	0.267 ± 0.013	-157 ± 3	0.0088
NR	2.36 ± 0.07	155 ± 2	0.0615

Fit case	Parameter	Fit result	95% C.L. interval
No	$x(\%)$	$0.80 \pm 0.29 ^{+0.09}_{-0.07} {}^{+0.10}_{-0.14}$	(0.0, 1.6)
CPV	$y(\%)$	$0.33 \pm 0.24 ^{+0.08}_{-0.12} {}^{+0.06}_{-0.08}$	(−0.34, 0.96)
CPV	$x(\%)$	$0.81 \pm 0.30 ^{+0.10}_{-0.07} {}^{+0.09}_{-0.16}$	$\lvert x \rvert < 1.6$
	$y(\%)$	$0.37 \pm 0.25 ^{+0.07}_{-0.13} {}^{+0.07}_{-0.08}$	$\lvert y \rvert < 1.04$
	$\lvert q/p \rvert$	$0.86 ^{+0.30}_{-0.29} {}^{+0.06}_{-0.03} \pm 0.08$	-
	$\arg(q/p)(°)$	$-14 ^{+16}_{-18} {}^{+5}_{-3} {}^{+2}_{-4}$	-

D→Kπ (x′², y′) contours







$$x'^2 = (0.018^{+0.021}_{-0.023})\% \qquad y' = (0.06^{+0.40}_{-0.39})\%$$

Phys.Rev.Lett.96:151801,2006

$$x'^2 = (-0.22 \pm 0.30 \pm 0.21)\% \qquad y' = (9.7 \pm 4.4 \pm 3.1)\%$$

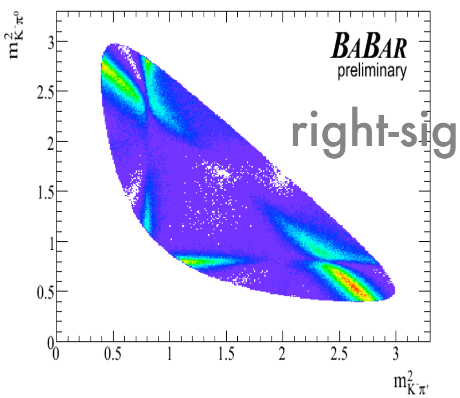
Phys.Rev.Lett.98:211802,2007

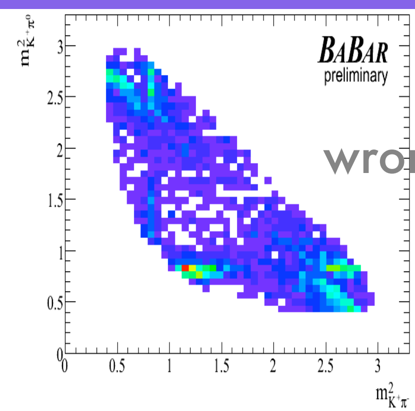
$$x'^2 = (-0.012 \pm 0.035)\% \qquad y' = (0.85 \pm 0.76)\%$$

Phys.Rev.Lett.100:121802,2008

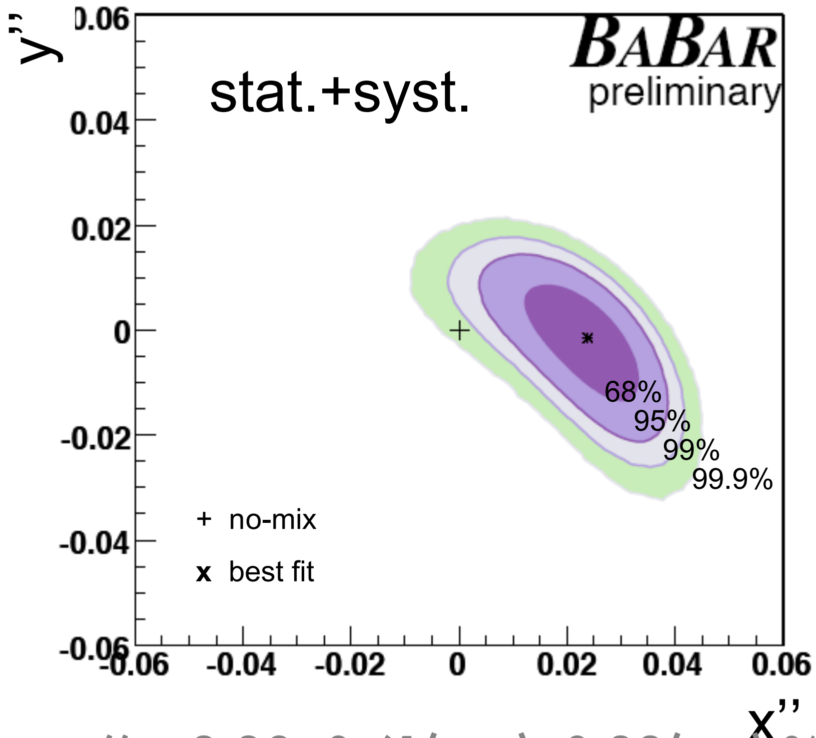
$$\Gamma(D^0(t) \to K^+\pi^-) \propto e^{-\Gamma t}\left[R_D + \sqrt{R_D}\, y' \,(\Gamma t) + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\right]$$

Mixing with time-dependent Dalitz analysis D/Dbar→$K^+\pi^-\pi^0$





- Time-dependent Dalitz analysis
- Equivalent to Kπ analysis
- Measure (x″, y″) = Rotate($\delta_{K\pi\pi0}$) (x,y) where $\delta_{K\pi\pi0}$=strong phase between CF and DCS.



x″= 2.39±0.61(stat)±0.32(sys) %

y″=-0.14±0.60(stat)±0.40(sys) %

William Lockman for the BaBar Collaboration
Lepton-Photon 2007, Daegu, S. Korea

Compatible with no mixing at <0.8% CL

Charm mixing with time-dependent Dalitz Plots at BELLE

- HFAG 2008* (no CPV):

  x=(0.91±0.26)%

  y=(0.73±0.18)%

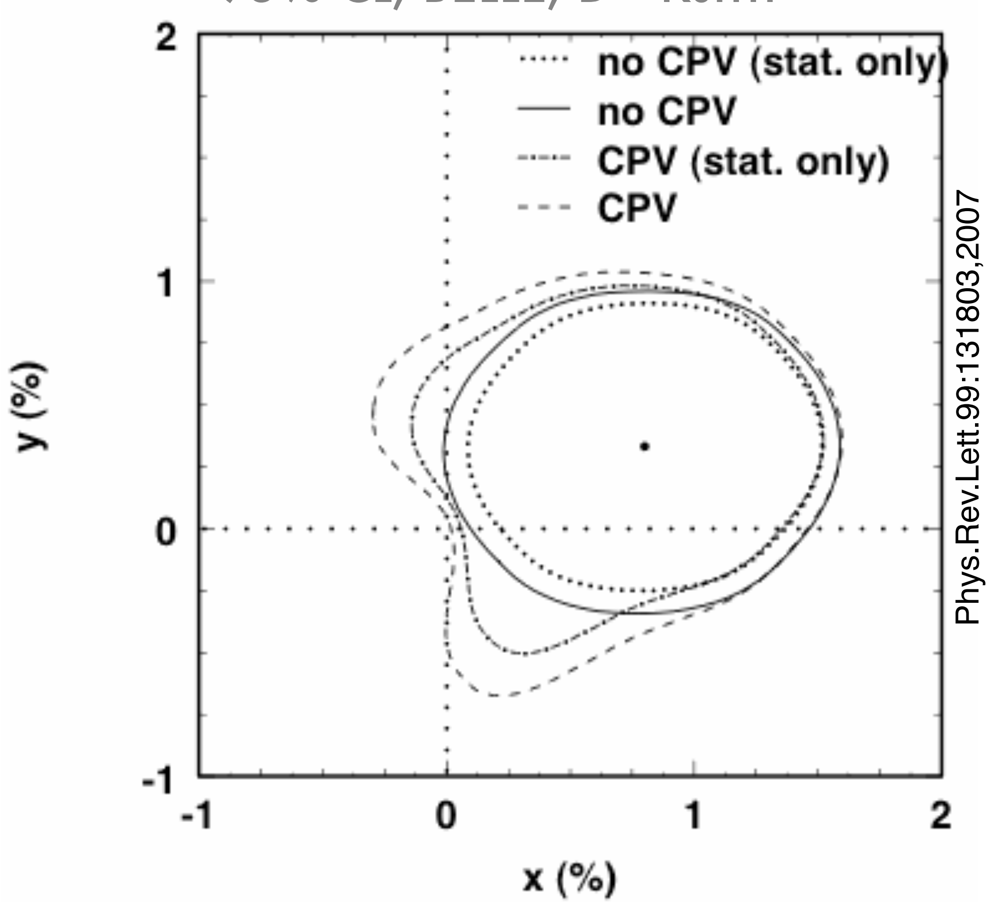
- BELLE's $D \to K_S \pi^+ \pi^-$ alone (assuming no CPV)*

  x=(0.80±0.29±0.16)%

  y=(0.33±0.24±0.14)%

- Best result on x.

95% CL, BELLE, D→Ksππ

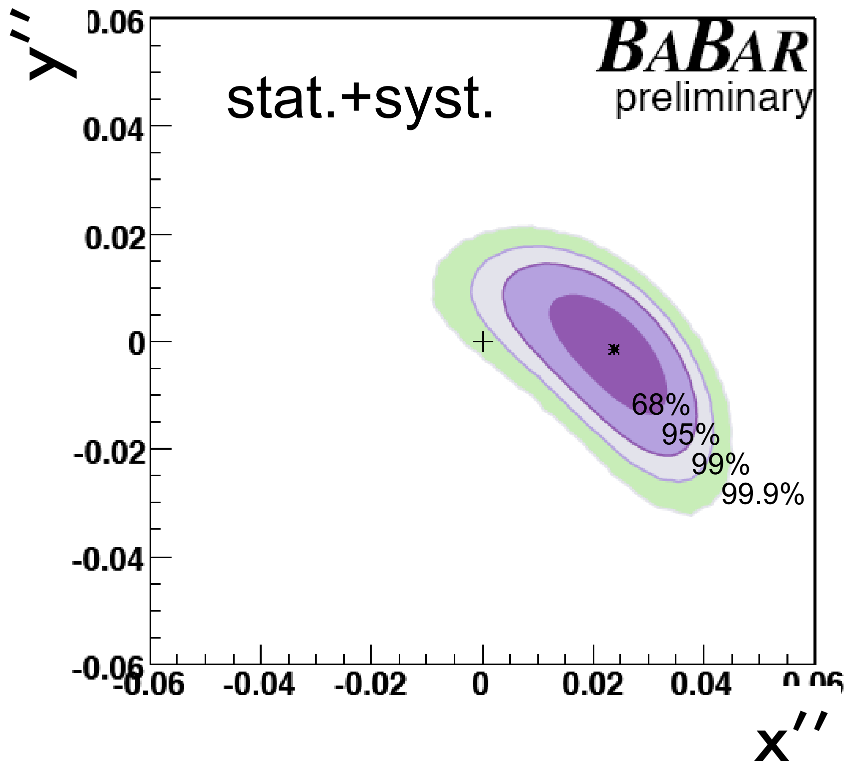


**Phys.Rev.Lett.99:131803,2007

*http://www.slac.stanford.edu/xorg/hfag/charm/FPCP08/results_mix+cpv.html

Mixing with D/Dbar→$K^+\pi^-\pi^0$

- Requires Dalitz fit since each point in Dalitz space has different $\delta(m_{12}, m_{23})$.
- Can fit for relative phases within Dalitz plot, but an over-all phase difference remains between the plots, hence measure (x'', y'') = Rotate($\delta_{K\pi\pi 0}$) (x,y)



$x''=2.39\pm0.61(stat)\pm0.32(sys)$ %
$y''=-0.14\pm0.60(stat)\pm0.40(sys)$ %

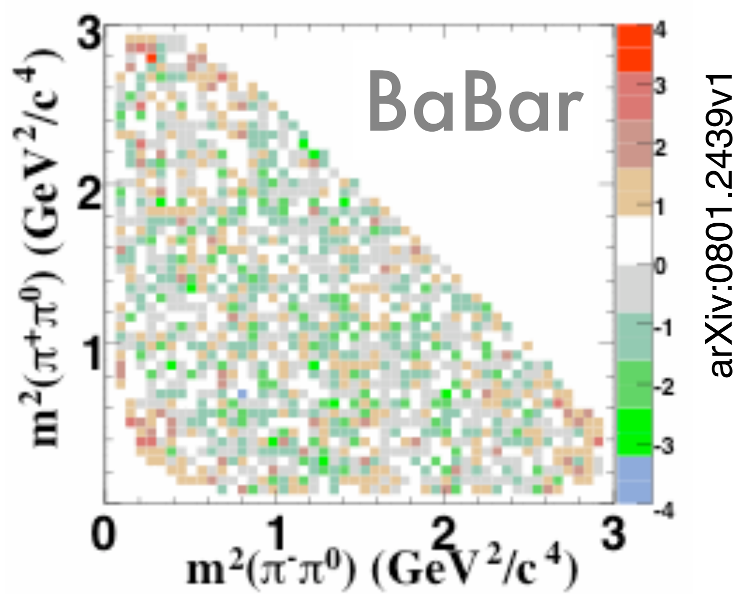
CPV in $D \to \pi^+\pi^-\pi^0$, $D \to K^+K^-\pi^0$?

- Four approaches (BaBar): Look for differences between D, $\bar{D}$...
  - across Dalitz space (plot→)
  - in fit to Dalitz model
  - angular distributions
  - total decay rates (also BELLE)
- No evidence for CPV. Limits CPV in SCS charm to < few % level.

BaBar result: arXiv:0801.2439, submitted to PRL

BELLE result: arXiv:0801.2439, submitted to PRD

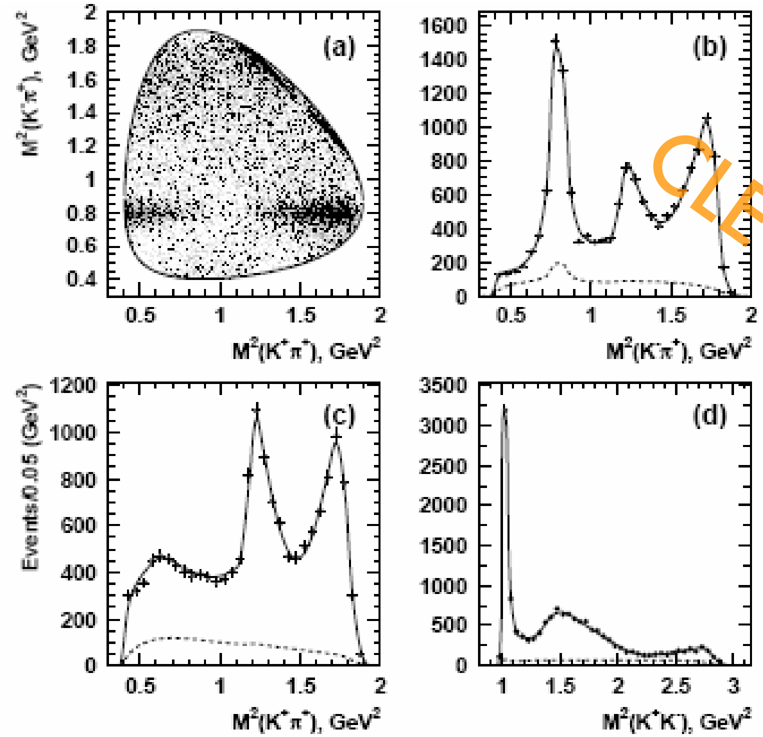
Normalised residuals (Difference/error) between $D \to \pi^+\pi^-\pi^0$ and its CP conjugate



χ^2 test: consistent with no CPV at 33% CL (17% for $KK\pi^0$)

CPV in SCS decay $D^+ \to K^+K^-\pi^+$?

The Fit



Kπ S-wave described by
LASS* model for Kπ→Kπ
elastic scattering

*Nucl. Phys. B **296**, 493 (1899)

The CP asymmetry

$$A_{CP} = \frac{N_{D+}/\epsilon_{D+} - N_{D-}/\epsilon_{D-}}{N_{D+}/\epsilon_{D+} + N_{D-}/\epsilon_{D-}}$$

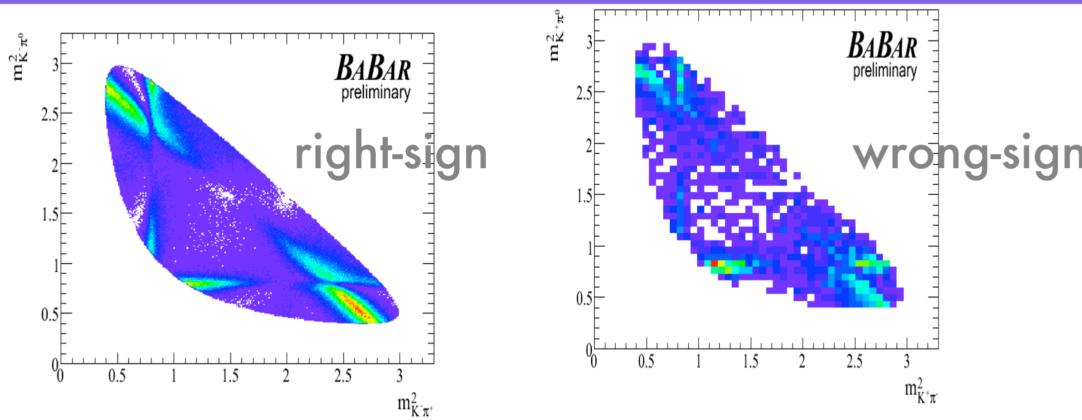
CLEO-c preliminary

Component	A_{CP}(fraction) (%)
$\overline{K}^*(892)^0K^+$	$0.2 \pm 2.7^{+2.3+0.7}_{-0.4-0.4}$
$K^-\pi^+(S)K^+$	$-1 \pm 5^{+1+6}_{-2-4}$
$a_0(980)\pi^+$	$-18 \pm 23^{+4+24}_{-9-6}$
$\phi(1020)\pi^+$	$-3.7 \pm 1.9^{+0.1+0.2}_{-0.2-0.3}$
$f_2(1270)\pi^+$	$5 \pm 26^{+3+22}_{-4-46}$
$a_0(1450)\pi^+$	$-20 \pm 13^{+0+16}_{-8-9}$
$\phi(1680)\pi^+$	$-6 \pm 21^{+22+7}_{-4-3}$
$\overline{K}^*_2(1430)^0K^+$	$59 \pm 41^{+1+8}_{-28-41}$

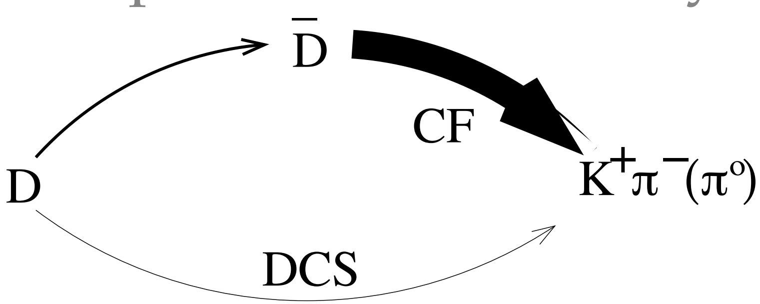
No evidence for CPV

precision in some channels: few %

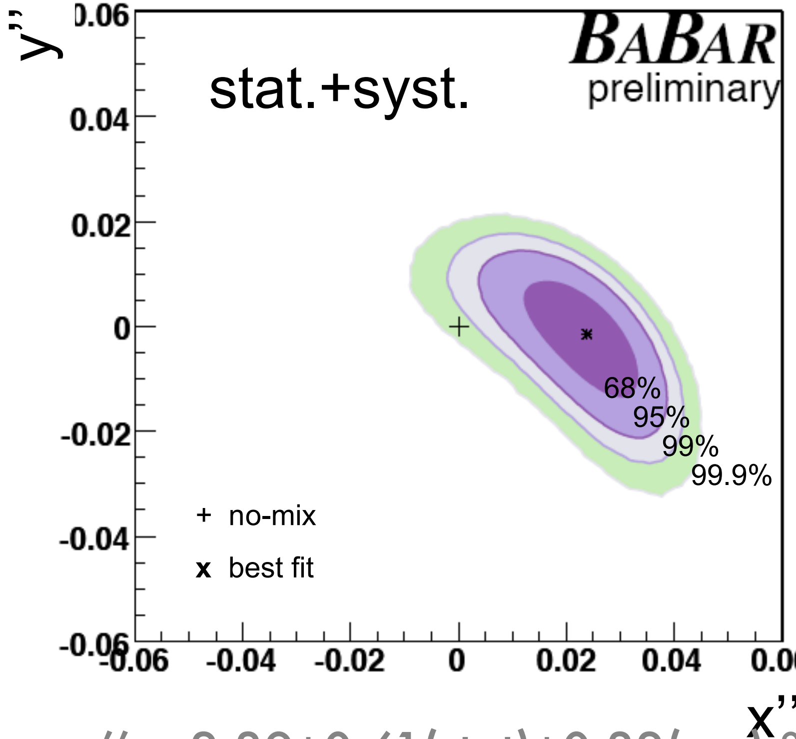
Mixing with time-dependent Dalitz analysis D/Dbar→$K^+\pi^-\pi^0$



- Time-dependent Dalitz analysis



- Measure (x'', y'') = Rotate($\delta_{K\pi\pi0}$)(x,y) where $\delta_{K\pi\pi0}$=strong phase between CF and DCS.



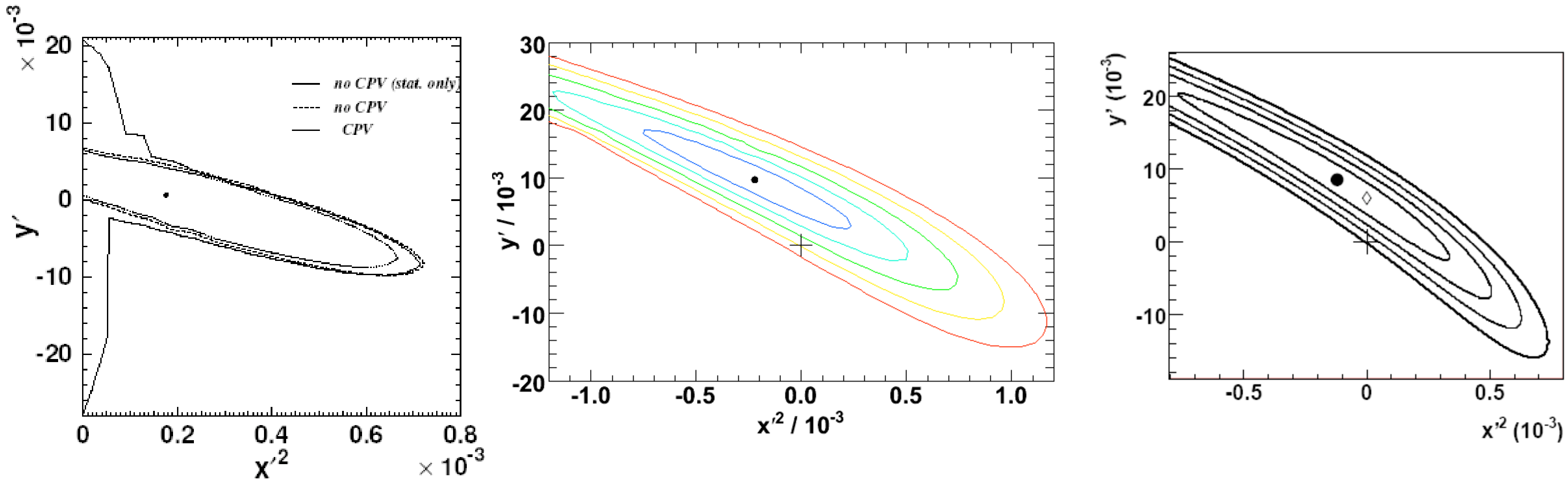
x''= 2.39±0.61(stat)±0.32(sys) %

y''=-0.14±0.60(stat)±0.40(sys) %

Compatible with no mixing at <0.8% CL

D→Kπ y′, x′² contours

BELLE BaBar CDF



$$\Gamma(D^0(t) \to K^+\pi^-) \propto e^{-\Gamma t}\left[R_D + \sqrt{R_D}\, y' \,(\Gamma t) + \frac{x'^2 + y'^2}{4} (\Gamma t)^2\right]$$

CPV in $D \to \pi^+\pi^-\pi^0$, $D \to K^+K^-\pi^0$

- Dalitz fit allows to differentiate the contributions of different resonances, CP and flavour eigenstates, etc
- Tables (unreadable, but included for completeness) differences between D and $\bar{D}$ amplitudes at BaBar. Results: ~percent, none significant.
- So, no evidence for CPV.

$D \to K^+K^-\pi^0$

State	f_r (%)	Δa_r (%)	$\Delta\phi_r$ (°)	Δf_r (%)
$K^*(892)^+$	45	2±3±2	10±12±3	0.8±1.1±0.4
$K^*(1410)^+$	4	101±65±37	1±21±6	1.7±1.8±0.6
$K^+\pi^0(S)$	16	-130±64±51	-9±10±6	-2.3±4.7±1.0
$\phi(1020)$	19	-1±2±1	-10±20±5	-0.4±0.8±0.2
$f_0(980)$	7	14±16±6	-12±25±8	0.4±2.6±0.2
$[a_0(980)^0]$	[6]	[19±16±6]	[-7±16±8]	[0.6±1.9±0.2]
$f_2'(1525)$	0.1	-38±74±8	6±36±12	0.0±0.1±0.3
$K^*(892)^-$	16	1±3±1	-7±4±2	1.7±1.3±0.4
$K^*(1410)^-$	5	133±93±68	-23±13±9	1.7±2.8±0.7
$K^-\pi^0(S)$	3	8±68±36	32±39±14	0.4±2.4±0.5

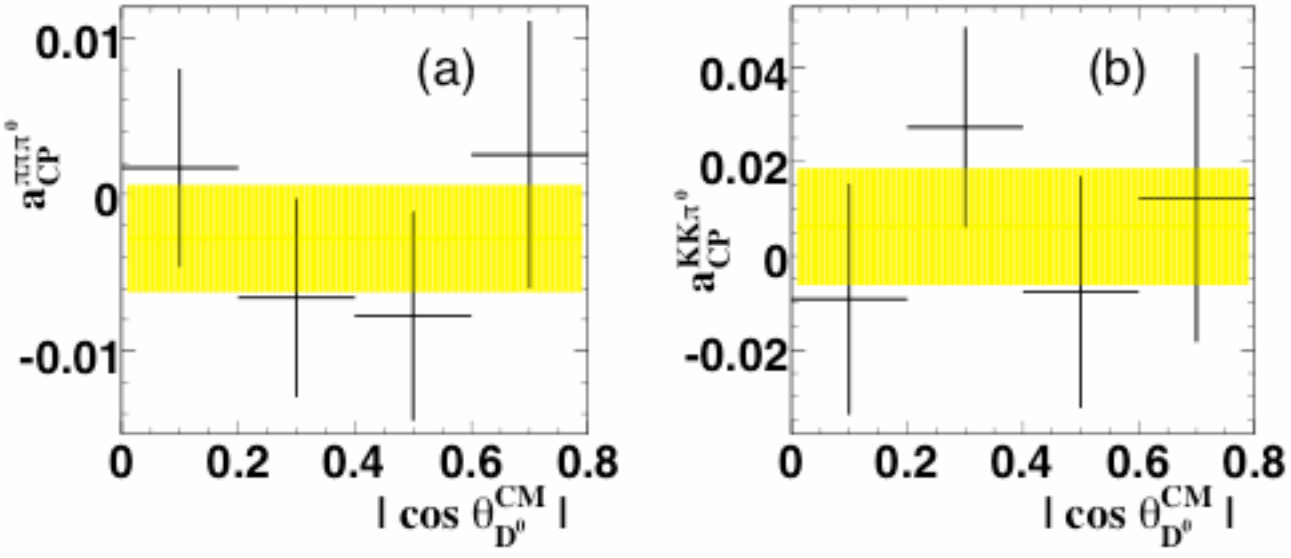
$D \to \pi^+\pi^-\pi^0$

State	f_r (%)	Δa_r (%)	$\Delta\phi_r$ (°)	Δf_r (%)
$\rho^+(770)$	68	-3.2±1.7±0.8	-0.8±1.0±1.0	-1.6±1.1±0.4
$\rho^0(770)$	26	2.1±0.9±0.5	0.8±1.0±0.4	1.6±1.4±0.6
$\rho^-(770)$	35	2.0±1.1±0.8	-0.6±0.9±0.4	0.7±1.1±0.5
$\rho^+(1450)$	0.1	2±11±8	-30±25±9	0.0±0.1±0.1
$\rho^0(1450)$	0.3	13±8±6	-1±14±3	0.1±0.2±0.1
$\rho^-(1450)$	1.8	-3±6±5	8±7±3	-0.2±0.3±0.1
$\rho^+(1700)$	4	19±27±9	9±7±3	0.4±1.0±0.4
$\rho^0(1700)$	5	-31±20±12	-7±6±2	-1.3±0.8±0.3
$\rho^-(1700)$	3	-3±14±11	-3±8±3	-0.5±0.6±0.3
$f_0(980)$	0.2	0.0±0.1±0.2	-3±7±4	0.0±0.1±0.1
$f_0(1370)$	0.4	-0.3±1.3±1.2	7±14±5	-0.2±0.1±0.1
$f_0(1500)$	0.4	0.4±1.1±0.7	-1±12±1	0.0±0.1±0.1
$f_0(1710)$	0.3	-3±3±2	-25±13±11	0.0±0.1±0.1
$f_2(1270)$	1.3	8±4±5	2±5±2	0.1±0.1±0.1
$\sigma(400)$	0.8	-0.3±0.7±2.0	-4±7±3	-0.1±0.1±0.1
Nonres	0.8	12±7±8	11±9±4	0.2±0.3±0.2

Results from BaBar: arXiv:0801.2439, submitted to PRL

CPV in D→KKπ, D→3π

BaBar's A_{CP} result by angular distribution →



A_{CP} from integrated decay rates:

- $A_{CP}(3\pi)$ BaBar $= (-0.31 \pm 0.41\ (\text{stat}) \pm 0.17\ (\text{syst}))\%$

  $A_{CP}(3\pi)$ BELLE $= (-0.43 \pm 1.30\ (\text{stat+sys}))\%$

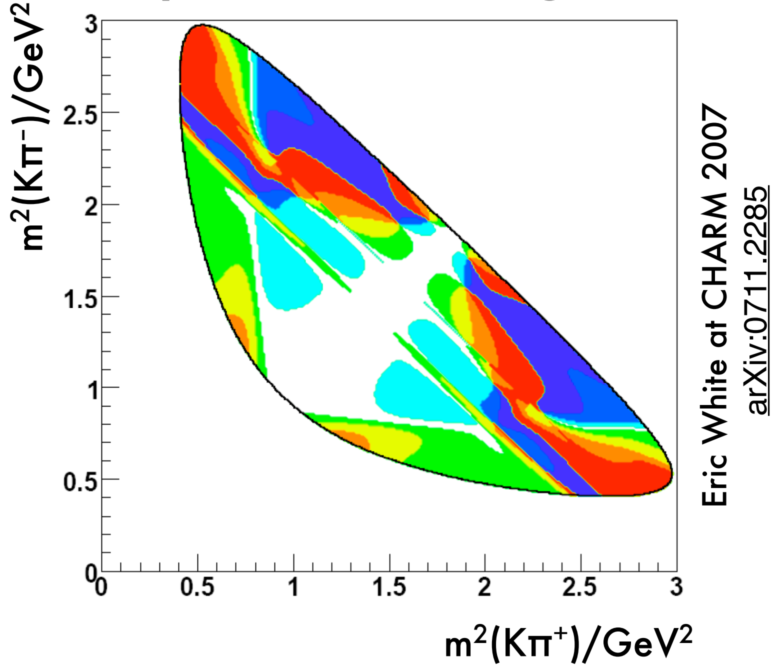
  $(0.43 \pm 0.41(\text{stat}) \pm 1.01(\text{track}) \pm 0.70(\text{other syst}))\%$
- $A_{CP}(KK\pi)$ BaBar $= (1.00 \pm 1.67\ (\text{stat}) \pm 0.25\ (\text{syst}))\ \%$

BaBar result: arXiv:0801.2439, submitted to PRL BELLE result: arXiv:0801.2439, submitted to PRD

Model-independent Fit

- Binned analysis allows model independent fit* for γ at B-factories, LHCb.
- CLEO-c's quantum-correlated data provide crucial input **:
    - CP-tagged Dalitz plots $D_a \rightarrow CP\pm$, $D_b \rightarrow K_s\pi\pi$
    - Simultaneous Dalitz analysis of $D_a \rightarrow K_s\pi\pi$, $D_b \rightarrow K_s\pi\pi$

Optimal binning**



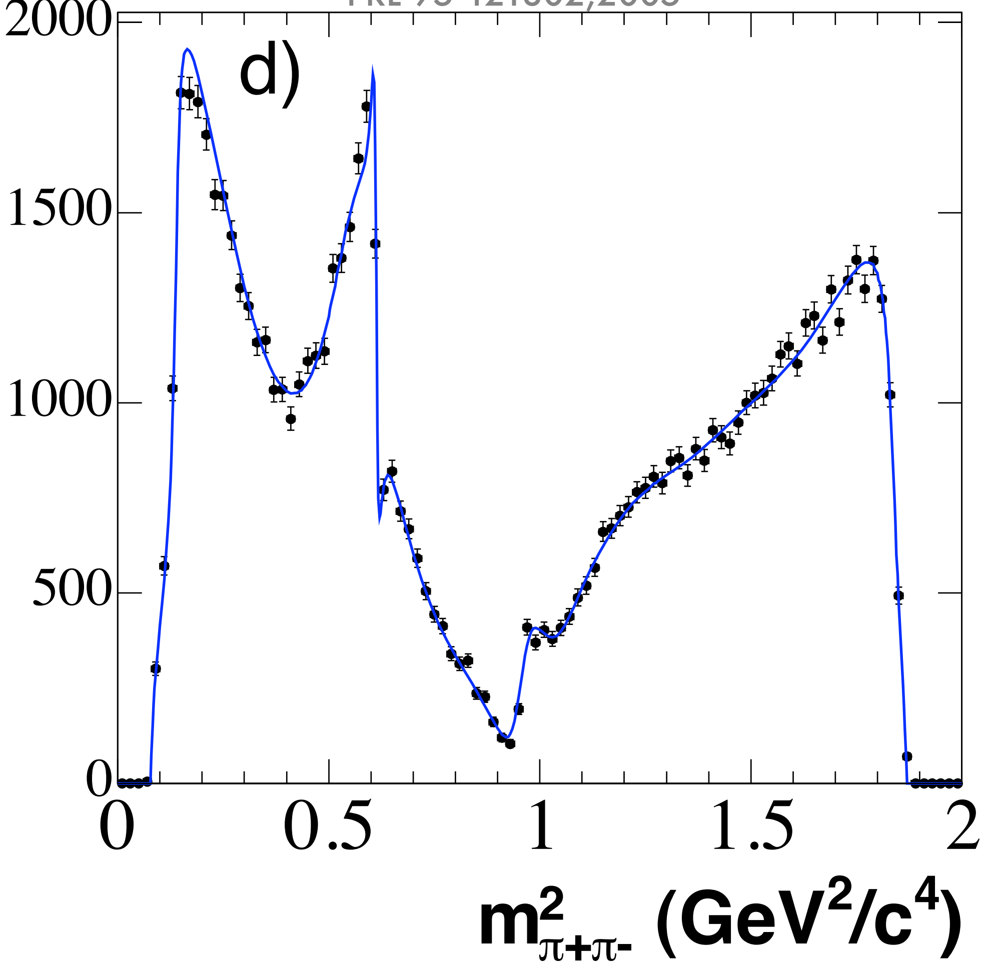
*Giri, Grossmann, Soffer, Zupan, Phys Rev D 68, 054018 (2003).

**Bondar, Poluektov hep-ph/0703267v1 (2007)

Comparing the ππ projections

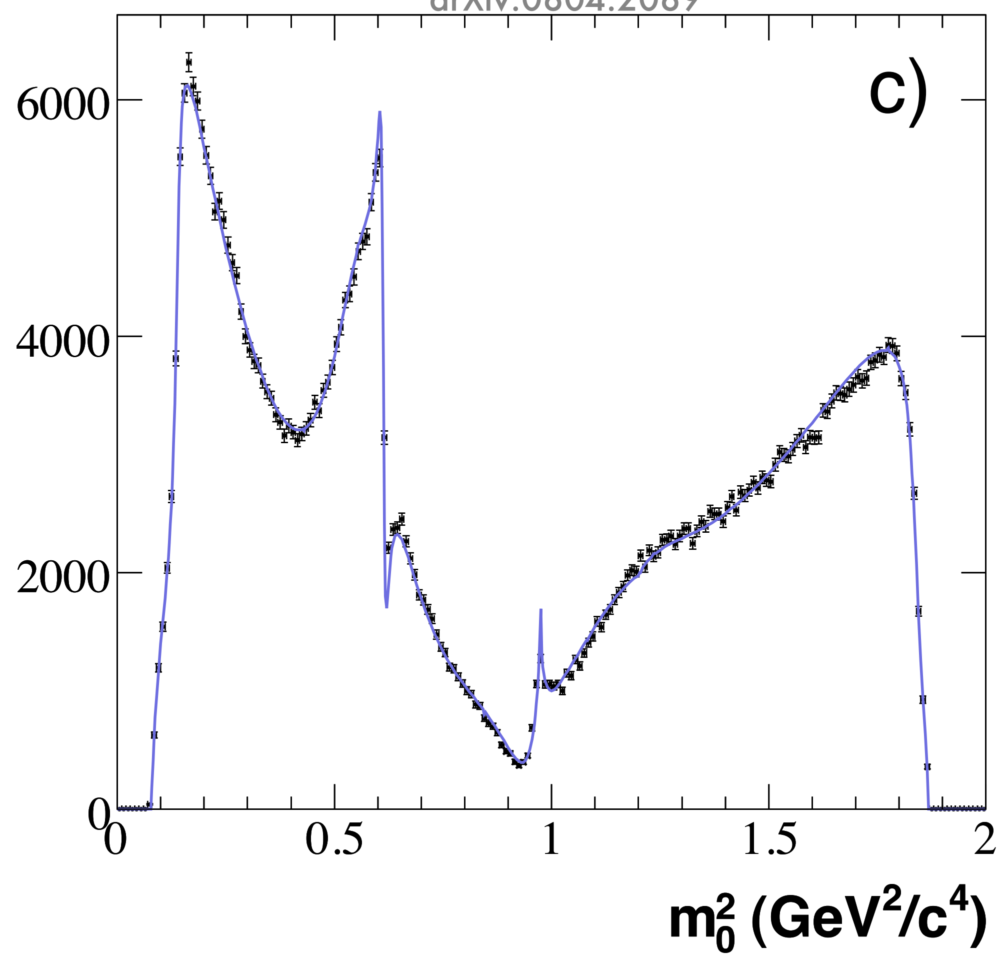
227M BB, isobar model

PRL 95 121802,2005

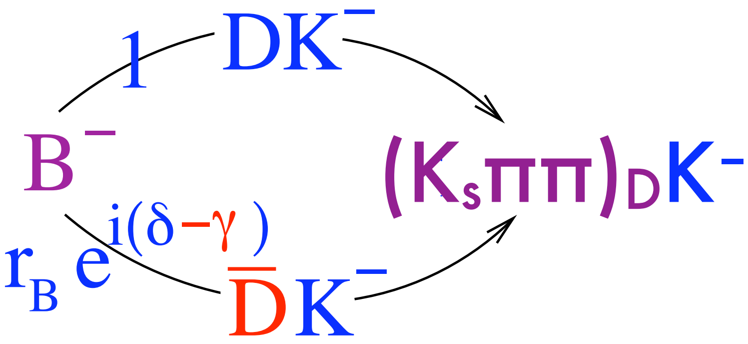


383M BB, K-matrix model

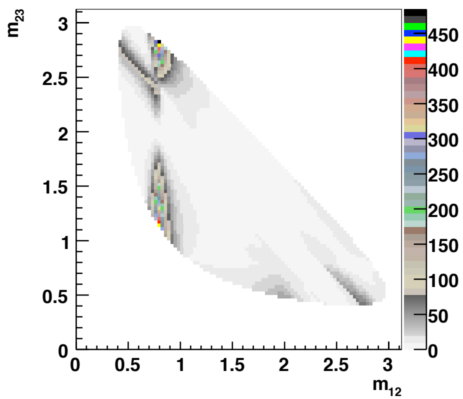
arXiv:0804.2089

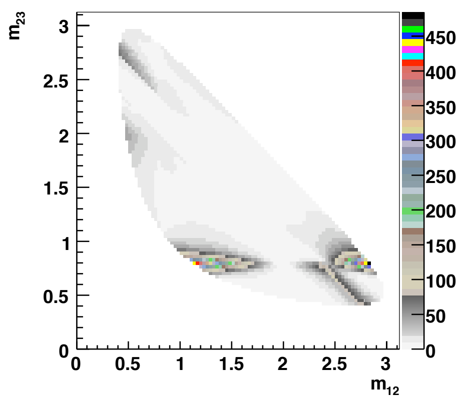


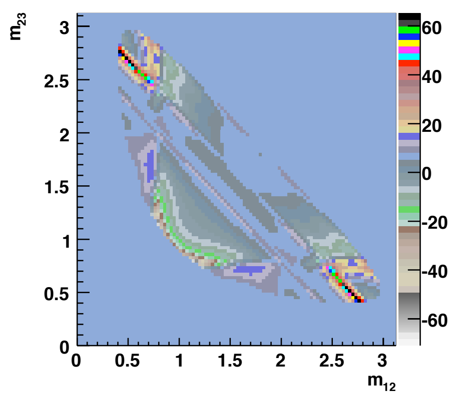
$D \to K_s \pi\pi$ Dalitz plot



$$|A_B|^2 = |A_D|^2 + r_B^2 |\bar{A}_D|^2 + 2r_B \mathrm{Re}(A_D \bar{A}_D^* e^{i(\delta-\gamma)})$$







Giri, Grossman, Soffer and Zupan Phys.Rev. D68 (2003) 054018
Belle Collaboration Phys.Rev. D70 (2004) 072003

$\sigma(\gamma) \propto 1/r_B$

Same trick works with B→DK*

- K* tags flavour of B at decay.
- Same Ks$\pi\pi$ analysis, but different r, δ.
- BaBar analysis (May 2008): arXiv:0805.2001

$$\begin{aligned} \gamma &= (162 \pm 56)^\circ \text{ or } (342 \pm 56)^\circ; \\ \delta_S &= (62 \pm 57)^\circ \text{ or } (242 \pm 57)^\circ; \\ r_S &< 0.55 \text{ at } 95\% \text{ probability.} \end{aligned}$$

Model independent γ fit

Giri, Grossmann, Soffer, Zupan, Phys Rev D 68, 054018 (2003).

$\mathcal{T}_i$ known from D* decays

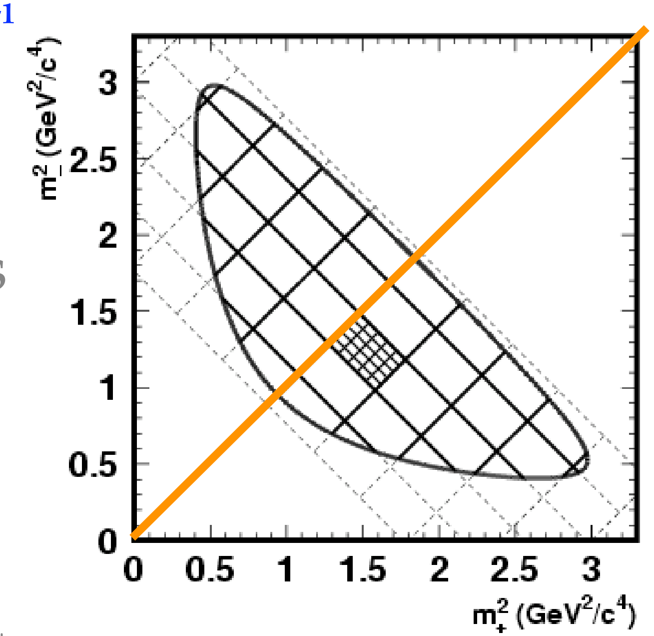
- Binned decay rate:

$$\Gamma\left(B^{\pm} \to D(K_s\pi^+\pi^-)K^{\pm}\right)_i =$$

$$\mathcal{T}_i + r_B^2\mathcal{T}_{-i} + 2\mathrm{r_B}\sqrt{\mathcal{T}_i\mathcal{T}_{-i}}\{c_i \cos(\delta-\gamma) + s_i \sin(\delta-\gamma)\}$$

$\cos(\delta_D(s_{12},s_{34}))$ and $\sin(\delta_D(s_{12},s_{34}))$ averaged over bin i

- Binning such that such that $c_i = c_{-i}$, $s_i = -s_{-i}$
- Can in principle fit c_i, s_i, δ and γ.
- However, not feasible with with statistics at BaBar, BELLE, or even LHCb.
- Need external input from CLEO.



CLEO-c's impact on γ

- CPV-sensitive factor in $B^{\pm} \to D(K_S\pi\pi)K^{\pm}$ Dalitz analysis:

$$c_i \cos\left(\delta - \gamma\right) + s_i \sin\left(\delta - \gamma\right)$$

$\cos(\delta_D(s_{12},s_{34}))$ and $\sin(\delta_D(s_{12},s_{34}))$ averaged over bin i

- CLEO-c can
  - Measure c_i with CP-tagged $D \to K_{S,L}\pi\pi$ Dalitz plot
  - Measure both c_i, s_i with simultaneous Dalitz plot analysis $D_1 \to K_S\pi\pi$, $D_2 \to K_S\pi\pi$

Bondar, Poluektov hep-ph/0703267v1 (2007)   Belle Collaboration, A. Poluektov *et al*. Phys. Rev. **D73**, 112009 (2006)

Optimal binning

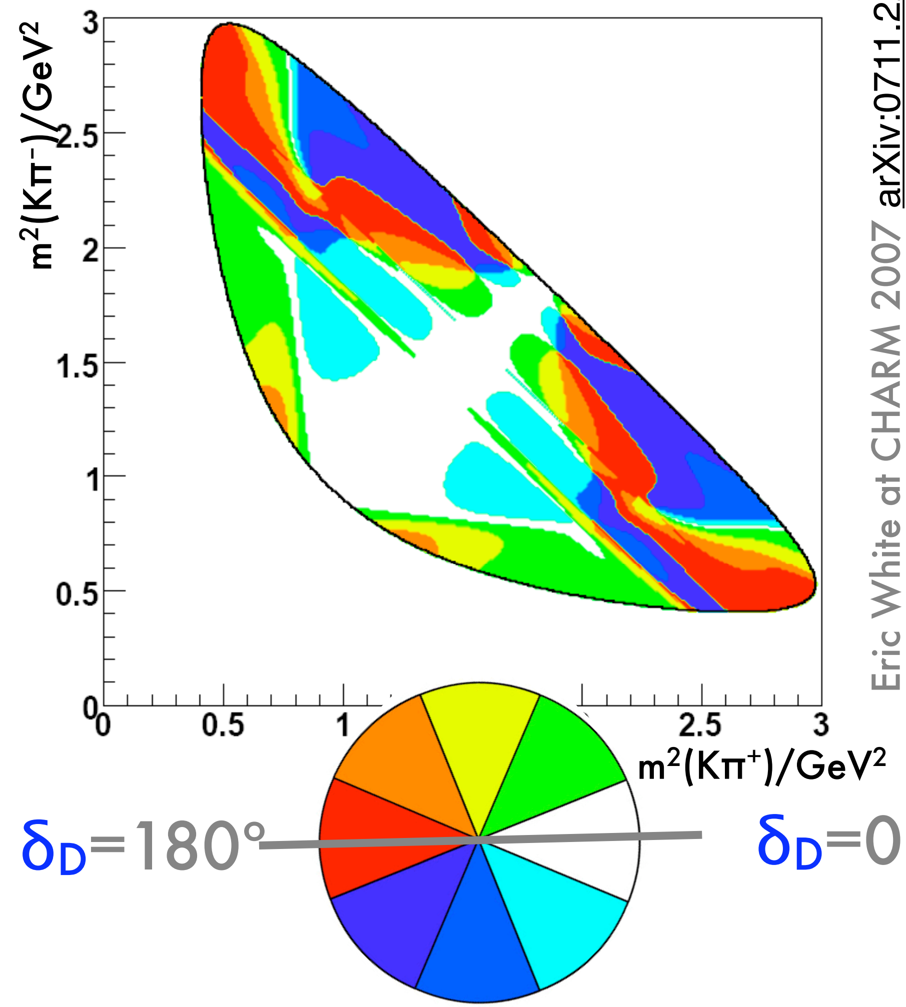
Bondar, Poluektov hep-ph/0703267v1 (2007)

$$c_i \cos(\delta - \gamma) + s_i \sin(\delta - \gamma)$$

$\cos(\delta_D(s_{12}, s_{34}))$ and $\sin(\delta_D(s_{12}, s_{34}))$ averaged over bin i

- Best if strong phase δ_D is as constant as possible over each bin, since then $s_i^2 = 1 - c_i^2$
- Plot shows CLEO-c's 8 bins (based on BELLE model)

CLEO-c's binning

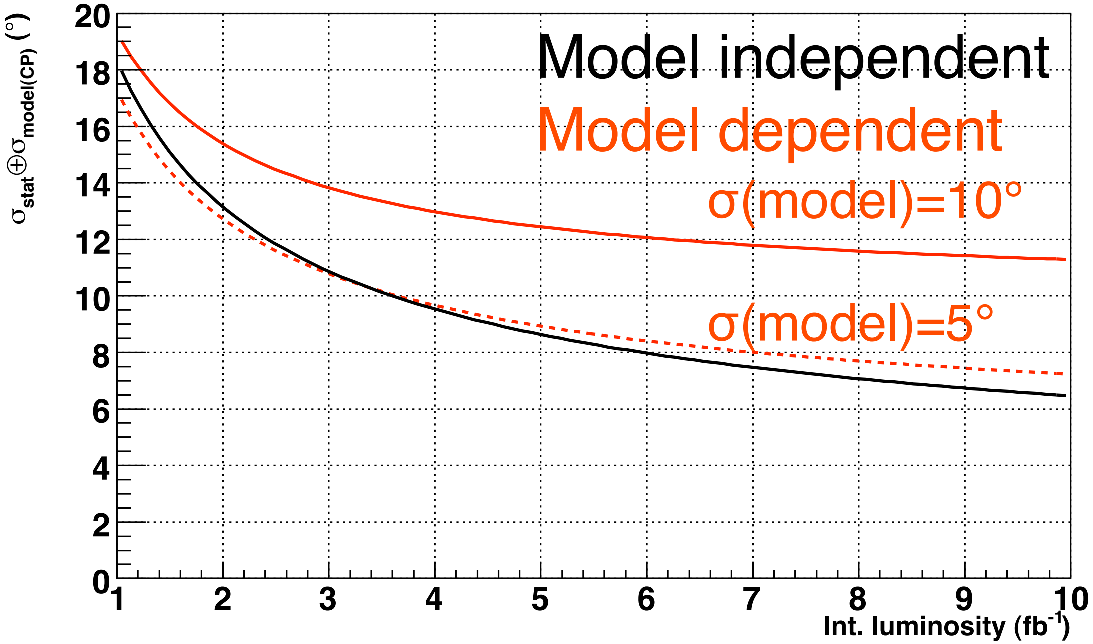


Eric White at CHARM 2007 arXiv:0711.2285

LHCb-reach (with CLEO's input)

- Result will benefit BaBar and BELLE's measurement;
- But above all, future measurements of γ with high stats, such as LHCb.

LHCb's γ reach from $B^\pm \to D(K_s\pi\pi)K^\pm$, assuming r_B=0.1 (note: $\sigma_\gamma \propto 1/r_B$)



LHCb expects 2fb^{-1} per year

Achasov references

Privat communications with the authors of Phys. Rev. D 76, 012001 (2007) and:
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