Hadronic Charm Decays

Jonas Rademacker on behalf of CLEO-c

28 May 2009, FCPC Lake Placid

Outline

- Decay rates
- Dalitz analyses
- Charm for Beauty: Quantum correlations at CLEO-c and their impact on measuring γ.

BR of D,$D_{(S)} \to$PP

CLEO-c preliminary, full data set

818/pb at ψ(3770)
$3 \cdot 10^6$ $D^0 \bar{D}^0$
$2.4 \cdot 10^6$ D^+D^-

586/pb at ψ(4170)
$5.4 \cdot 10^5$ $D_s^+ D_s^-$

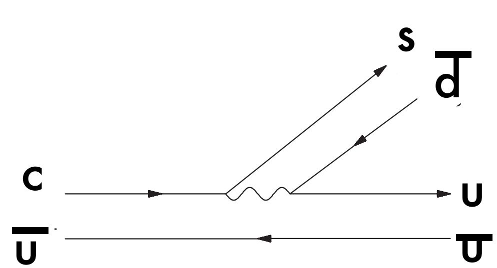
TABLE II: Ratios of branching fractions to the corresponding normalization modes $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D_s^+ \to K_S^0 K^+$, branching fractions results from this analysis, and charge asymmetries $\mathcal{A}_{CP}$. Uncertainties are statistical error, systematic error, and the error from the input branching fractions of normalization modes.

Mode	$\mathcal{B}_{\rm mode}/\mathcal{B}_{\rm Normalization}$ (%)	This result $\mathcal{B}$ (%)	$\mathcal{A}_{CP}$ (%)
$D^0 \to K^+K^-$	10.4138 ± 0.1064 ± 0.1128	0.4052 ± 0.0041 ± 0.0044 ± 0.0080	
$D^0 \to K_S^0 K_S^0$	0.4095 ± 0.0432 ± 0.0214	0.0159 ± 0.0017 ± 0.0008 ± 0.0003	
$D^0 \to \pi^+\pi^-$	3.7023 ± 0.0561 ± 0.0893	0.1441 ± 0.0022 ± 0.0035 ± 0.0029	
$D^0 \to \pi^0\pi^0$	2.1491 ± 0.0740 ± 0.0758	0.0836 ± 0.0029 ± 0.0030 ± 0.0017	
$D^0 \to K^-\pi^+$	100	3.8910 external input [2]	0.5 ± 0.4 ± 0.9
$D^0 \to K_S^0\pi^0$	31.0495 ± 0.2964 ± 0.7467	1.2081 ± 0.0115 ± 0.0291 ± 0.0239	
$D^0 \to K_S^0\eta$	12.2575 ± 0.2872 ± 0.6677	0.4769 ± 0.0112 ± 0.0260 ± 0.0094	
$D^0 \to \pi^0\eta$	1.7714 ± 0.1481 ± 0.1047	0.0689 ± 0.0058 ± 0.0041 ± 0.0014	
$D^0 \to K_S^0\eta'$	24.7307 ± 0.8154 ± 1.1433	0.9623 ± 0.0317 ± 0.0445 ± 0.0190	
$D^0 \to \pi^0\eta'$	2.4084 ± 0.2874 ± 0.1519	0.0937 ± 0.0112 ± 0.0059 ± 0.0019	
$D^0 \to \eta\eta$	4.2495 ± 0.2838 ± 0.3522	0.1653 ± 0.0110 ± 0.0137 ± 0.0033	
$D^0 \to \eta\eta'$	2.7318 ± 0.6235 ± 0.2500	0.1063 ± 0.0243 ± 0.0097 ± 0.0021	
$D^+ \to K^-\pi^+\pi^+$	100	9.1400 external input [2]	-0.1 ± 0.4 ± 0.9
$D^+ \to K_S^0 K^+$	3.3502 ± 0.0573 ± 0.0720	0.3062 ± 0.0052 ± 0.0066 ± 0.0066	-0.2 ± 1.5 ± 0.9
$D^+ \to \pi^+\pi^0$	1.3208 ± 0.0382 ± 0.0443	0.1207 ± 0.0035 ± 0.0041 ± 0.0026	2.9 ± 2.9 ± 0.3
$D^+ \to K_S^0\pi^+$	16.8160 ± 0.1239 ± 0.3679	1.5370 ± 0.0113 ± 0.0336 ± 0.0331	-1.3 ± 0.7 ± 0.3
$D^+ \to K^+\pi^0$	0.1923 ± 0.0206 ± 0.0063	0.0176 ± 0.0019 ± 0.0006 ± 0.0004	-3.5 ± 10.7 ± 0.9
$D^+ \to K^+\eta$	< 0.1442 (90% C.L.)	< 0.0132 (90% C.L.)	
$D^+ \to \pi^+\eta$	3.8538 ± 0.0895 ± 0.1916	0.3522 ± 0.0082 ± 0.0175 ± 0.0076	-2.0 ± 2.3 ± 0.3
$D^+ \to K^+\eta'$	< 0.2032 (90% C.L.)	< 0.0187 (90% C.L.)	
$D^+ \to \pi^+\eta'$	5.2061 ± 0.1762 ± 0.2565	0.4758 ± 0.0161 ± 0.0234 ± 0.0103	-4.0 ± 3.4 ± 0.6
$D_s^+ \to K_S^0 K^+$	100	1.4900 external input [3]	4.7 ± 1.8 ± 0.9
$D_s^+ \to \pi^+\pi^0$	< 2.3492 (90% C.L.)	< 0.0376 (90% C.L.)	
$D_s^+ \to K_S^0\pi^+$	8.4766 ± 0.7147 ± 0.1778	0.1263 ± 0.0106 ± 0.0026 ± 0.0073	16.3 ± 7.3 ± 0.3
$D_s^+ \to K^+\pi^0$	4.2383 ± 1.4756 ± 0.2304	0.0632 ± 0.0220 ± 0.0034 ± 0.0036	-26.6 ± 23.8 ± 0.9
$D_s^+ \to K^+\eta$	11.7933 ± 2.1753 ± 0.5888	0.1757 ± 0.0324 ± 0.0088 ± 0.0101	9.3 ± 15.2 ± 0.9
$D_s^+ \to \pi^+\eta$	123.1123 ± 4.2907 ± 6.2133	1.8344 ± 0.0639 ± 0.0926 ± 0.1059	-4.6 ± 2.9 ± 0.3
$D_s^+ \to K^+\eta'$	11.9866 ± 3.6840 ± 0.6158	0.1786 ± 0.0549 ± 0.0092 ± 0.0103	6.0 ± 18.9 ± 0.9
$D_s^+ \to \pi^+\eta'$	269.8080 ± 8.9375 ± 14.0957	4.0201 ± 0.1332 ± 0.2100 ± 0.2320	-6.1 ± 3.0 ± 0.6

U-spin and $D^0 \to K_{S,L}\pi^0$

I. Bigi and H. Yamamoto, Physics Letters 349 (1995) 363-366

- $\Gamma(D^0 \to K_S \pi^0) \neq \Gamma(D^0 \to K_L \pi^0)$
- $A(D^0 \to K_{S,L}\pi^0) = A(D \to \overline{K}^0 \pi^0) \quad \pm \quad A(D \to K^0 \pi^0)$

CF


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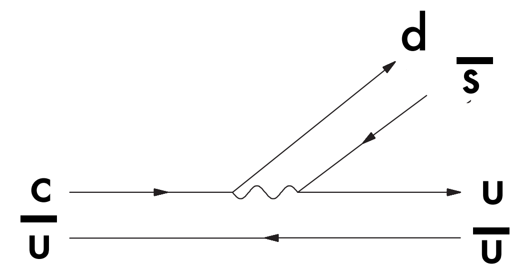


DCS

U-spin* prediction

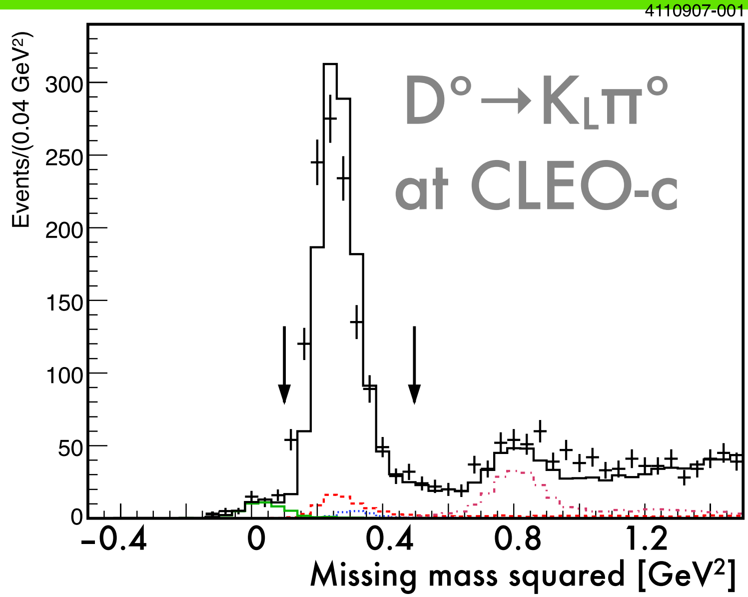
*U-spin: swap d↔s quarks, important e.g. for extracting γ from $B_S \to KK$, $B_d \to \pi\pi$

- $$\frac{\Gamma\left(D^0 \to K_S \pi^0\right) - \Gamma\left(D^0 \to K_L \pi^0\right)}{\Gamma\left(D^0 \to K_S \pi^0\right) + \Gamma\left(D^0 \to K_L \pi^0\right)} = -2\frac{A_{DCS}}{A_{CF}} = 2\tan^2\theta_C = 0.109$$

- Challenging in practice - K_L invisible. Can be done at CLEO-c from beam constraints.

$D^\circ \to K_{L,S}\pi^0$, at CLEO-c

- Clean missing mass-squared peak at $m^2_{K^\circ} = 0.28 GeV^2$



- Lines: MC simulation. Crosses: Data.
- Result

$$\frac{\Gamma\left(D^0 \to K_S\pi^0\right) - \Gamma\left(D^0 \to K_L\pi^0\right)}{\Gamma\left(D^0 \to K_S\pi^0\right) + \Gamma\left(D^0 \to K_L\pi^0\right)} = 0.108 \pm 0.025 \pm 0.024$$

- In good agreement with U-spin prediction of $2\tan^2\theta = 0.109$

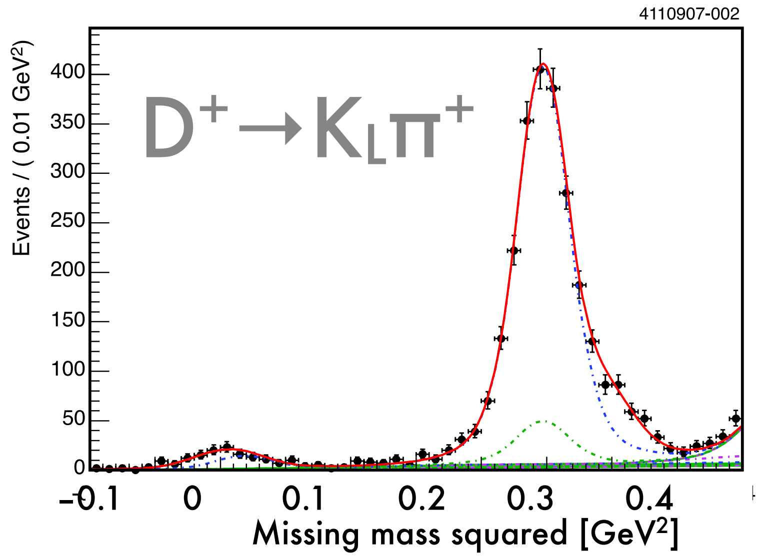
281/pb at CLEO: PRL **100,** 091801 (2008)

$D^+ \to K_{L,S}\pi^+$ at CLEO-c

- Similar logic as for D°, but no U-spin symmetry.
- Still, possible to estimate effect, expect

$$\frac{\Gamma\left(D^+ \to K_S\pi^+\right) - \Gamma\left(D^+ \to K_L\pi^+\right)}{\Gamma\left(D^+ \to K_S\pi^+\right) + \Gamma\left(D^+ \to K_L\pi^+\right)} \approx 0.04$$

D.-N. Gao, Phys. Lett. B **645**, 59 (2007)

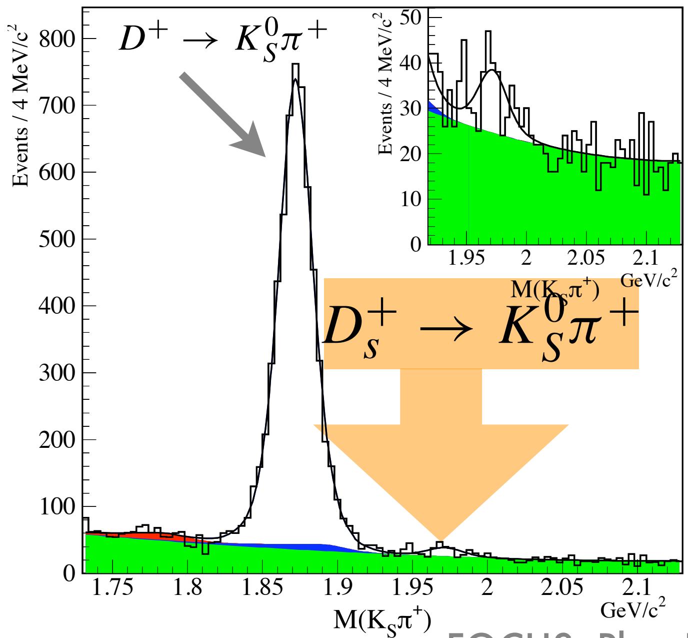


- Result:

$$\frac{\Gamma\left(D^+ \to K_S\pi^+\right) - \Gamma\left(D^+ \to K_L\pi^+\right)}{\Gamma\left(D^+ \to K_S\pi^+\right) + \Gamma\left(D^+ \to K_L\pi^+\right)} = 0.022 \pm 0.016 \pm 0.018$$

281/pb at CLEO: PRL **100,** 091801 (2008)

$D_S^+ \to K_S\pi^+(\pi^-\pi^+)$



FOCUS: Phys.Lett.B660:147-153,2008

Recently discovered by FOCUS

$$\frac{\Gamma\left(D_S^+ \to K_S^0\pi^+\right)}{\Gamma\left(D_S^+ \to K_S^0 K^+\right)} = 0.104 \pm 0.024 \pm 0.013$$

$$\frac{\Gamma\left(D_S^+ \to K_S^0\pi^+\pi^-\pi^+\right)}{\Gamma\left(D_S^+ \to K_S^0 K^+\pi^-\pi^+\right)} = 0.18 \pm 0.04 \pm 0.05$$

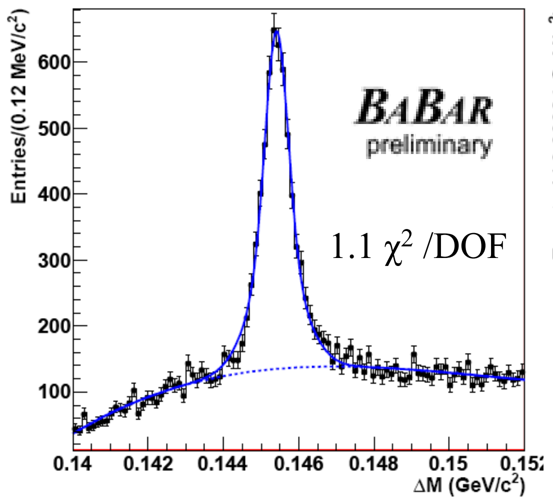
$D_S^+ \to K_S\pi^+$ now confirmed by CLEO: CLEO-c preliminary, full data set

$$\Gamma\left(D_S^+ \to K_S^0\pi^+\right) = (0.1263 \pm 0.0106 \pm 0.0026 \pm 0.0073)\ \%$$

$D^{\circ} \to V\eta$

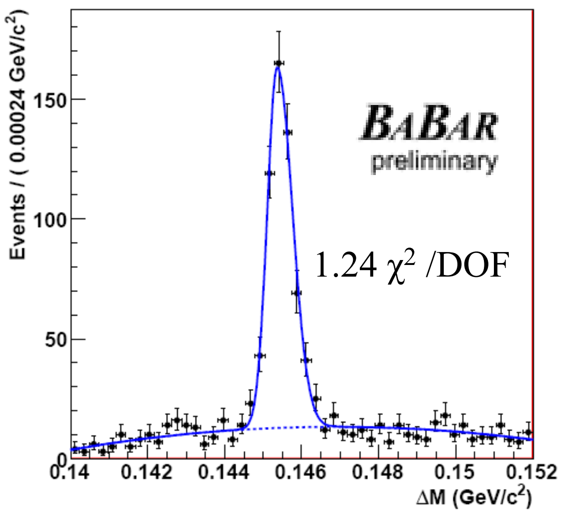
- BaBar analysed 467 fb^{-1} data (on and off resonance)
- About 1 billion D mesons in sample
- Preliminary result shown in April 2009 APS Meeting*:

$D^0 \to \omega\eta$ new mode



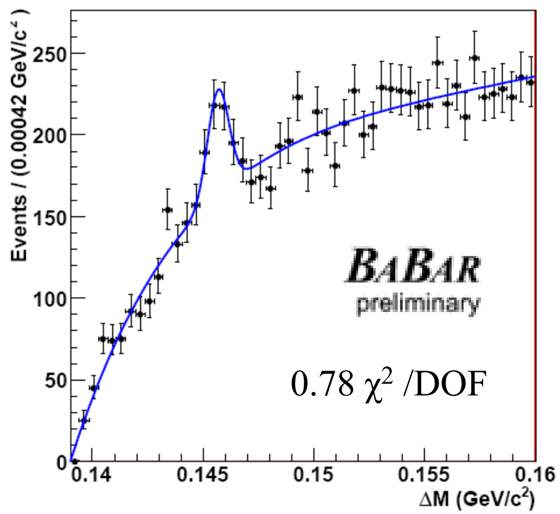
$N = 4450 \pm 103$

$D^0 \to \varphi\eta$



$N = 513 \pm 26$

$D^0 \to K^{*0}\eta$ new mode



$N=117 \pm 37$

*) Caitlin Malone on behalf of the BaBar Collaboration at APS April Meeting 2009

$D^o \to V\eta$

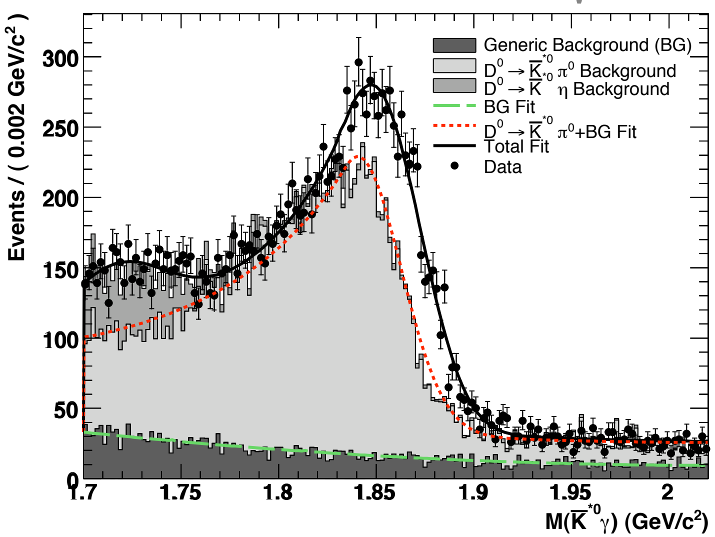
Mode	Theory B.F. $/10^{-3}$ B. Bhattacharya, J. L. Rosner, arXiv: 0812.3167v1 [hep-ph] (2008)		Experiment previously[1]	BaBar Results (preliminary) April 08 [2]	
	Sol A	Sol B		BF	yield
$D^o \to \phi\eta$	0.93 ± 0.09	1.4 ± 0.1	0.14 ± 0.04	$0.21 \pm 0.01 \pm 0.02$	513 ± 26
$D^o \to \omega\eta$	1.4 ± 0.09	1.27 ± 0.09		$2.21 \pm 0.08 \pm 0.22$	4450 ± 103
$D^o \to K^{*o}\eta$	0.038 ± 0.004	0.037 ± 0.004		$0.048 \pm 0.010 \pm 0.004$	117 ± 37

[1] BELLE: Phys.Rev.Lett.92:101803,2004

[2] Caitlin Malone on behalf of the BaBar Collaboration at APS April Meeting 2009

D°→K*°γ and D°→φγ

BaBar: D°→K*⁰γ



- New CLEO-c study confirms BaBar result.

BaBar:

$$\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma) = (3.22 \pm 0.20 \pm 0.27) \times 10^{-4}$$

$$\mathcal{B}(D^0 \to \phi\gamma) = (2.73 \pm 0.30 \pm 0.26) \times 10^{-5}$$

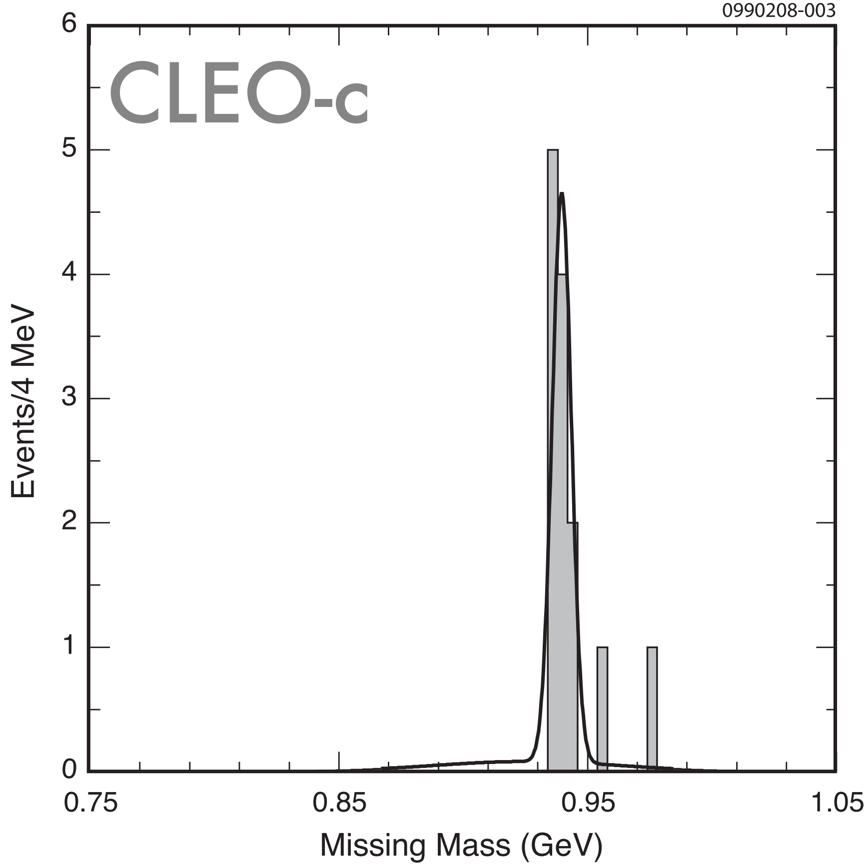
First Observation of D°→K*°γ

BaBar, Phys. Rev. D 78, 071101 (2008)

CLEO-c preliminary

Channel	$\mathcal{B}$
$D^0 \to \bar{K}^*\gamma$	$(4.37 \pm 0.37 \pm 0.52) \cdot 10^{-4}$
$D^0 \to \phi\gamma$	$(2.21 \pm 0.95 \pm 0.28) \cdot 10^{-5}$
$D^0 \to \gamma\gamma$	$< 8.93 \cdot 10^{-6} (90\% CL)$
$D^0 \to \rho\gamma$	$< 3.63 \cdot 10^{-5} (90\% CL)$
$D^0 \to \omega\gamma$	$< 3.00 \cdot 10^{-5} (90\% CL)$

First Observation of $D_s^+ \to p\bar{n}$



CLEO-c: Phys. Rev. Lett. 100, 181802 (2008)

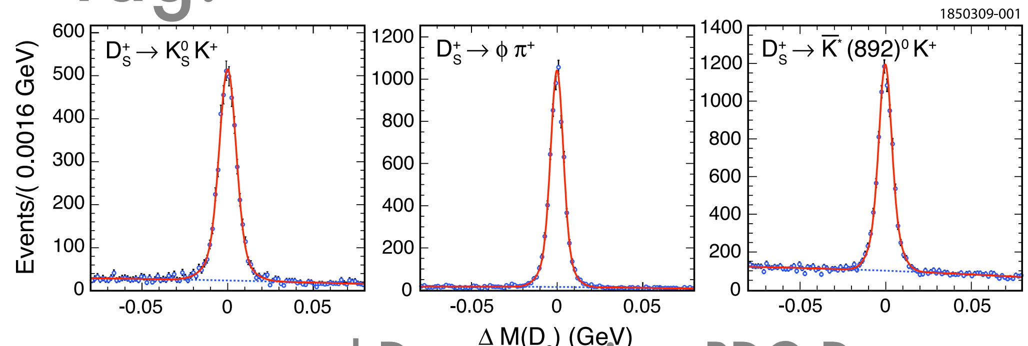
- Only baryonic state kinematically accessible to D^o D^+ D_s^+
- Virtually background-free reconstruction at CLEO-c
- First observation of meson → 2 baryons plus nothing else.

$$\mathcal{B}(D_s^+ \to p\bar{n}) = (1.30 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$$

Inclusive Ds BF

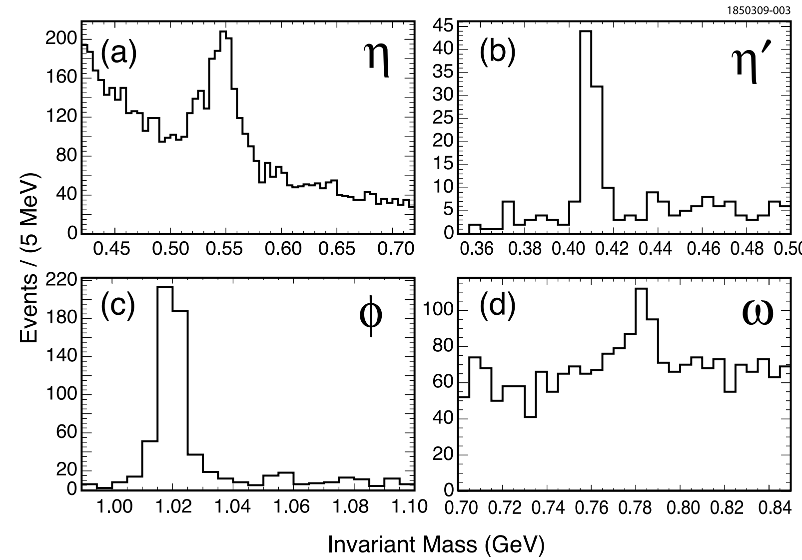
- $e^+e^- \to \psi(4170) \to D_S^{+*} D_S^-$
- Fully reconstruct one Ds as tag
- Reconstruction of desired decay product on other side gives absolute, inclusive BF.

Tag:



reconstructed Ds mass minus PDG Ds mass

Inclusive reconstruction:



CLEO: arXiv:0904.2417 [hep-ex], submitted to PRD

Inclusive Ds BF Results

Mode	Yield(%)	K_L^0 Mode	Yield(%)	$\mathcal{B}$(PDG)(%)
$D_s^+ \to \pi^+ X$	$119.3 \pm 1.2 \pm 0.7$			
$D_s^+ \to \pi^- X$	$43.2 \pm 0.9 \pm 0.3$			
$D_s^+ \to \pi^0 X$	$123.4 \pm 3.8 \pm 5.3$			
$D_s^+ \to K^+ X$	$28.9 \pm 0.6 \pm 0.3$			$20\ ^{+\ 18}_{-\ 14}$
$D_s^+ \to K^- X$	$18.7 \pm 0.5 \pm 0.2$			$13\ ^{+\ 14}_{-\ 12}$
$D_s^+ \to \eta X$	$29.9 \pm 2.2 \pm 1.7$			
$D_s^+ \to \eta' X$	$11.7 \pm 1.7 \pm 0.7$			
$D_s^+ \to \phi X$	$15.7 \pm 0.8 \pm 0.6$			
$D_s^+ \to \omega X$	$6.1 \pm 1.4 \pm 0.3$			
$D_s^+ \to f_0(980)X, f_0(980) \to \pi^+\pi^-$	$< 1.3\%$ (90% CL)			
$D_s^+ \to K_S^0 X$	$19.0 \pm 1.0 \pm 0.4$	$D_s^+ \to K_L^0 X$	15.6 ± 2.0	20 ± 14
$D_s^+ \to K_S^0 K_S^0 X$	$1.7 \pm 0.3 \pm 0.1$	$D_s^+ \to K_L^0 K_S^0 X$	5.0 ± 1.0	
$D_s^+ \to K_S^0 K^+ X$	$5.8 \pm 0.5 \pm 0.1$	$D_s^+ \to K_L^0 K^+ X$	5.2 ± 0.7	
$D_s^+ \to K_S^0 K^- X$	$1.9 \pm 0.4 \pm 0.1$	$D_s^+ \to K_L^0 K^- X$	1.9 ± 0.3	
$D_s^+ \to K^+ K^- X$	$15.8 \pm 0.6 \pm 0.3$			
$D_s^+ \to K^+ K^+ X$	$< 0.26\%$ (90% CL)			
$D_s^+ \to K^- K^- X$	$< 0.06\%$ (90% CL)			

CLEO result: arXiv:0904.2417 [hep-ex], submitted to PRD

Exclusive vs inclusive $D_S \to \omega X$

- Most incl. rates[1] accounted for by known excl. ones[2], except, at first: $\Sigma_i \, \Gamma_{excl} \, (D_S \to \omega X_i) \sim 0.13 \times \Gamma_{incl} \, (D_S \to \omega X)$
- A closer look at exclusive $D_S \to \omega X$ BR:

CLEO Preliminary

Mode	$\mathcal{B}_{\mathrm{mode}}(\%)$
$D_s^+ \to \pi^+\omega$	$0.21 \pm 0.09 \pm 0.01$
$D_s^+ \to \pi^+\pi^0\omega$	$2.78 \pm 0.65 \pm 0.25$
$D_s^+ \to \pi^+\pi^+\pi^-\omega$	$1.58 \pm 0.45 \pm 0.09$
$D_s^+ \to \pi^+\eta\omega$	$0.85 \pm 0.54 \pm 0.06$
	< 2.13 (90% CL)
$D_s^+ \to K^+\omega$	< 0.24 (90% CL)
$D_s^+ \to K^+\pi^0\omega$	< 0.82 (90% CL)
$D_s^+ \to K^+\pi^+\pi^-\omega$	< 0.54 (90% CL)
$D_s^+ \to K^+\eta\omega$	< 0.79 (90% CL)

[1] CLEO result: arXiv:0904.2417 [hep-ex], submitted to PRD
[2] Gronau, Rosner , arXiv:0903.2287, Mar 2009, Submitted to Phys.Rev.D

Exclusive vs inclusive Ds→ωX

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The two $D_S \to \omega X$ decay modes with the largest B.R. were previously unknown

- Now, sum of known $D_S \to \omega X$ modes = $(5.4 \pm 1.0)\%$, accounts for most of inclusive $BR(D_S \to \omega X) = (6.1 \pm 1.4)\%$

[1] CLEO result: arXiv:0904.2417 [hep-ex], submitted to PRD
[2] Gronau, Rosner , arXiv:0903.2287, Mar 2009, Submitted to Phys.Rev.D

Dalitz Analyses

- Kinematics of 3-body decay $D \to A,B,C$ fully described by

  $m^2_{AB} \equiv (p_A + p_B)^2$

  $m^2_{BC} \equiv (p_B + p_C)^2$.

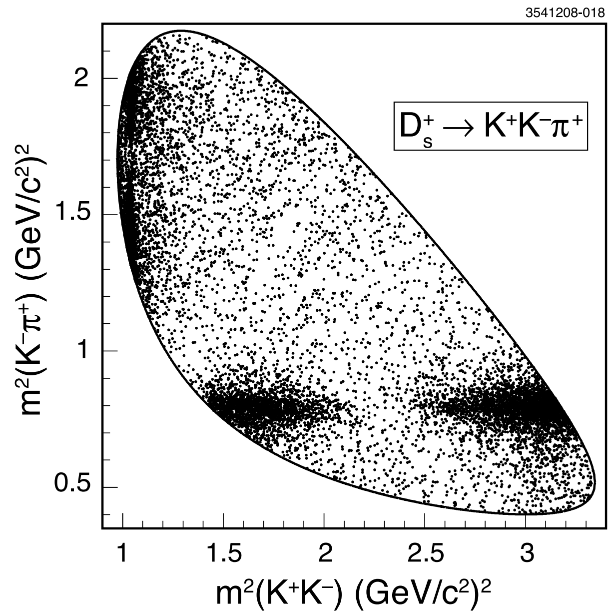
- Phase-space is flat in m^2_{AB}, m^2_{BC}

- Decay rates:

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

- Strength: Access to **magnitudes AND phases** of amplitudes.

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



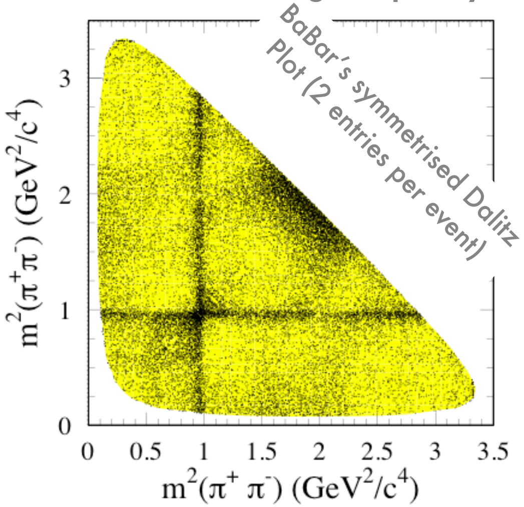
"Isobar" Model

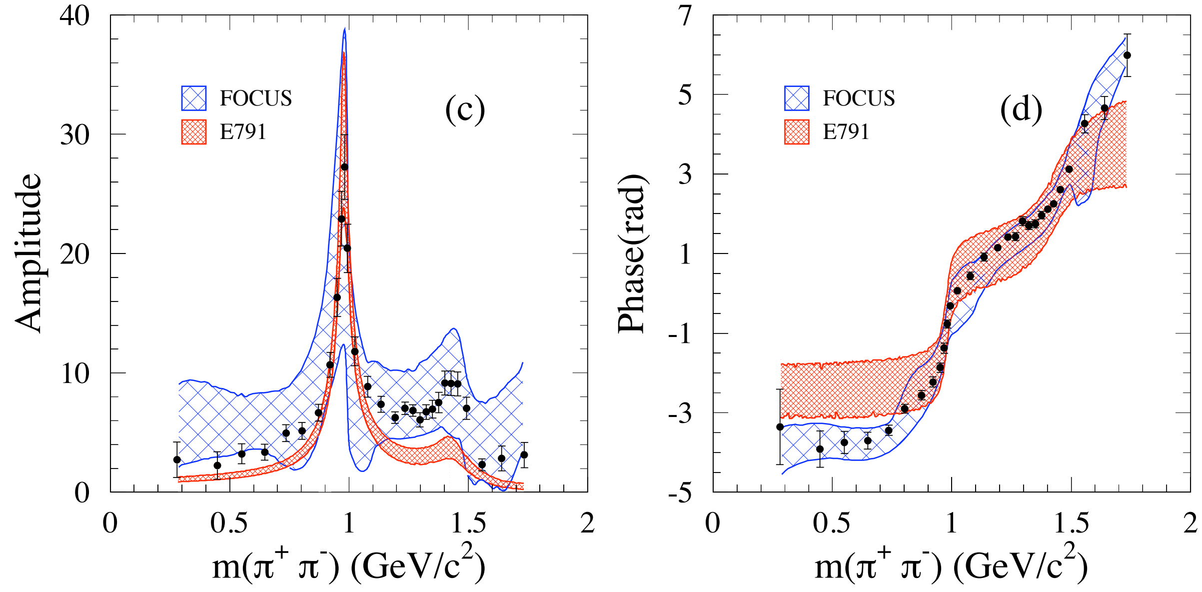
- Each resonance = Breit Wigner lineshape (or similar) times factors accounting for spin.
- Popular amongst experimentalists, less so amongst theorists: violates unitarity. OK as long as resonances are reasonably narrow, don't overlap too much.
- Alternatives exist, e.g. K-matrix formalism, which respects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

$D_s^+ \to \pi^-\pi^+\pi^+$

BaBar: arXiv:0808.0971v3 [hep-ex], submitted to PRD

10.5k signal events at BaBar, with 80% signal purity





All plots and dots by BaBar: arXiv:0808.0971v3 [hep-ex]
Red and blue bands based on FOCUS [2] and E791 [3]

- Dominated by S-wave (fit fraction 83%).
- BaBar: model-independent analysis[1] of S-wave component. Result compatible with FOCUS (K-matrix) [2] and E791 (isobar) [3] analyses.
- Many more results in paper.

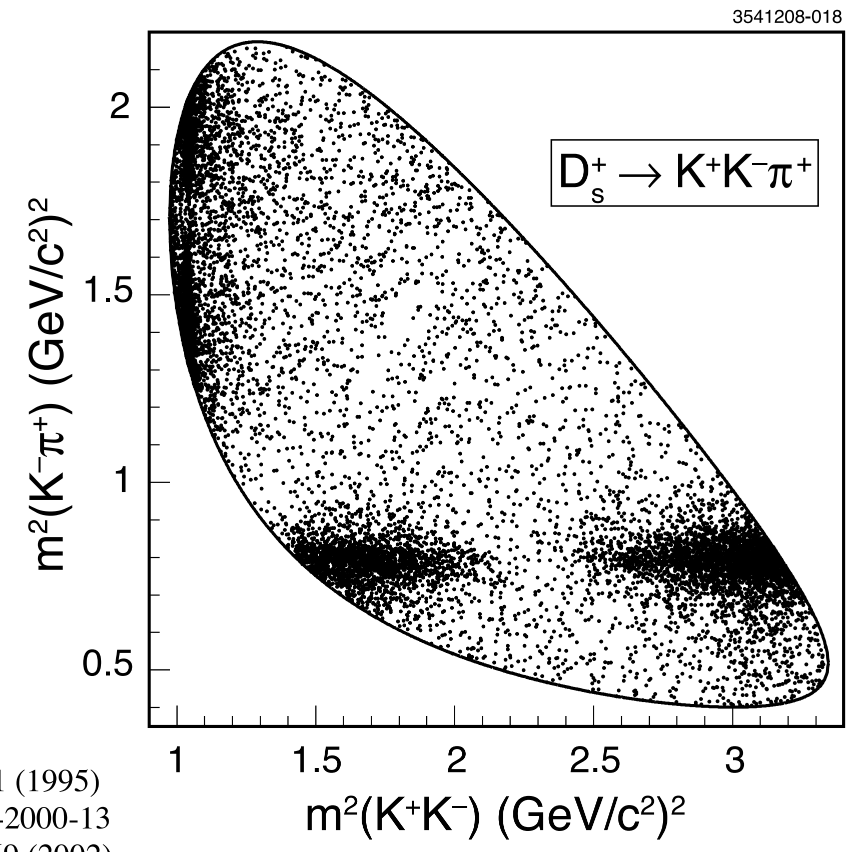
[1] Method pioneered by E791: Phys. Rev. D 73, 032004 (2006).
[2] E791: Phys. Rev. Lett. 86, 765 (2001)
[3] FOCUS: Phys. Lett. B 585, 200 (2004)

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

- Isobar fit. Good agreement with previous E687 (701 event) fit[1].
- Get much-improved fit to CLEO-c data with additional KK S-wave contribution.
- Best results by adding an $f_0(1370)$ resonance.

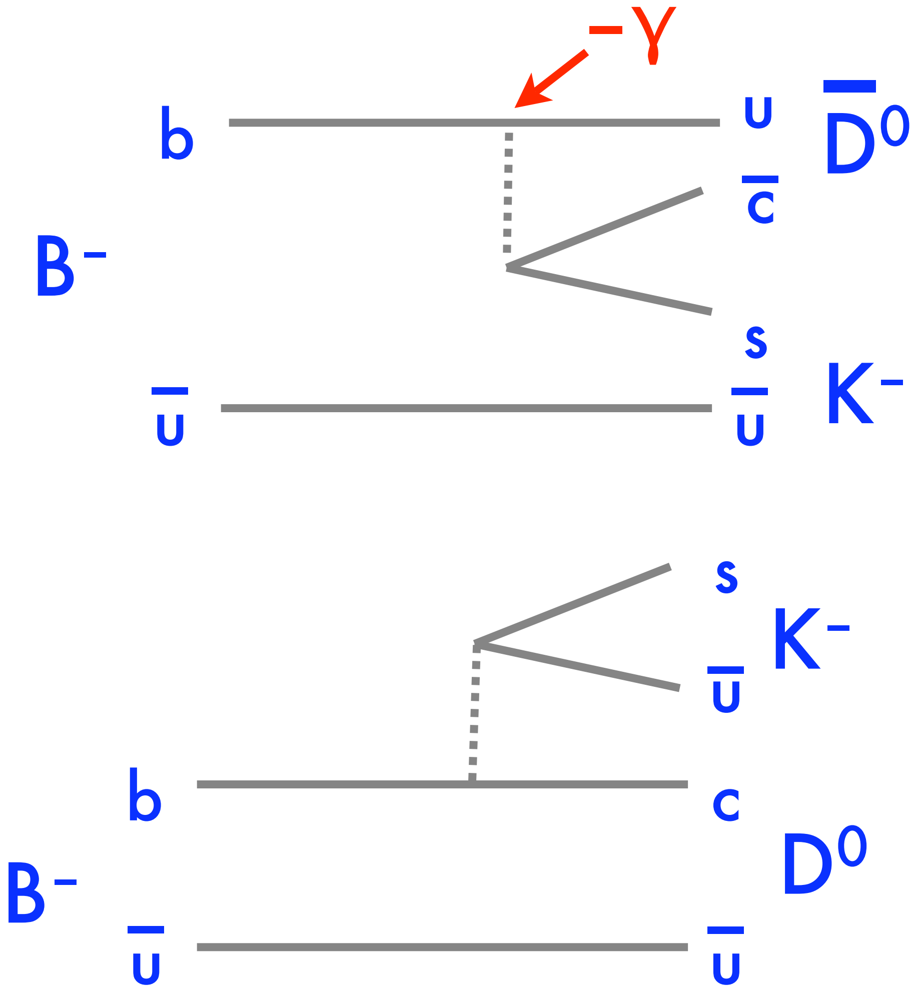
12k $D_s^+ \to K^- K^+ \pi^+$ events at CLEO-c

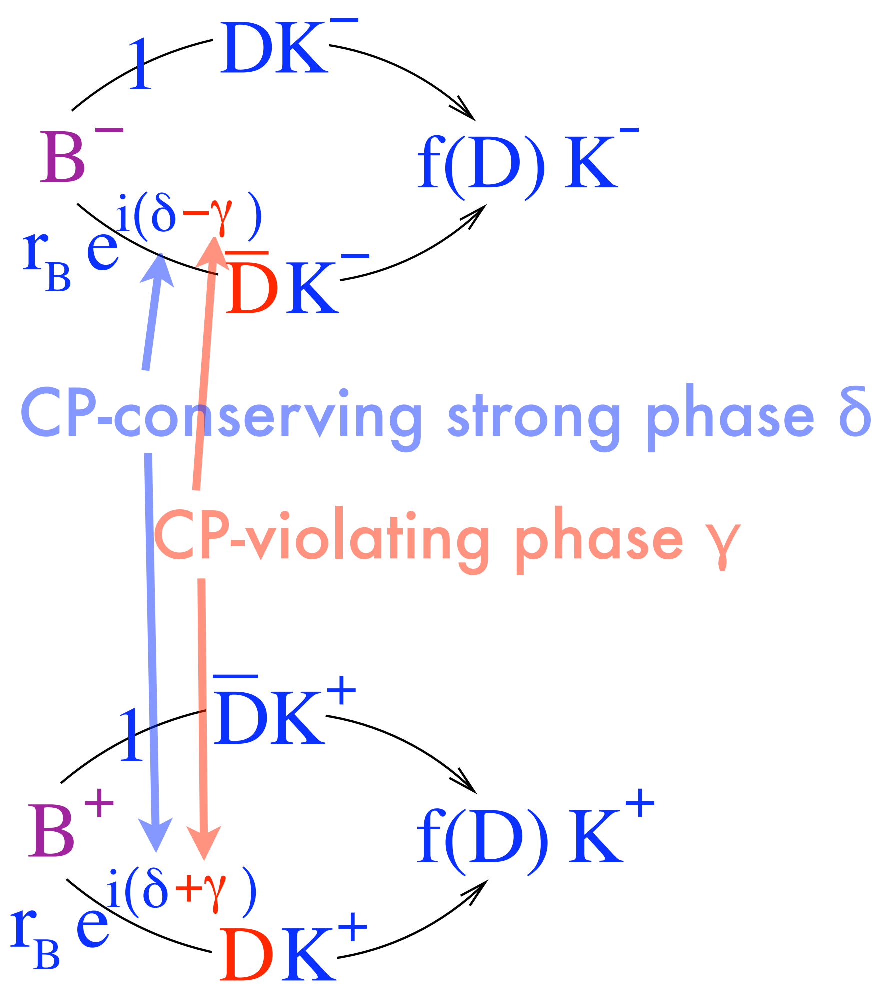
CLEO: PRD 79, 072008 (2009), arXiv:0903.1301



[1] E687: P.L. Frabetti et al. (E687 Collaboration), Phys. Lett., B351, 591 (1995)
see also unpublished FOCUS result: A.M. Rahimi, FERMILAB-THESIS-2000-13
and S. Malvezzi, AIP Conf. Proc. 549, 569 (2002)

Charm for Bottom: $B^{\pm} \rightarrow DK^{\pm}$

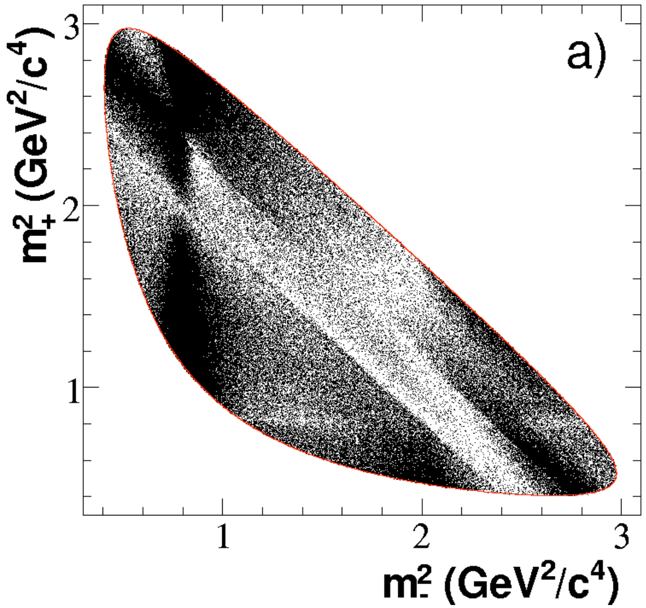


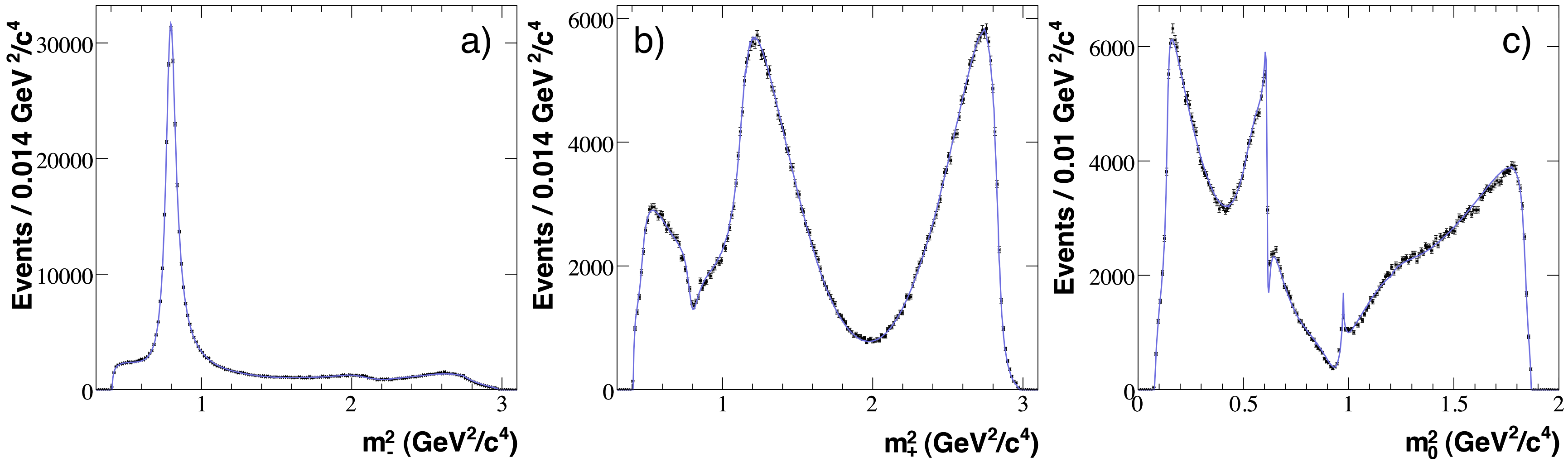


Gronau, Wyler Phys.Lett.B265:172-176,1991, (GLW), Gronau, London Phys.Lett.B253:483-488,1991 **(GLW)** Atwood, Dunietz and Soni Phys.Rev.Lett. 78 (1997) 3257-3260 (ADS) Giri, Grossman, Soffer and Zupan Phys.Rev. D68 (2003) 054018 Belle Collaboration Phys.Rev. D70 (2004) 072003

BaBar fit to D°→Ksππ

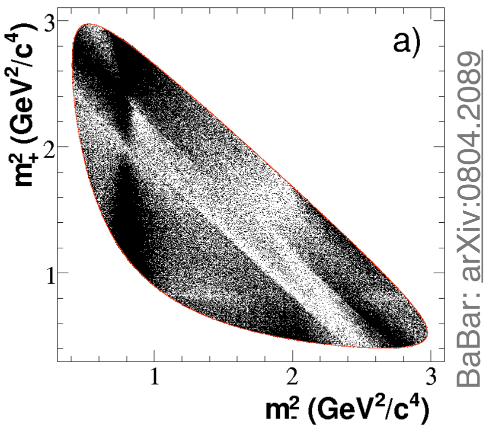
- Fit to 0.5M $D^o \rightarrow K_S\pi\pi$ events
- K-matrix for $\pi\pi$ S-wave contribution, LASS for $K\pi$ S-wave.
- $\chi^2/\text{ndof} = 1.11$





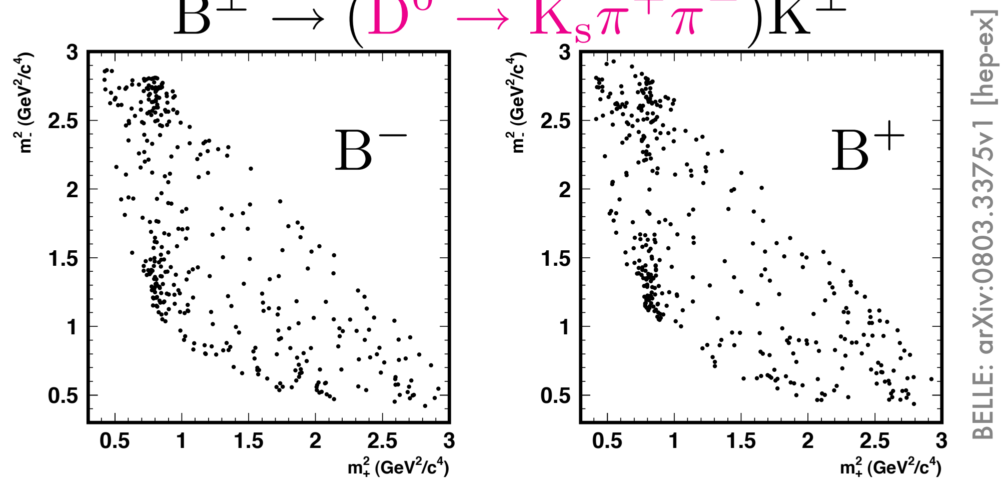
Dalitz Plots for γ at Belle&BaBar

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



+ $D_{flavour}$ amplitude model +

$B^{\pm} \rightarrow (D^0 \rightarrow K_s \pi^+ \pi^-) K^{\pm}$



Combined result (CKM-fitter, summer 08): $\gamma = 70^{o}{}^{+27^o}_{-29^o}$

Model required to interpret measured D-Dalitz plot in terms of complex amplitudes (magnitudes *and* phases)

Source of largest systematic uncertainty: Model dependence, ca 7º–9º. Would limit LHCb's precision soon.

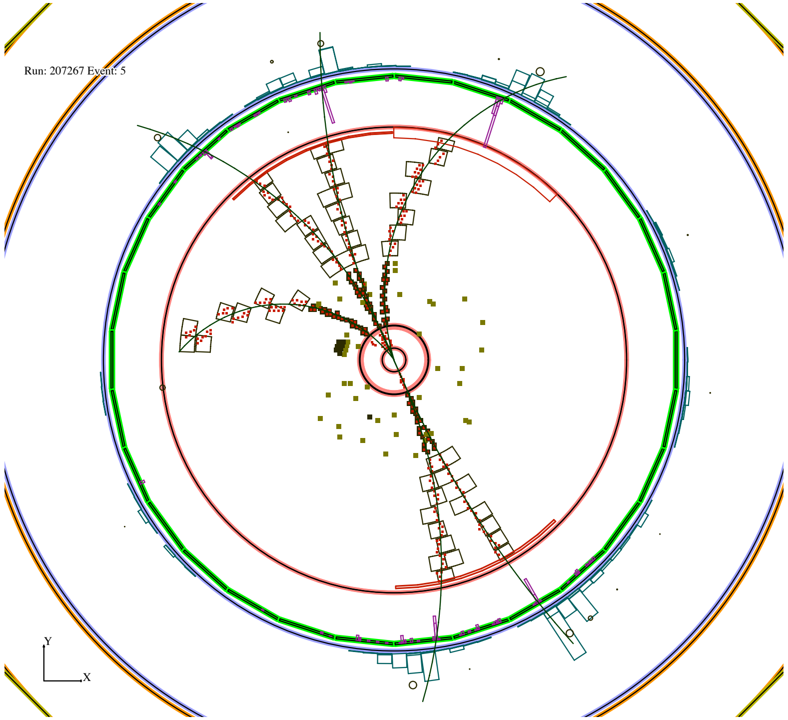
BaBar: Phys.Rev.D78:034023,2008, BELLE: arXiv:0803.3375v1 [hep-ex]
CKMfitter: Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], http://ckmfitter.in2p3.fr

CLEO-c

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

- 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.

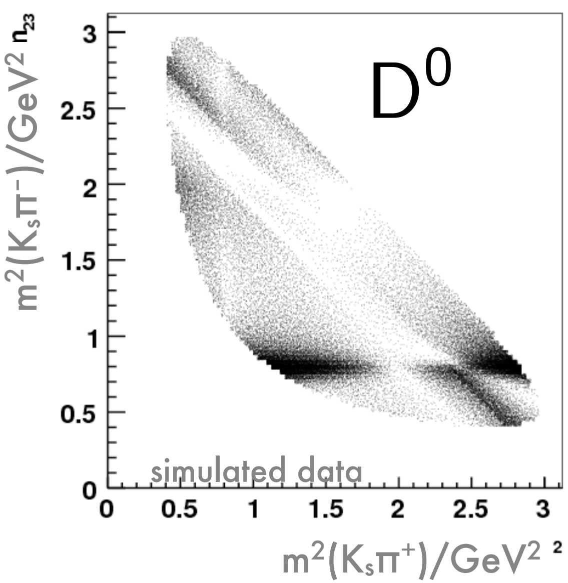
CLEAN-c



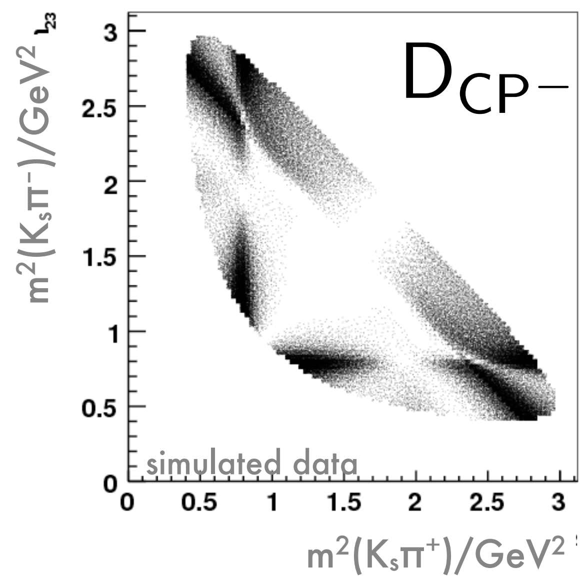
$$\psi(3770) \rightarrow D^0(K_S\pi^+\pi^-)\bar{D}^0(K^+\pi^-)$$

CP and flavour tagged D°

$$\psi'' \rightarrow \bar{D}_{flavour} \rightarrow K^+ e^- \nu_e, \quad D_{flavour} \rightarrow K_s \pi^+ \pi^-$$



$$\psi'' \rightarrow D_{CP+} \rightarrow KK, \quad D_{CP-} \rightarrow K_s \pi^+ \pi^-$$



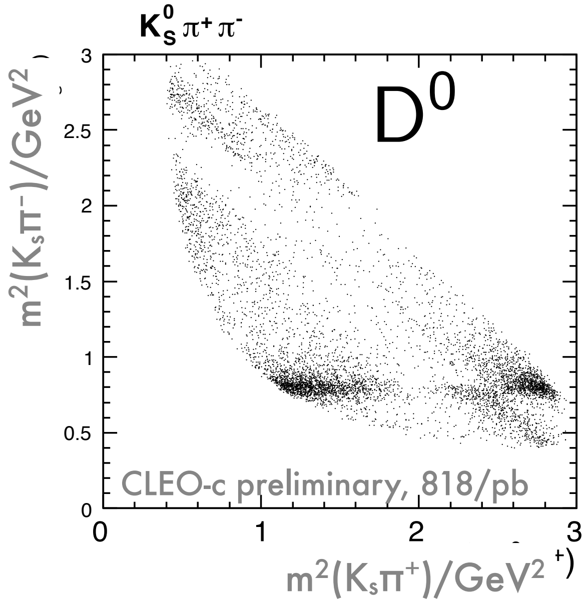
CP and flavour tagged D° at CLEO

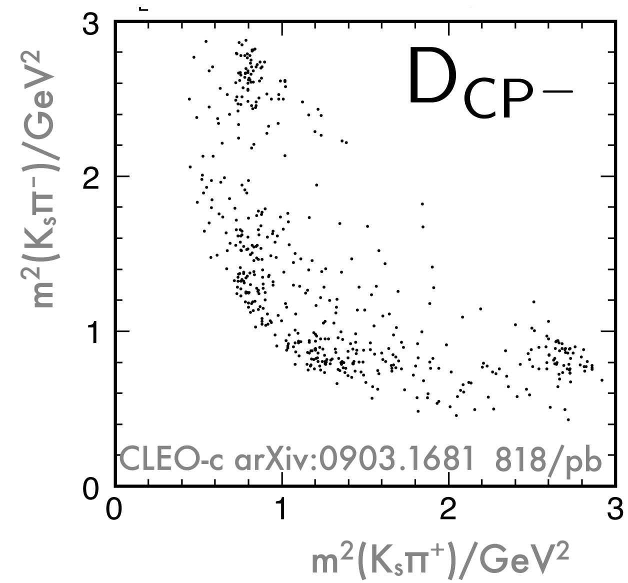
$\psi'' \to \bar{D}_{flavour} \to K^+ e^- \nu_e$

$\psi'' \to D_{flavour} \to K_s \pi^+ \pi^-$

$\psi'' \to D_{CP+} \to KK$

$\psi'' \to D_{CP-} \to K_s \pi^+ \pi^-$





CLEO-c's input to γ

- CLEO-c's input is concerned with δ_D, the phase difference between

  $A(D^o \to K_S\pi^+\pi^-)$ and $A(\bar{D}^o \to K_S\pi^+\pi^-)$

  at a point on the Dalitz plot.

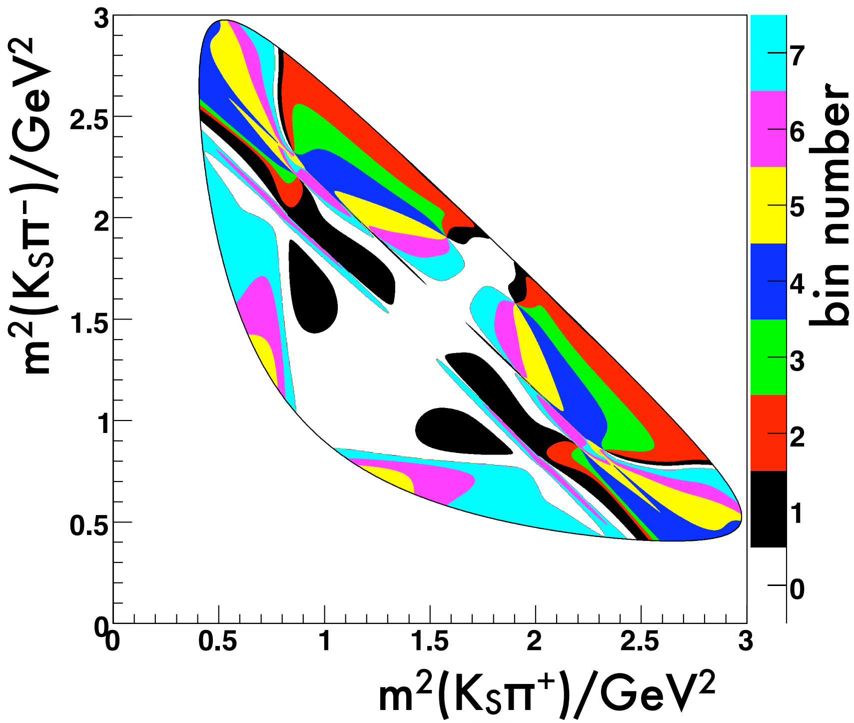
- Measure the cosine and sine of this phase, averaged over bins:

  $c_i = \langle\cos(\delta_D)\rangle_i,\ s_i = \langle\sin(\delta_D)\rangle_i$

- This input allows model-independent γ measurement.

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

Binning used at CLEO-c*



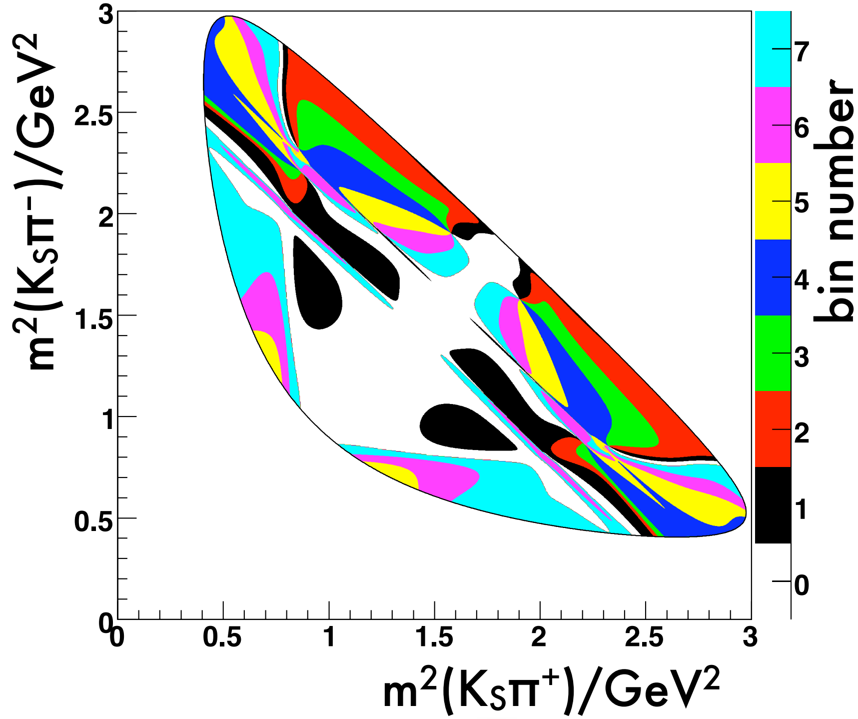
*bin width uniform in δ_D based on BaBar model PRL 95 (2005) 121802

CLEO-c arXiv:0903.1681v1 [hep-ex], submitted to PRD

Optimal binning

- Best γ sensitivity if phase difference δ_D is as constant as possible over each bin[1].
- Plot shows CLEO-c's 8 bins, uniform in δ_D, (based on BaBar isobar model*).
- Choice of model will not bias result. (At worst a bad model would reduce the statistical precision of the result.)

Binning at CLEO-c based on BaBar model*



CLEO-c arXiv:0903.1681v1 [hep-ex], submitted to PRD

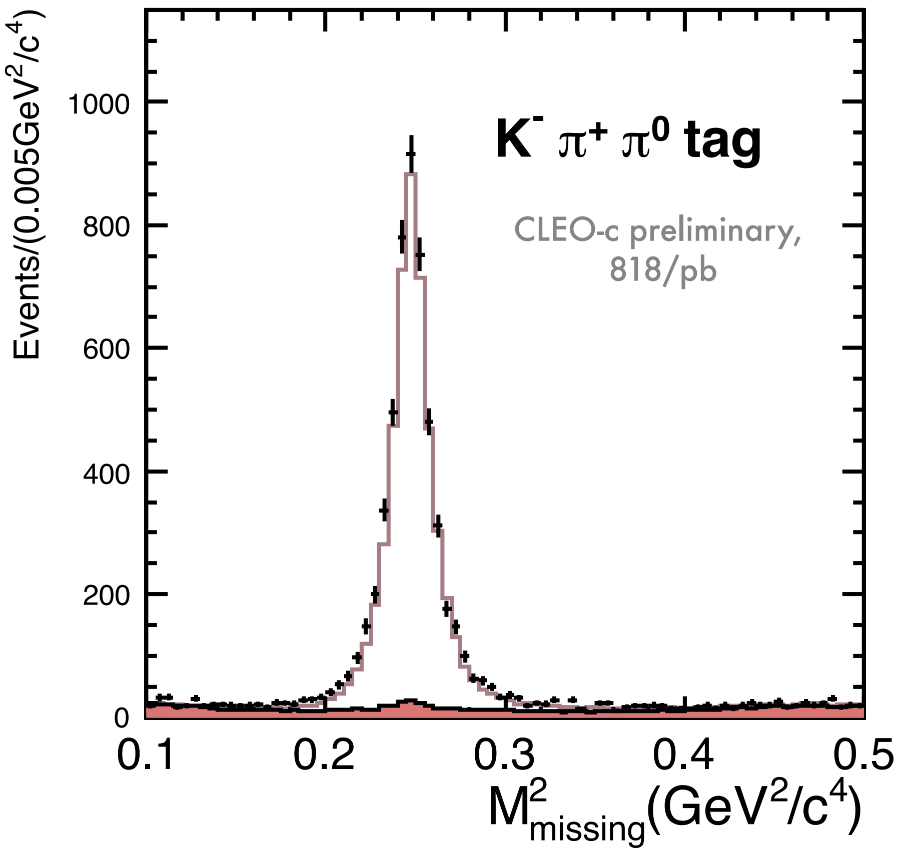
[1] Bondar, Poluektov hep-ph/0703267v1 (2007)

*model = BaBar PRL 95 (2005) 121802

CP-even $K_L\pi\pi \approx$ CP-odd $K_S\pi\pi$

- CLEO-c's clean environment allows the reconstruction of K_L from kinematic constraints.
- Significantly increases statistics.
- There is price to pay: A $\mathcal{O}(\tan^2\theta_C)$ model-dependent correction. Carefully evaluated (small) systematic uncertainty.

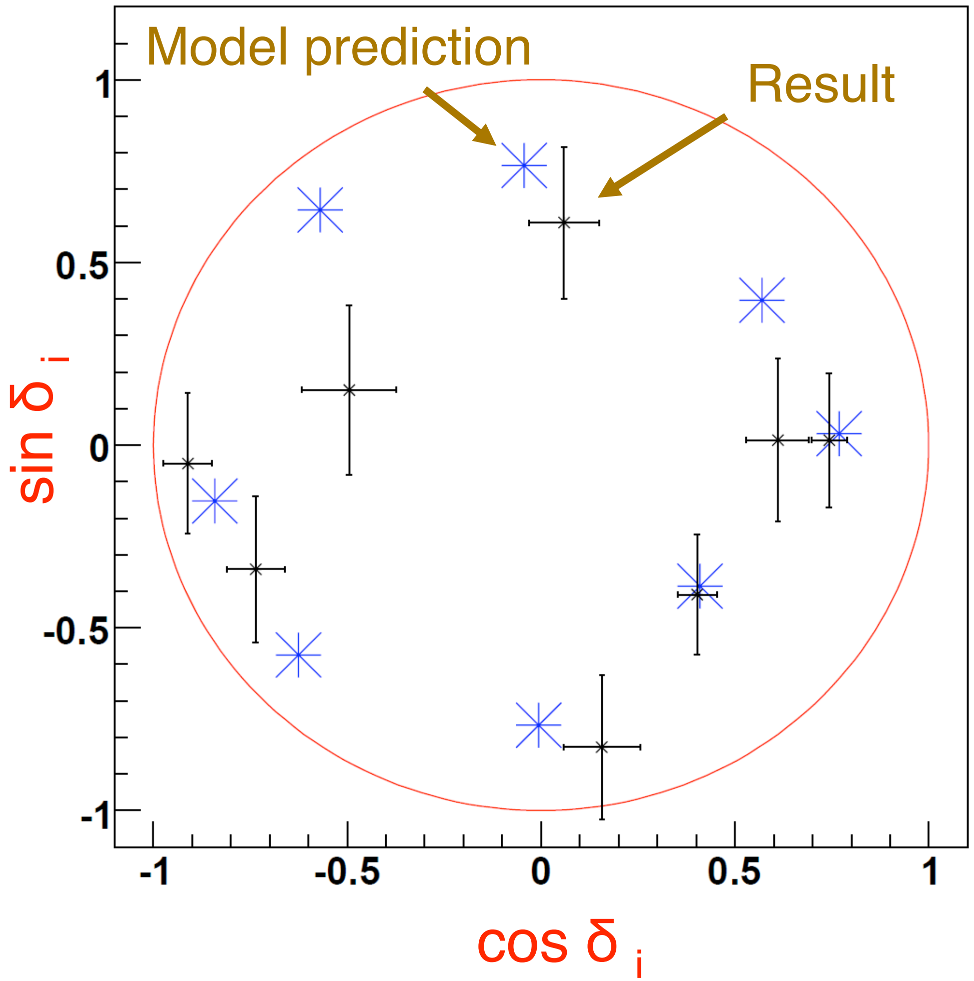
Overlaying Data (black) and MC (red) for missing M^2 in K_L reconstruction in $K_L\pi^+\pi^-$ vs $K^-\pi^+\pi^0$



CLEO-c arXiv:0903.1681v1 [hep-ex], submitted to PRD

CLEO-c results

- 818/fb at CLEO-c
- 20k flavour tagged events (for magnitude of $A(D^o \to K_S \pi^+ \pi^-)$)
- 1.6 k CP-tagged events (for c_i extraction)
- 1.3k $K_{L,S}\pi\pi$ vs $K_S\pi\pi$ (for c_i *and* s_i extraction)
- S/B between 10 and 100, depending on tag mode.



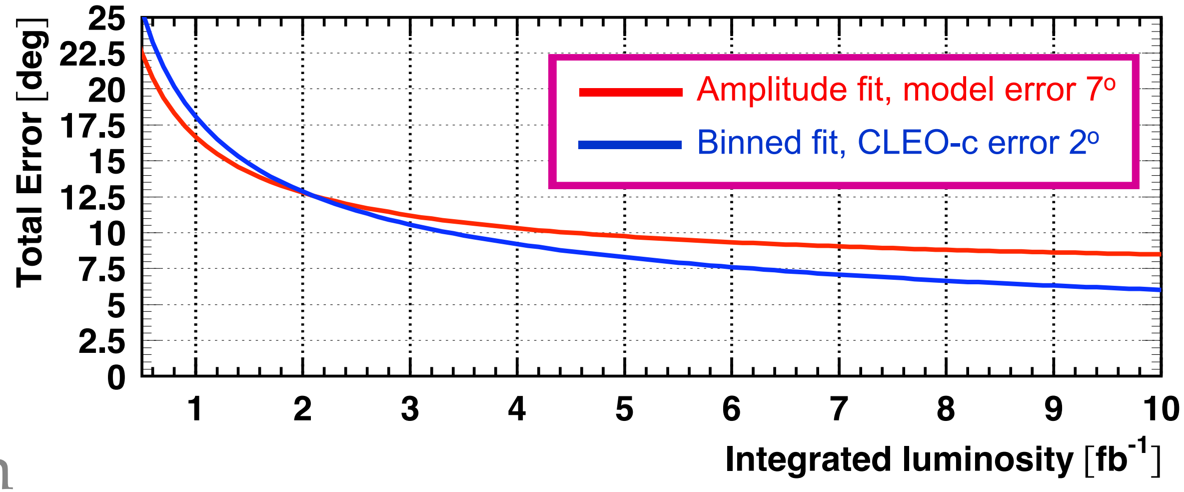
Result = CLEO-c arXiv:0903.1681v1 [hep-ex], submitted to PRD
model = BaBar PRL 95 (2005) 121802

Impact on γ from $B^{\pm}\to D(K_S\pi\pi)K^{\pm}$

- Replace 7° model systematic on γ from $B^{\pm}\to D(K_S\pi\pi)K^{\pm}$ with

  $\sigma_{CLEO\text{-}input}(\gamma) \sim 1.7°$

- Significant reduction in BaBar/BELLE's systematic.
- Especially important for future flavour experiments, which will be systematics limited.



Error at the end of baseline LHCb (10 fb^{-1}) for γ from $B^{\pm}\to D(K_S\pi\pi)K^{\pm}$:

8.5°(amplitude model);

6°(binned, with CLEO-c input)

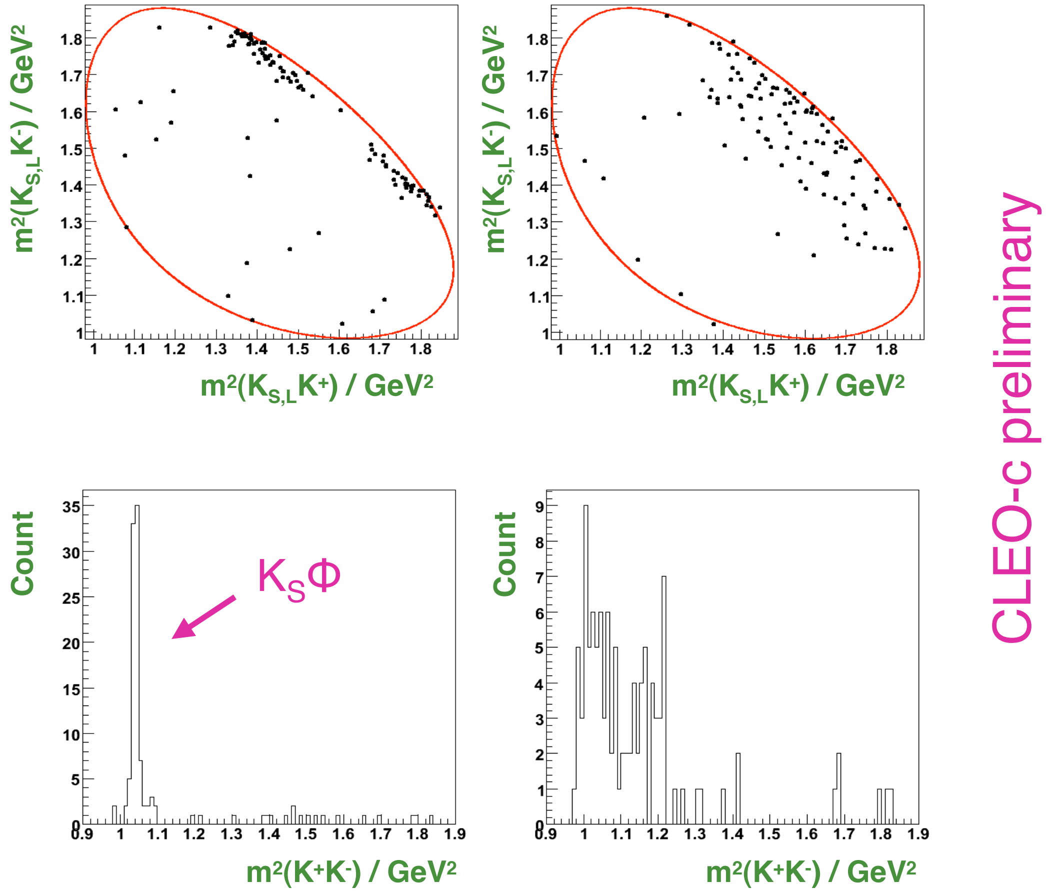
(numbers for r_B=0.1)

Extend to $B^+ \to (D^\circ \to K_S KK) K^+$

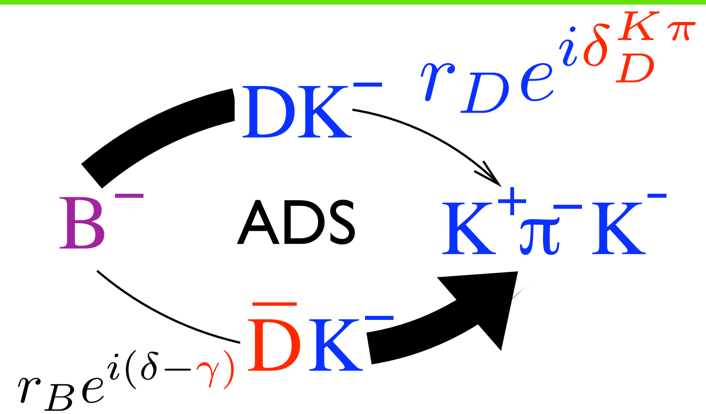
- Pioneered at BaBar: PRD78:034023 (2008)
- CLEO-c input: ca 550 quantum-correlated events.
- Results from CLEO-c soon...

CP+ tag vs $K_S KK$
CP- tag vs $K_L KK$

CP- tag vs $K_S KK$
CP+ tag vs $K_L KK$



γ from 2-body decays, ADS



- Extract γ from 2-body decays[1]
- Particularly powerful: "ADS" modes with large interference terms (when $r_D \sim r_B$).

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

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

- CLEO-c's provides as input: $\delta_D^{K\pi} = 22^{o}{}^{+11^o}_{-12^o}{}^{+9^o}_{-11^o}$ PRL 100, 221801 (2008), PRD 78, 012001 (2008)
- Also important input for D-mixing! *

* Result shown includes external input on y, y′ from mixing measurements. Without external inputs: $\cos\delta = 1.03^{+0.31}_{-0.17} \pm 0.06$

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

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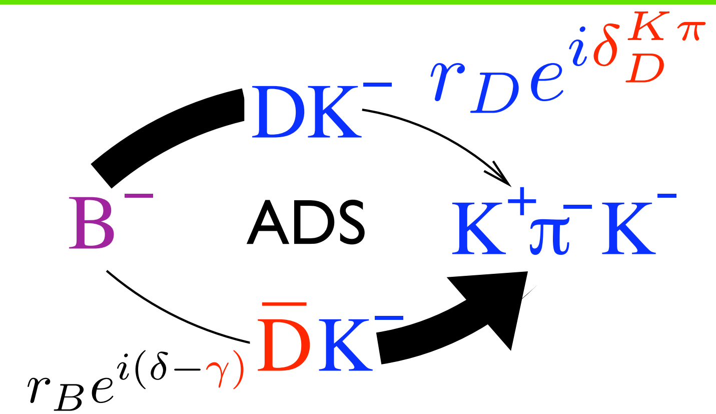

$$\Gamma(B^- \to (K^+\pi^-)_D K^-) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B + \delta_D^{K\pi} - \gamma)$$

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

CLEO-c $\delta_D^{K\pi}$ result based on 1/3 of data set update with full 818/fb and more tag modes, soon.

- CLEO-c's provides as input: $\delta_D^{K\pi} = 22^{o}{}^{+11^o}_{-12^o}{}^{+9^o}_{-11^o}$ PRL 100, 221801 (2008), PRD 78, 012001 (2008)

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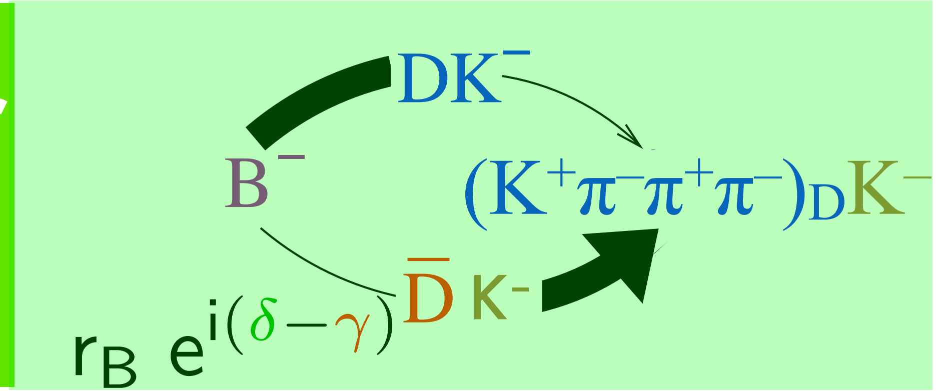
Coherence Factor Analysis of:

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



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

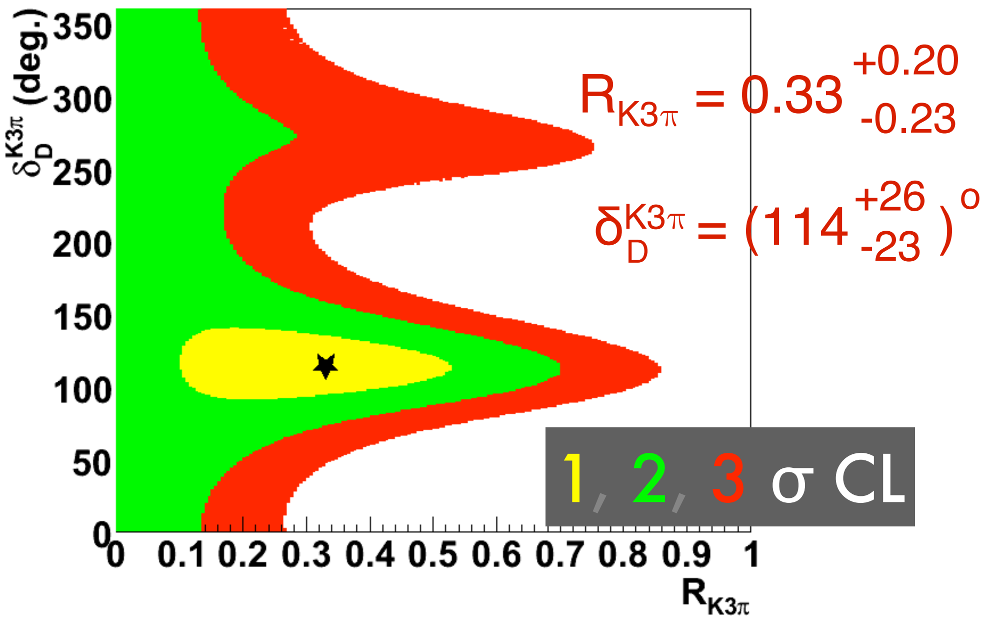
$$\Gamma\left(B^- \to \left(K^+ 3\pi\right)_D K^-\right) \propto r_B^2 + \left(r_D^{K3\pi}\right)^2 + 2 R_{K3\pi} r_B r_D^{K3\pi} \cdot \cos\left(\delta_B + \delta_D^{K3\pi} - \gamma\right)$$

- CLEO-c's coherent ψ(3770)→DD 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

- Low value preferred. This channel on its own would not be very sensitive to γ.
- For a combined analysis of $B^{\pm} \to DK^{\pm}$ modes, this provides powerful constraints.



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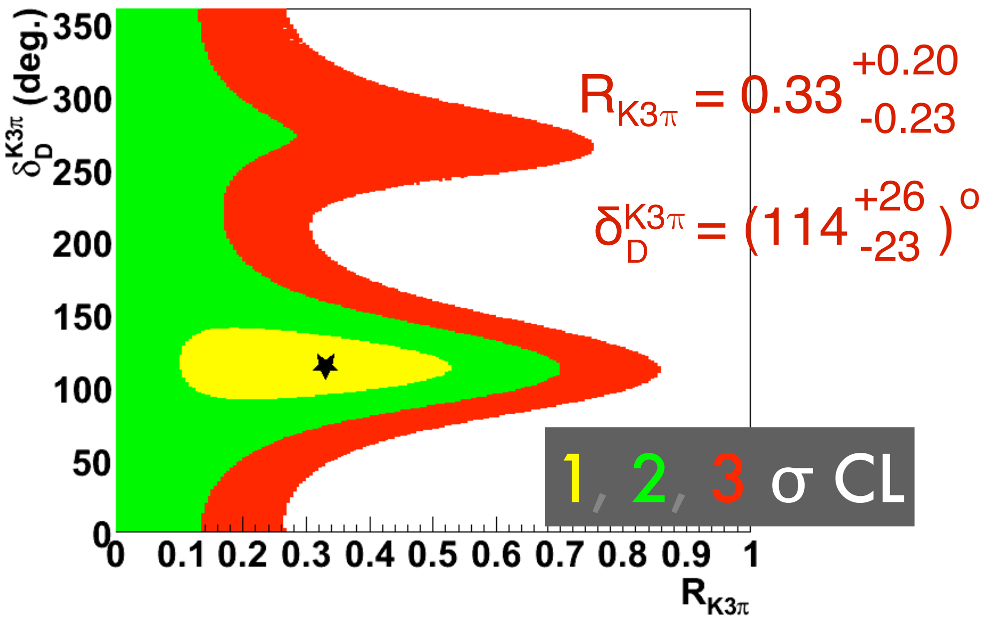

$$\Gamma\left(B^- \to \left(K^+3\pi\right)_D K^-\right) \propto r_B^2 + \left(r_D^{K3\pi}\right)^2 + 2R_{K3\pi} r_B r_D^{K3\pi} \cdot \cos\left(\delta_B + \delta_D^{K3\pi} - \gamma\right)$$

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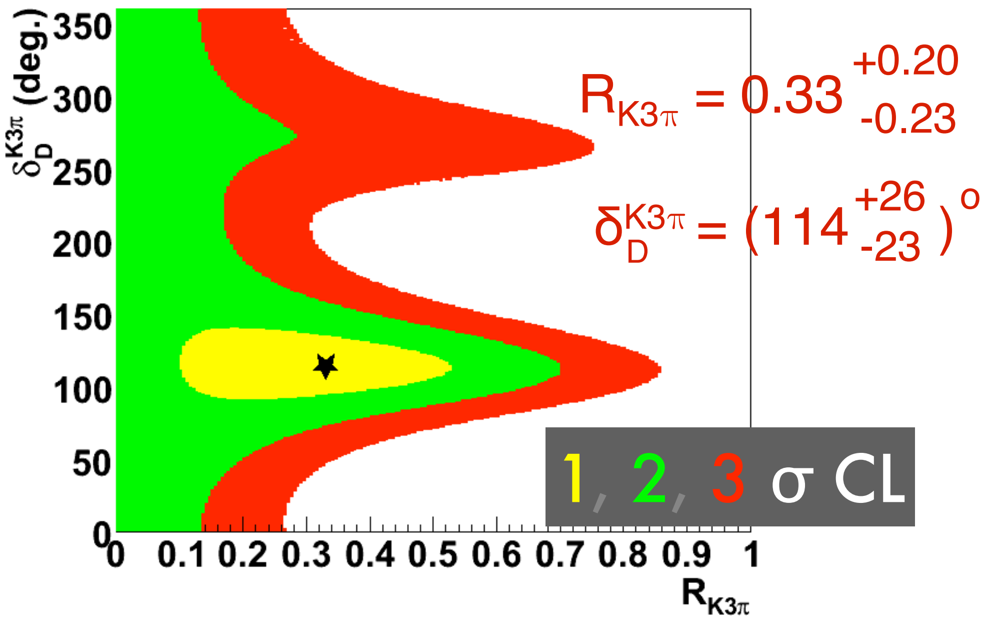

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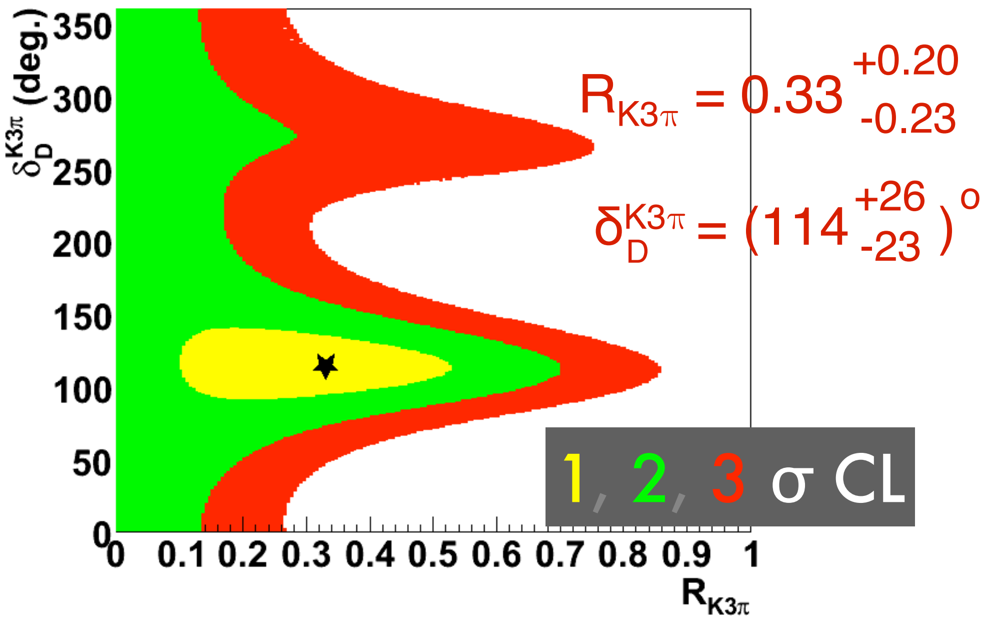

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badly known

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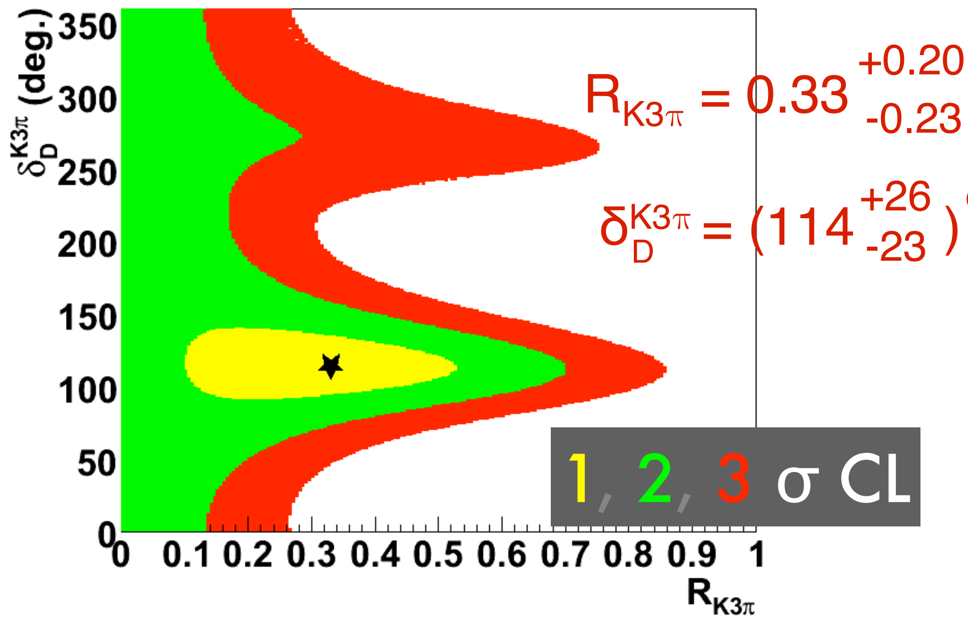

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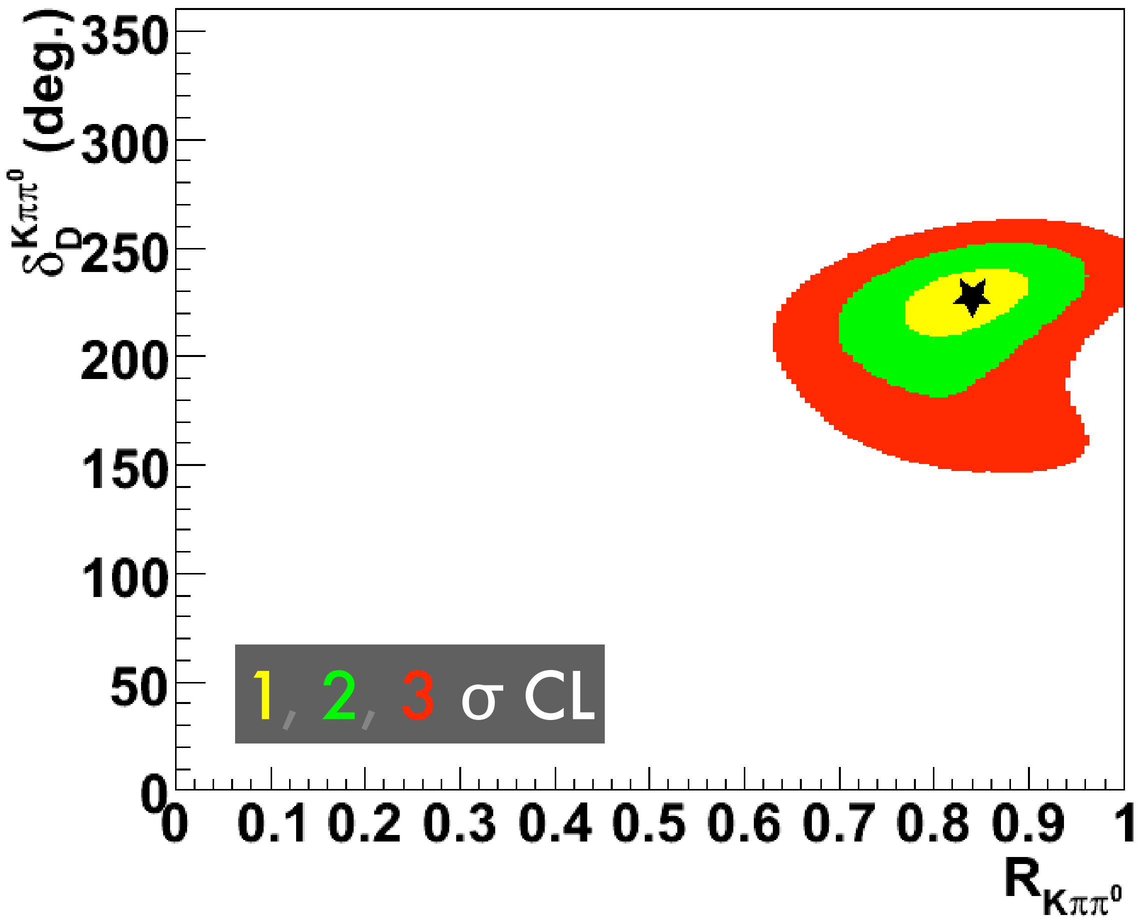
badly known

- At LHCb, using $B^\pm \to D(hh)K^\pm$, $B^\pm \to D(K\pi\pi\pi)K^\pm$, for 2/fb (average year): This input improves σ(γ) from 9.5° to 7.9°.

(typical values used - exact size of improvement depends on input parameters and can be larger).

Kππ° Coherence Factor



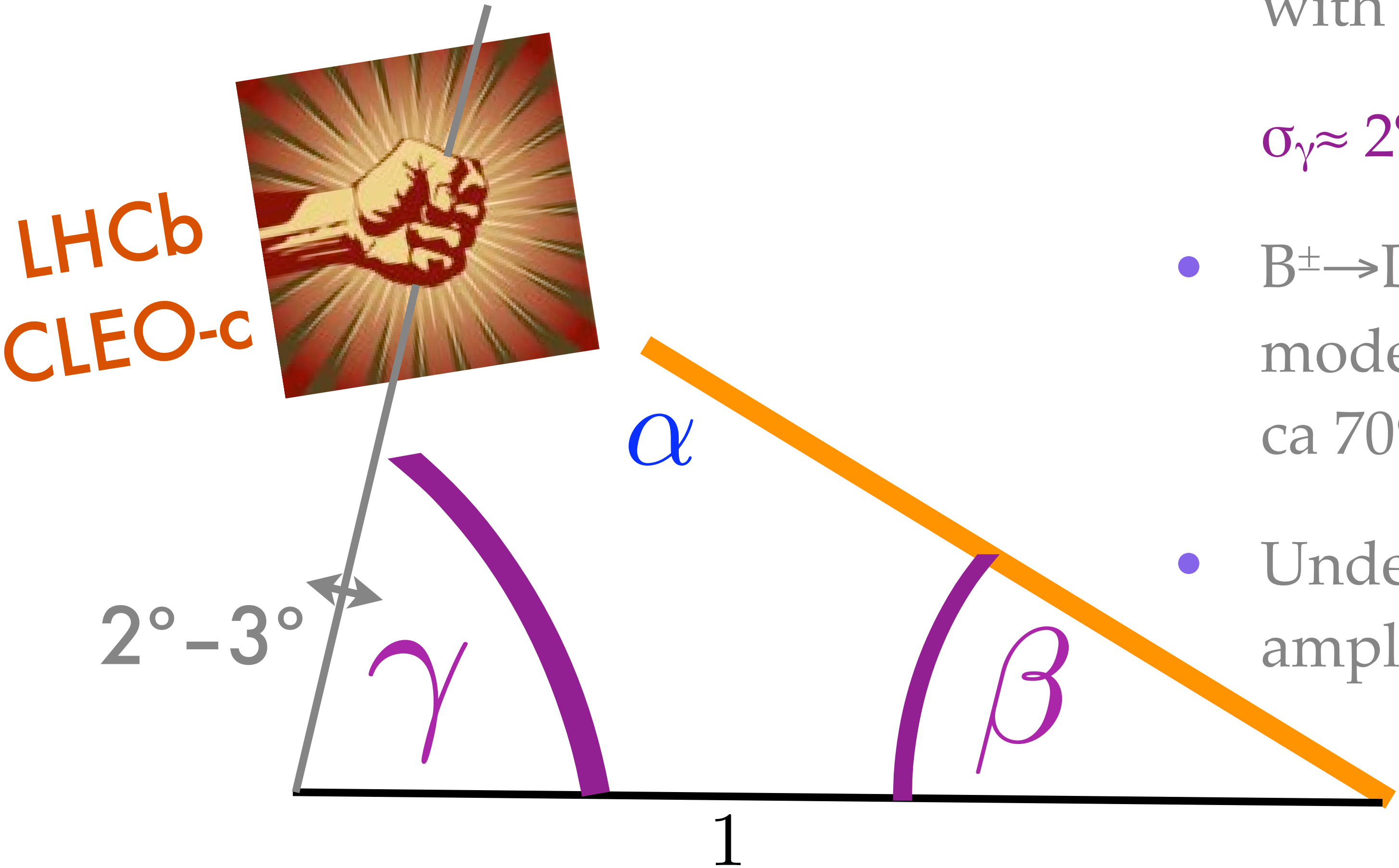
$R_{K\pi\pi^0} = 0.84 \pm 0.07$

$\delta^{K\pi\pi^0} = (227^{+14}_{-17})^{o}$

Very coherent!

Expect significant further improvement (not evaluated at LHCb, yet)

CLEO-c & γ



- Combining tree-level γ modes, LHCb expects with 10/fb (5 years):

  $\sigma_\gamma \approx 2^o – 3^o$

- $B^\pm \to DK^\pm$ and $B^o \to DK^{*o}$ modes have a weight of ca 70% in that result.
- Understanding D amplitudes crucial!

CLEO-c & γ

See also Sean Brisbane's excellent poster

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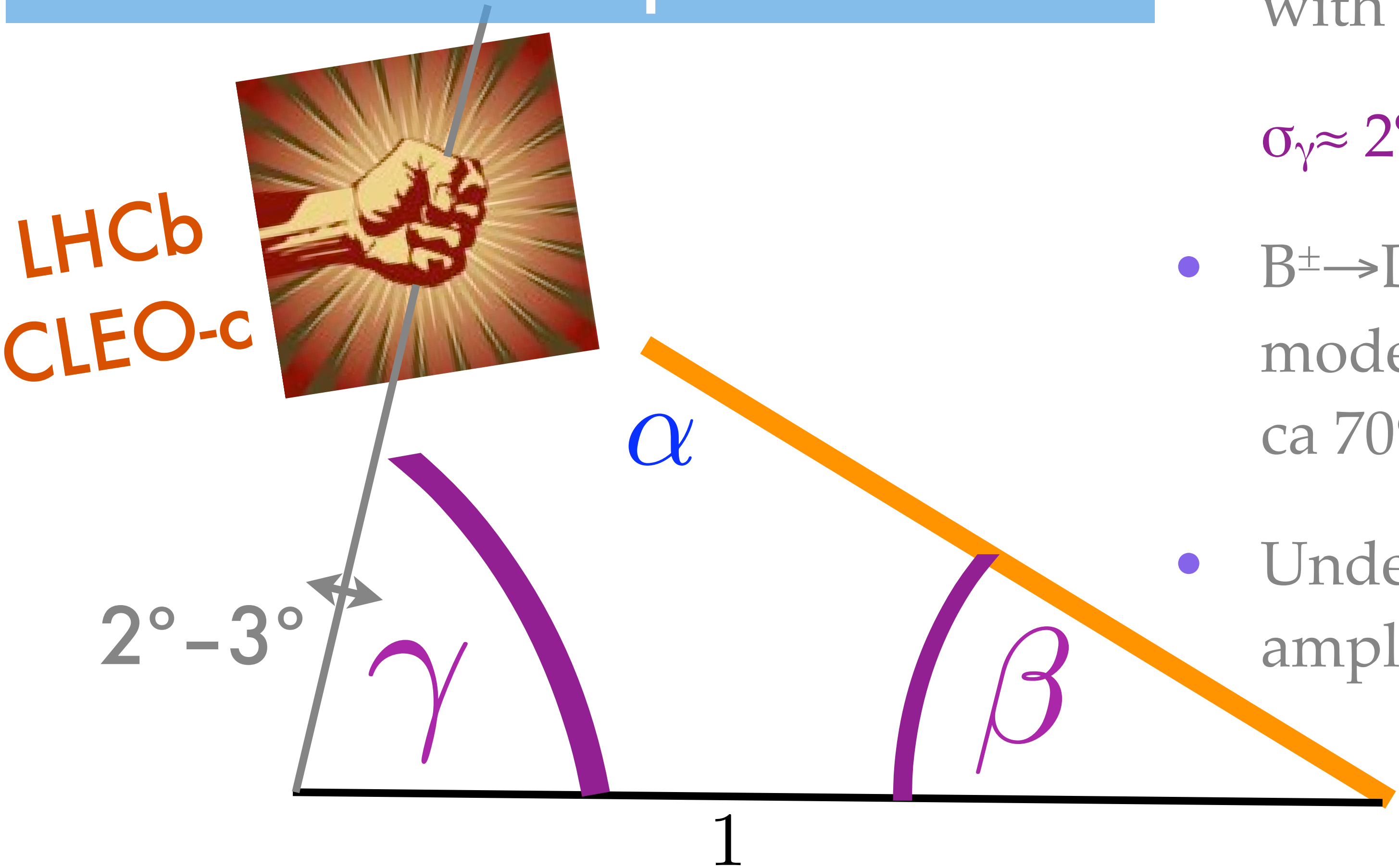


Summary & Outlook

- Huge statistics, very clean data samples and renewed interest in charm $\Rightarrow$ lots of new, important results, only a few shown here.
- Comprehensive set of charm BF's, several new modes • First Meson→2baryon decay • U-spin test in $D^o \to K^o \pi^o$. • A lot of new D_S results • Dalitz analyses to study light resonances: nature and composition of S-wave remains intriguing.
- Quantum-correlated charm provides crucial input to γ from $B^{\pm} \to DK^{\pm}$ and $B^o \to DK^{*o}$ • Dalitz analyses essential • Other powerful techniques benefit from quantum-correlated input, too
- Updates with more data and additional channels from CLEO-c, soon • BESIII will be able to extend these measurements with significantly increased statistics, once starting to run at $\psi(3770)$.

Backup

CLEO-c $D^0 \to K_S \pi\pi$

Format: result ± σ(stat) ± σ(sys) ± σ($K_S \leftrightarrow K_L$ residual model dependence)

bin i	c_i	s_i
0	$0.743 \pm 0.037 \pm 0.022 \pm 0.013$	$0.014 \pm 0.160 \pm 0.077 \pm 0.045$
1	$0.611 \pm 0.071 \pm 0.037 \pm 0.009$	$0.014 \pm 0.215 \pm 0.055 \pm 0.017$
2	$0.059 \pm 0.063 \pm 0.031 \pm 0.057$	$0.609 \pm 0.190 \pm 0.076 \pm 0.037$
3	$-0.495 \pm 0.101 \pm 0.052 \pm 0.045$	$0.151 \pm 0.217 \pm 0.069 \pm 0.048$
4	$-0.911 \pm 0.049 \pm 0.032 \pm 0.021$	$-0.050 \pm 0.183 \pm 0.045 \pm 0.036$
5	$-0.736 \pm 0.066 \pm 0.030 \pm 0.018$	$-0.340 \pm 0.187 \pm 0.052 \pm 0.047$
6	$0.157 \pm 0.074 \pm 0.042 \pm 0.051$	$-0.827 \pm 0.185 \pm 0.060 \pm 0.036$
7	$0.403 \pm 0.046 \pm 0.021 \pm 0.002$	$-0.409 \pm 0.158 \pm 0.050 \pm 0.002$

Dalitz Plot

R.H. Dalitz, Philos. Mag. 44, 1068 (1953)

Tags

Reconstructed, beam-constrained D mass in CLEO-c tag-side data

(2 example plots, before requiring $K_S\pi\pi$ on other side)

Flavour (semi-leptonic) (14k tagged $K_S\pi\pi$ evts, B/(S+B)=0.6%)

$K^-e^+\nu$

Flavour (hadronic) 4.4k tagged $K_S\pi\pi$ evts, B/(S+B)=3%

$K^-\pi^+$

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

$K^-\pi^+\pi^+$

CP-even, 470 tagged $K_S\pi\pi$ evts, B/(S+B)=6%

$\pi^+\pi^-$

K^+K^-

$K^0_S\pi^0\pi^0$

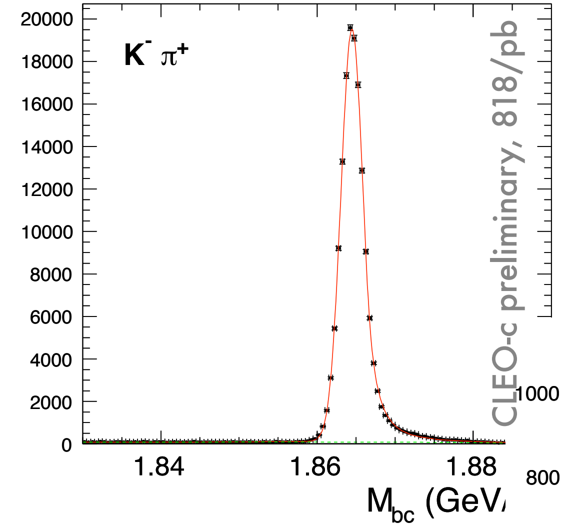
$K^0_L\pi^0$

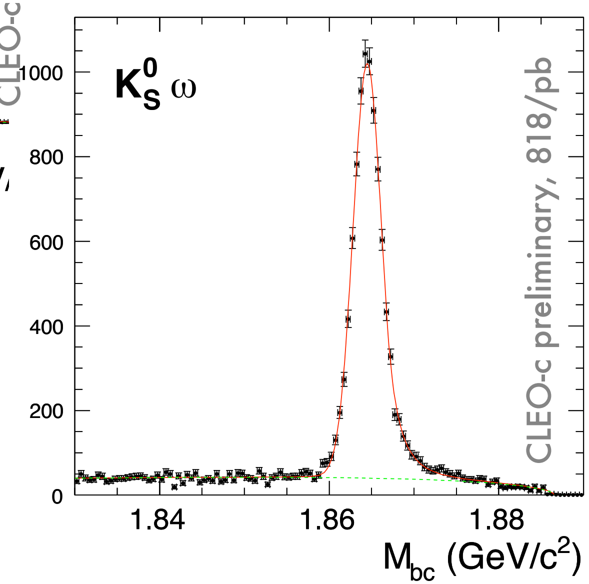
CP-odd, 310 tagged $K_S\pi\pi$ evts, B/(S+B)=4%

$K^0_S\pi^0$

$K^0_S\eta$

$K^0_S\omega$



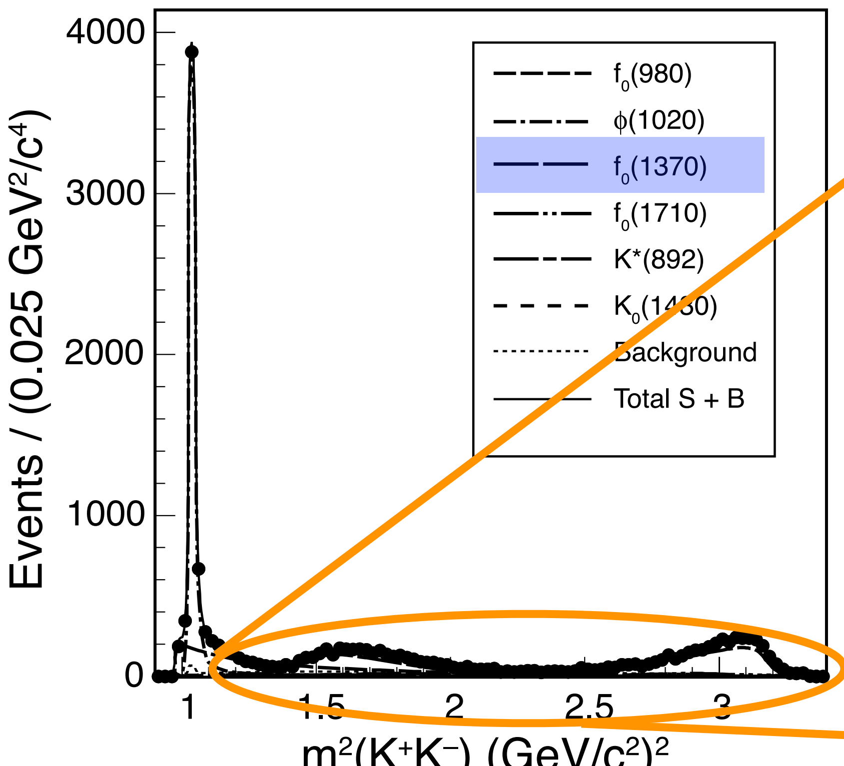


$D_s^+ \to K^- K^+ \pi^+$

Parameter	E687 Model	$f_2(1270)$	$a_2(1320)$	$f_0(1370)$	$f_0(1500)$	$f_2(1525)$	$a_0(1450)$	$\phi(1680)$
$m_{K^*(892)}$	895.8±0.5	–0.4	–0.1	–0.9	–0.5	0.0	–0.8	0.1
$\Gamma_{K^*(892)}$	44.2±1.0	2.3	2.4	1.5	0.6	0.6	1.0	1.2
$a_{K_0^*(1430)}$ (a.u.)	1.76±0.12	0.11	0.08	–0.25	–0.03	–0.16	–0.22	–0.18
$\phi_{K_0^*(1430)}$ (°)	145±8	–32	–28	1.0	–15	1.7	–15	18
$a_{f_0(980)}$ (a.u.)	3.67±0.13	0.29	0.26	1.05	0.52	0.03	1.09	0.20
$\phi_{f_0(980)}$ (°)	156±3	–2	–1.6	1.3	2.3	0.22	3.8	10.5
$a_{\phi(1020)}$ (a.u.)	1.15±0.02	–0.03	–0.04	–0.02	–0.003	–0.02	–0.007	–0.012
$\phi_{\phi(1020)}$ (°)	–15±4	–7	–6.3	7.2	–0.6	1.5	4.3	13.2
$a_{f_0(1710)}$ (a.u.)	1.27±0.07	0.08	0.07	–0.16	0.17	–0.04	0.03	–0.018
$\phi_{f_0(1710)}$ (°)	102±4	7	4.7	–13	–4.1	–3.8	–17	5.3
a_{add} (a.u.)		0.64±0.09	0.45±0.06	1.15±0.09	0.50±0.05	0.50±0.07	1.32±0.10	1.04±0.17
ϕ_{add} (°)		17±9	40±8	53±5	132±7	173±10	103±5	–4±11
χ^2/ν	278/119	237/117	237/117	178/117	229/117	249/117	192/117	256/117

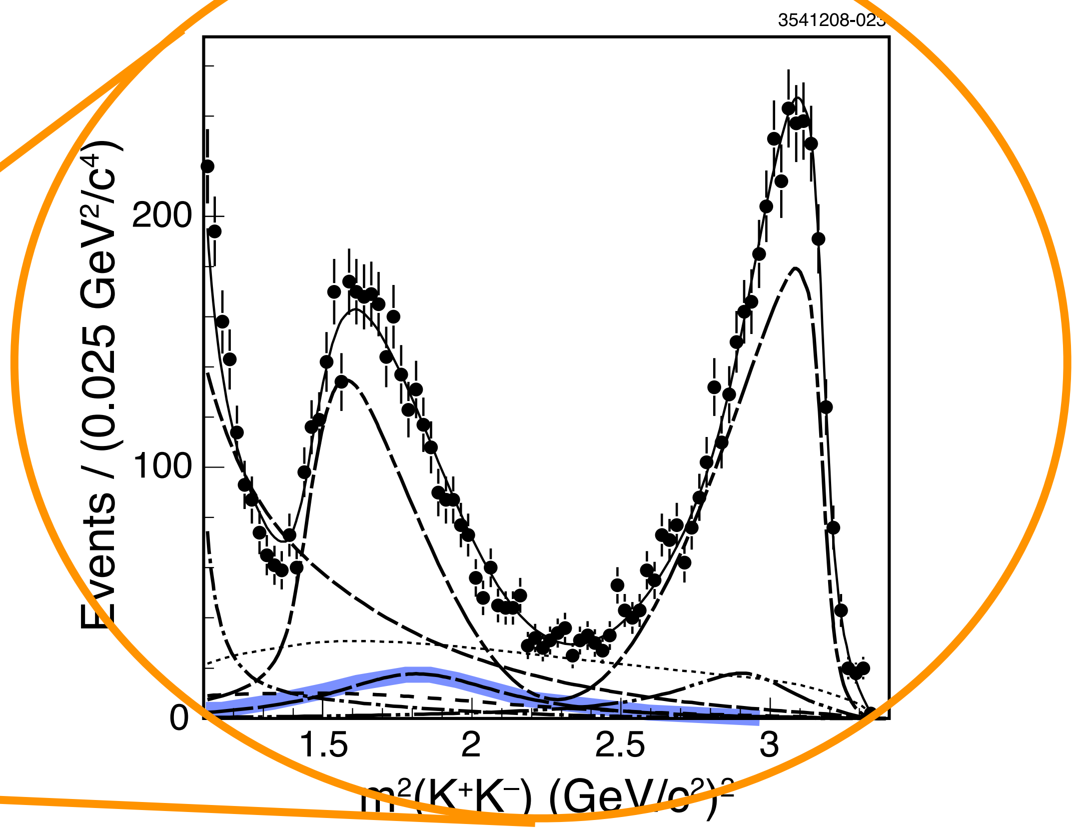
$D_s^+ \to K^-K^+\pi^+$

$M^2(KK)$ fit projection with $f_0(1370)$ S-wave contribution



$D_s^+ \to K^-K^+\pi^+$ $M^2(KK)$ projections

CLEO: arXiv:0903.1301v1 [hep-ex] (March 2009)



[1] P.L. Frabetti et al. (E687 Collaboration), Phys. Lett., B351, 591 (1995)
See also FOCUS: A.M. Rahimi, FERMILAB-THESIS-2000-13 and S. Malvezzi, AIP Conf. Proc. 549, 569 (2002)

Model independent γ fit

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

- Binned decay rate:

$\mathcal{T}_i$ known from flavour-specifc D decays (e.g. D*)

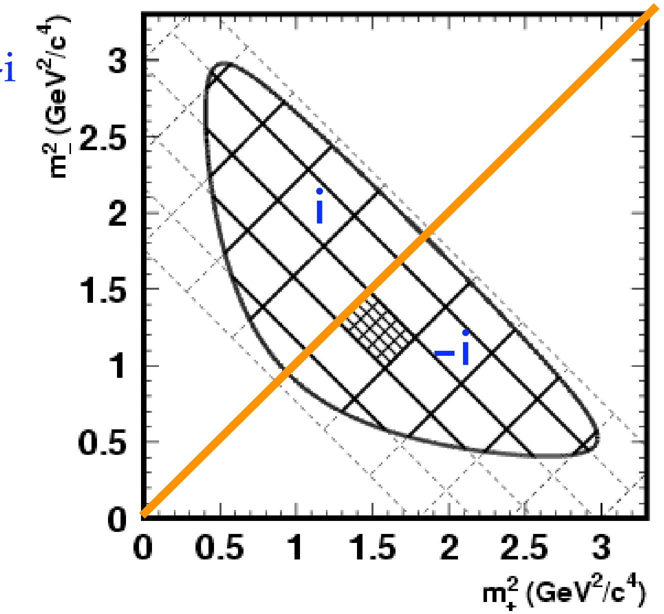
$$\Gamma\left(B^{\pm} \rightarrow D(K_s\pi^+\pi^-)K^{\pm}\right)_i =$$

$\delta_D \equiv$ phase of $A(D \rightarrow K_S\pi\pi)$

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

(weighted) average of $\cos(\delta_D(s_{12},s_{23})-\delta_D(s_{23},s_{12}))$ and $\sin(\delta_D(s_{12},s_{23})-\delta_D(s_{23},s_{12}))$ over bin i

- Binning such that such that $c_i = c_{-i}$, $s_i = -s_{-i}$
- Distribution sensitive to c_i, s_i, r_B, δ and γ.
- To extract γ from realistic numbers of B events need external input from CLEO's quantum-correlated DDbar pairs.



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(weighted) average of $\cos(\delta_D(s_{12},s_{23})-\delta_D(s_{23},s_{12}))$ and $\sin(\delta_D(s_{12},s_{23})-\delta_D(s_{23},s_{12}))$ over bin i

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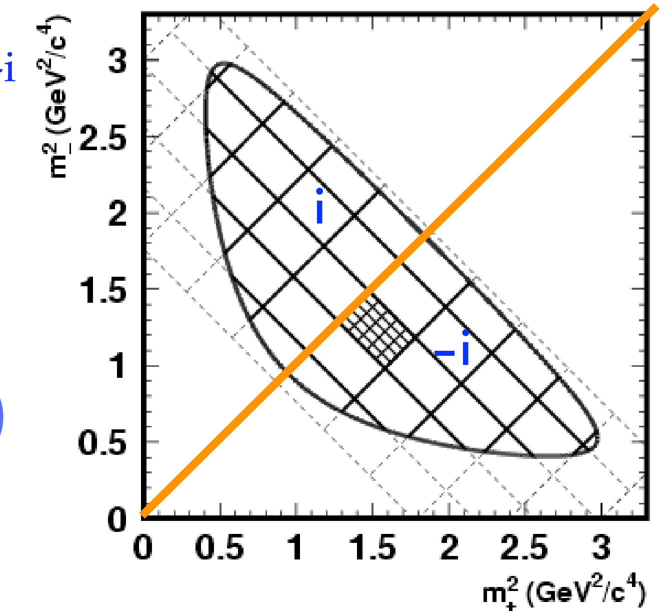
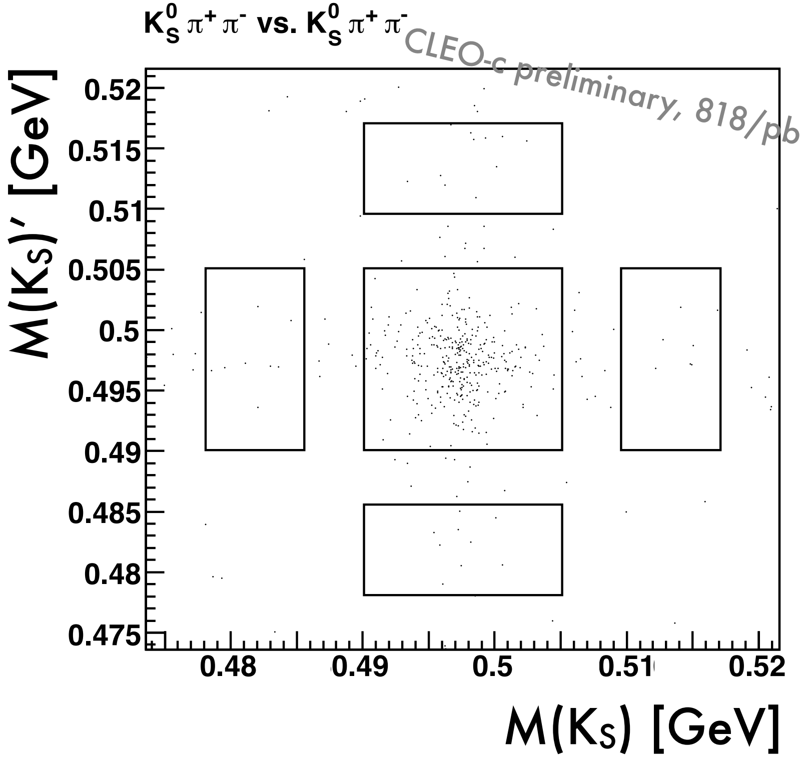
- Distribution sensitive to c_i, s_i, r_B, δ and γ.
- To extract γ from realistic numbers of B events need external input from CLEO's quantum-correlated DDbar pairs.



s_i, c_i from $K_S\pi\pi$ vs $K_S\pi\pi$

- CP-tagged binned Dalitz Plots sensitive to c_i only.
- Simultaneous, binned analysis of quantum-correlated $D_a \to K_S\pi\pi$, $D_b \to K_S\pi\pi$ pairs gives access to both c_i and s_i:



- 420 fully reconstructed events, S/(B+S) =90%
- 50 partially reconstructed events (ignore one π in reconstruction), S/(B+S)=85%

CP-even $K_L\pi\pi \approx$ CP-odd $K_S\pi\pi$

unfortunately only "≈", not quite "="

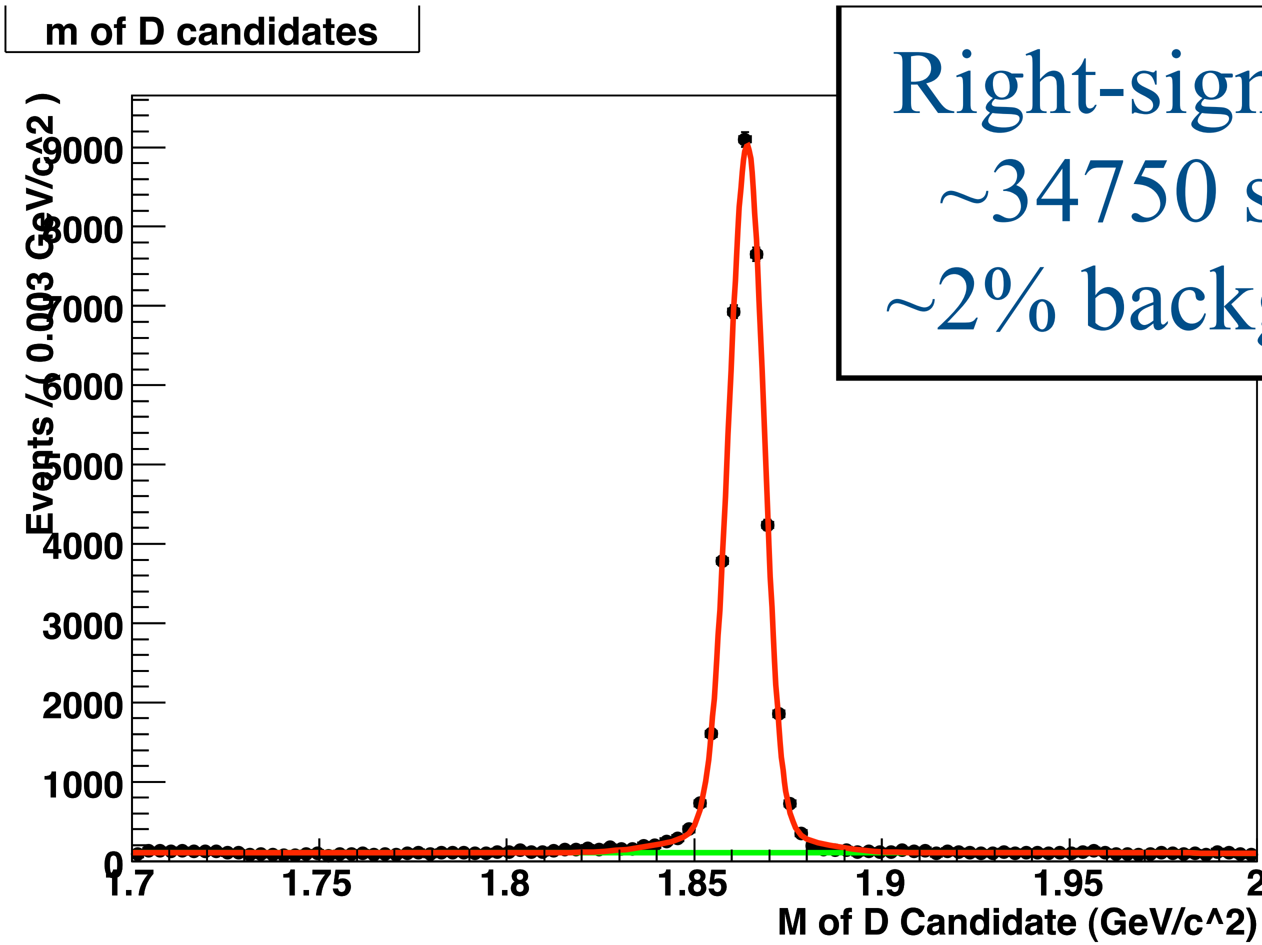
$$K_S^0 = (K^0 + \bar{K}^0)/\sqrt{2}$$
$$K_L^0 = (K^0 - \bar{K}^0)/\sqrt{2}.$$

$$-A\left(D^0 \to K_L^0\pi^+\pi^-\right) = \underbrace{A\left(D^0 \to K_S^0\pi^+\pi^-\right)}_{\text{CF+DCS}} \underbrace{-\sqrt{2}A\left(D^0 \to K^0_{\text{flavour}}\pi^+\pi^-\right)}_{\text{DCS}}$$

- Using $K_L\pi\pi$ significantly enhances statistics.
- However, need a correction of $\mathcal{O}(\tan^2\theta_C)$. Residual model dependence enters as an uncertainty on a small correction. Detailed systematics study shows effect is small.
- Notation: c_i, s_i from $K_S\pi\pi$. c_i', s_i' from $K_L\pi\pi$.

$\Delta c_i \equiv c_i - c_i'$, $\Delta s_i \equiv s_i - s_i'$

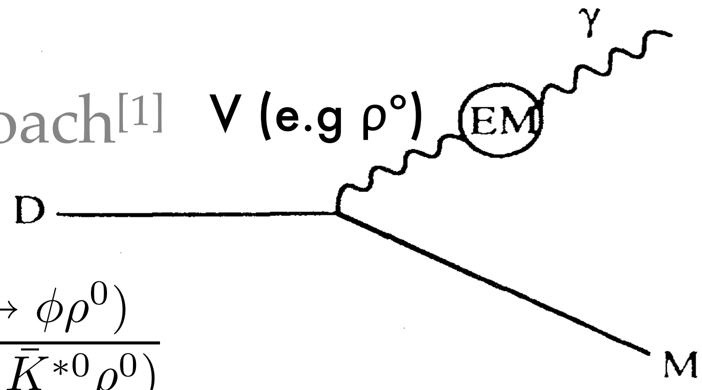
D→K3π events at CLEO



Right-sign Kπππ
~34750 signal
~2% background

VMD, D°→Vγ and D°→Vρ°

- Dominated by long-distance effects. Difficult to calculate.
- Vector-Meson-Dominance approach[1]



- Predicts

$$\frac{\mathcal{B}(D^0 \to \phi\gamma)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma)} = \frac{\mathcal{B}(D^0 \to \phi\rho^0)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\rho^0)}$$

- Find

$$\frac{\mathcal{B}(D^0 \to \phi\gamma)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma)} = (6.27 \pm 0.71 \pm 0.79) \times 10^{-2}$$ BaBar 08

$$\frac{\mathcal{B}(D^0 \to \phi\rho^0)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\rho^0)} = (6.7 \pm 1.6) \times 10^{-2}$$ PDG 07

[1] G. Burdman, E. Golowich, J. L. Hewett, and S. Pakvasa, Phys. Rev. , 6383 (1995)

Direct CP Violation

- Main focus there: time-dependent studies
- But direct CPV in time-integrated

$$A_{CP} = \frac{\Gamma(\mathrm{D} \to \mathrm{f}) - \Gamma\left(\bar{\mathrm{D}} \to \bar{\mathrm{f}}\right)}{\Gamma(\mathrm{D} \to \mathrm{f}) + \Gamma\left(\bar{\mathrm{D}} \to \bar{\mathrm{f}}\right)}$$

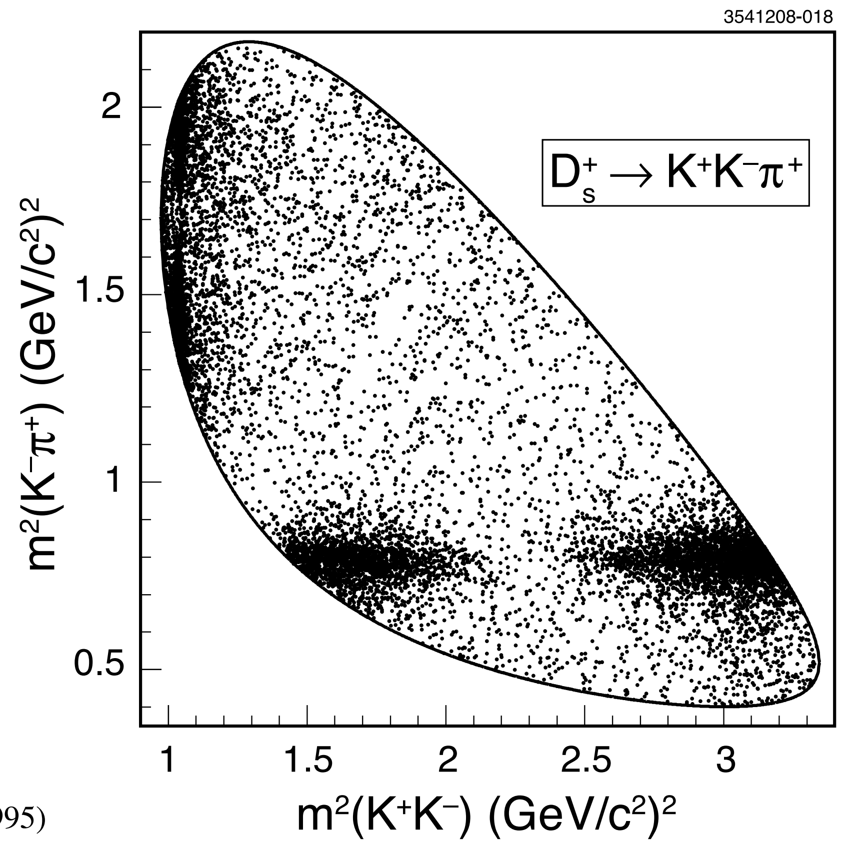
decays also interesting!

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

- Follows CLEO-c's $D_s^+ \to K^-K^+\pi^+$ absolute B.R. measurement.
- Isobar fit.
- Previously done at E687 with 701 events.

12k $D_s^+ \to K^-K^+\pi^+$ events at CLEO-c

CLEO: arXiv:0903.1301v1 [hep-ex] (March 2009)



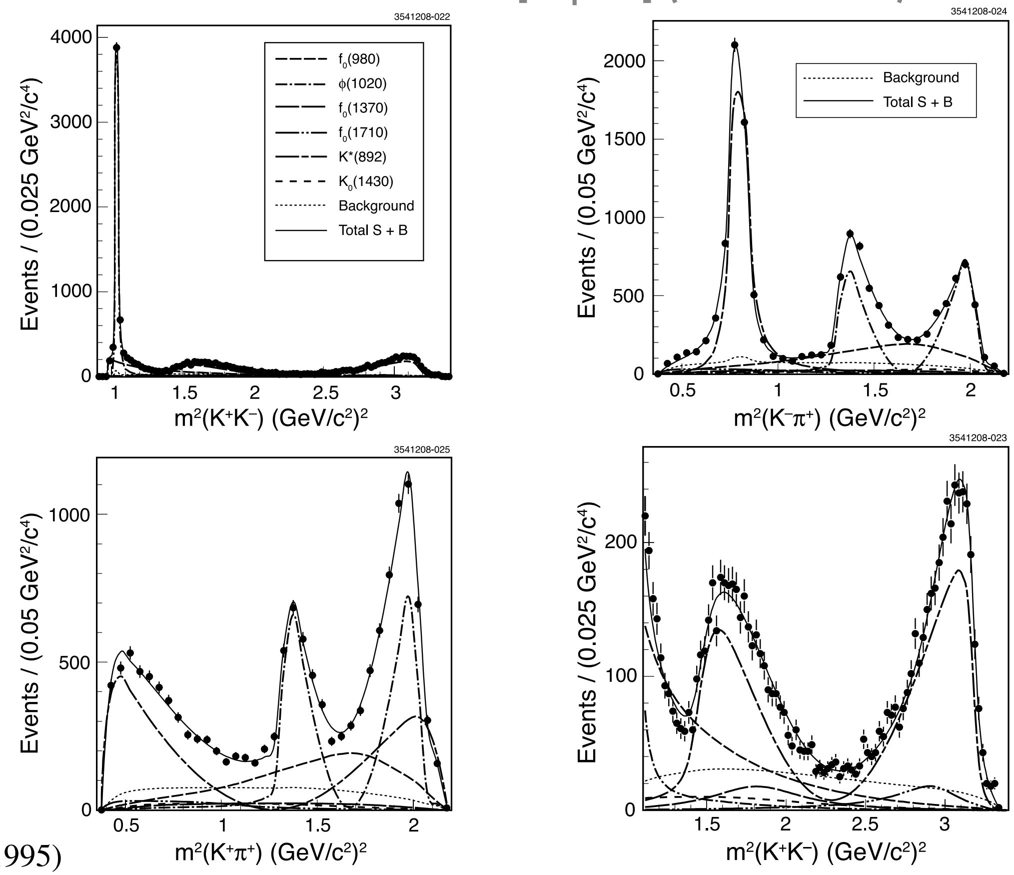
Previous measuemrents:
E687: P.L. Frabetti et al. (E687 Collaboration), Phys. Lett., B351, 591 (1995)
FOCUS: A.M. Rahimi, FERMILAB-THESIS-2000-13, S. Malvezzi, AIP Conf. Proc. 549, 569 (2002)

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

- Find good agreement with E687 model parameters.
- Get much-improved fit to our data with additional KK S-wave contribution.
- Tried many options. Best results with $f_0(1370)$

12k $D_s^+ \to K^- K^+ \pi^+$ fit projections

CLEO: arXiv:0903.1301v1 [hep-ex] (March 2009)



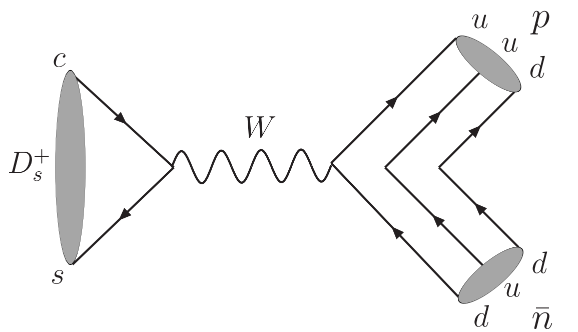
[1] P.L. Frabetti et al. (E687 Collaboration), Phys. Lett., B351, 591 (1995)
[2] [4]A.M. Rahimi, FERMILAB-THESIS-2000-13
[3] S. Malvezzi, AIP Conf. Proc. 549, 569 (2002)

Binned Dalitz Result

Format: bin, result ± σ_{stat} ±σ_{sys} ±$\sigma_{(KL \leftrightarrow KS)}$

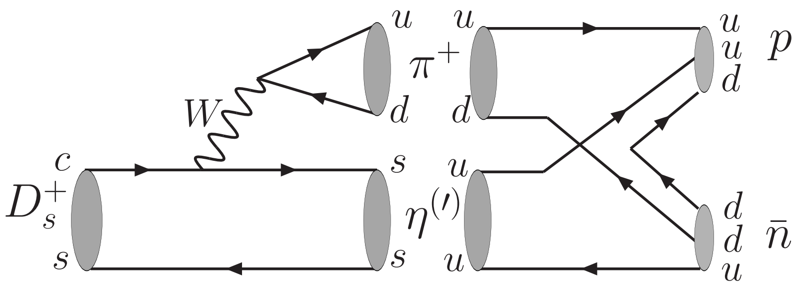
i	c_i	s_i
0	$0.743 \pm 0.037 \pm 0.022 \pm 0.013$	$0.014 \pm 0.160 \pm 0.077 \pm 0.045$
1	$0.611 \pm 0.071 \pm 0.037 \pm 0.009$	$0.014 \pm 0.215 \pm 0.055 \pm 0.017$
2	$0.059 \pm 0.063 \pm 0.031 \pm 0.057$	$0.609 \pm 0.190 \pm 0.076 \pm 0.037$
3	$-0.495 \pm 0.101 \pm 0.052 \pm 0.045$	$0.151 \pm 0.217 \pm 0.069 \pm 0.048$
4	$-0.911 \pm 0.049 \pm 0.032 \pm 0.021$	$-0.050 \pm 0.183 \pm 0.045 \pm 0.036$
5	$-0.736 \pm 0.066 \pm 0.030 \pm 0.018$	$-0.340 \pm 0.187 \pm 0.052 \pm 0.047$
6	$0.157 \pm 0.074 \pm 0.042 \pm 0.051$	$-0.827 \pm 0.185 \pm 0.060 \pm 0.036$
7	$0.403 \pm 0.046 \pm 0.021 \pm 0.002$	$-0.409 \pm 0.158 \pm 0.050 \pm 0.002$

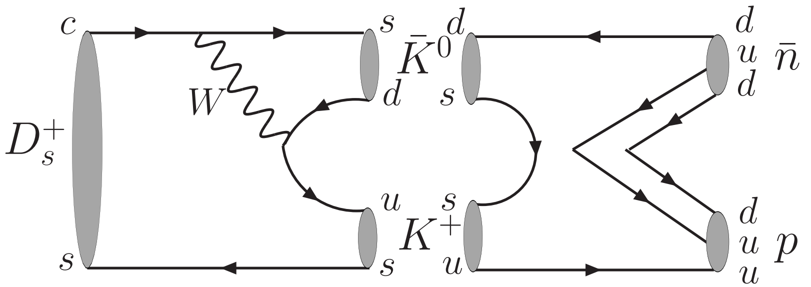
Theory of $D_s^+ \to p\bar{n}$



- Short Distance:

$$\mathcal{B}(D_s^+ \to p\bar{n})_{\rm SD} = (0.4^{+1.1}_{-0.3}) \times 10^{-6}$$





- Long Distance $\mathcal{B}(D_s^+ \to p\bar{n}) \approx \left(0.8^{+2.4}_{-0.6}\right) \times 10^{-3}$
- Measured $\mathcal{B}(D_s^+ \to p\bar{n}) = (1.30 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$

Chen, Cheng, Hsiao: Phys.Lett.B663:326-329,2008

Absolute BF

- Important normalising modes: $D^0 \to K^- \pi^+$

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

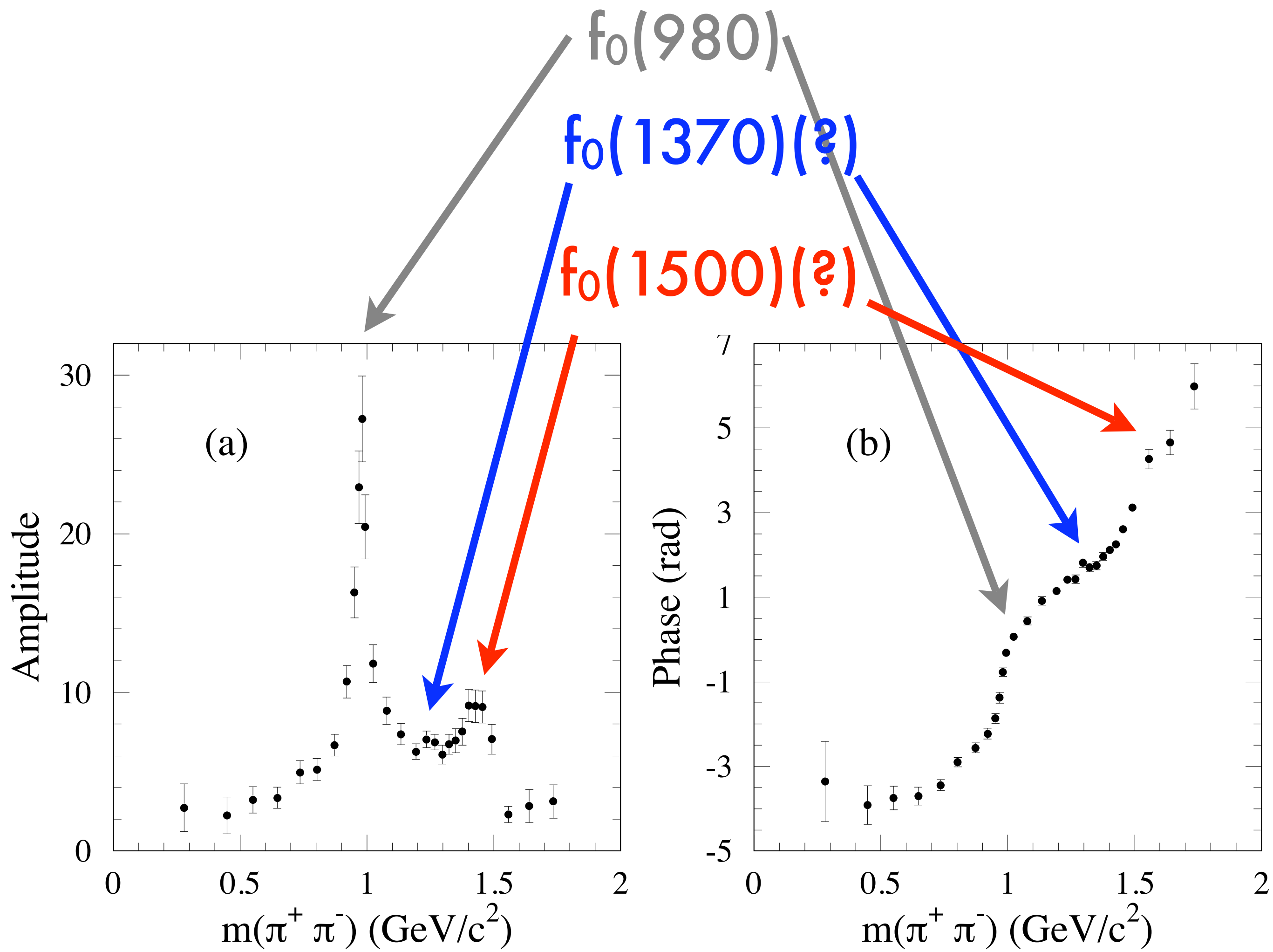
  $D_s^+ \to K^- K^+ \pi^+$

  (historically "$\phi\pi^+$")

- Methods - need to know there is a D before reconstructing it
  - BaBar: partial reconstruction of $D^* \to D\pi$, using only the π (and the rest of the event, but not the D)
  - BELLE: $e^+e^- \to D_s^{*+} D_{s1}^- (\to \overline{D}^{*0} K^-)$
  - CLEO-c: $e^+e^- \to \psi \to \overline{D}\, D$

$D_s^+ \to \pi^-\pi^+\pi^+$

Model independent S-wave parameterisation



BaBar: arXiv:0808.0971v3 [hep-ex], submitted to PRD

$D_S^+ \to \pi^- \pi^+ \pi^+$

- $D_S^+ \to (\pi^+\pi^-)_{S\text{-wave}} \pi^+$ dominates.
- Model-independent S-wave fit compatible with $f_0(980)$ resonance.
- Also with FOCUS's K-matrix and E791's isobar fit
- Signs of something going on near $f_0(1370)$, $f_0(1500)$.
- Large D-wave component with $f_2(1270)$

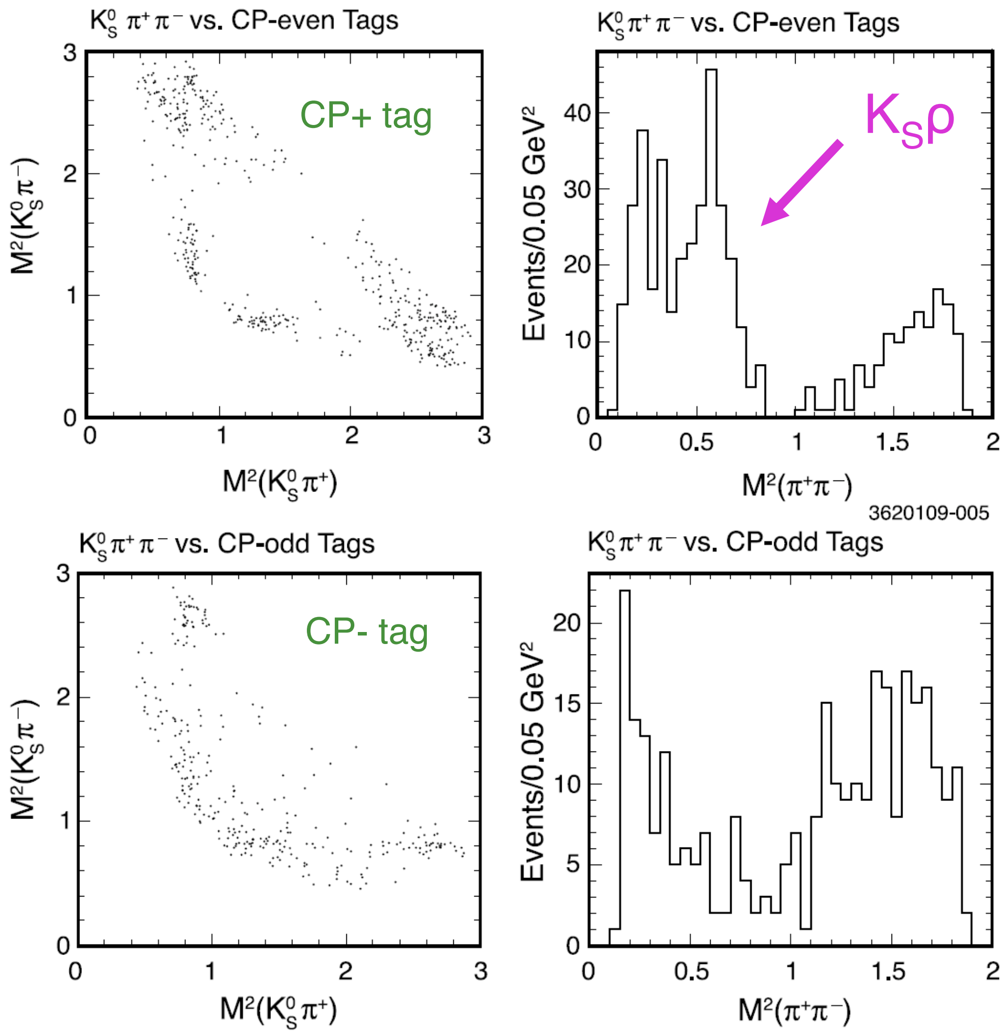
Fit Fractions

Decay Mode	Decay fraction(%)
$f_2(1270)\pi^+$	$10.1 \pm 1.5 \pm 1.1$
$\rho(770)\pi^+$	$1.8 \pm 0.5 \pm 1.0$
$\rho(1450)\pi^+$	$2.3 \pm 0.8 \pm 1.7$
$\mathcal{S}$-wave	$83.0 \pm 0.9 \pm 1.9$
Total	$97.2 \pm 3.7 \pm 3.8$
χ^2/NDF	$\frac{437}{422-64} = 1.2$

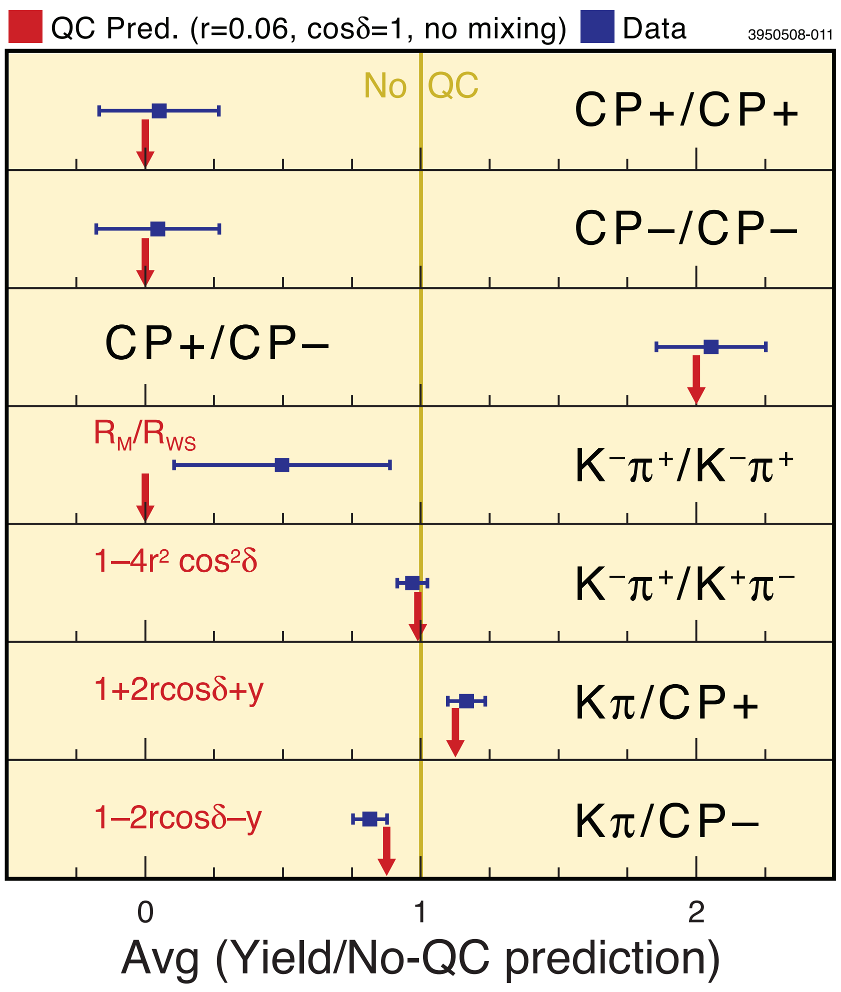
BaBar: arXiv:0808.0971v3 [hep-ex], submitted to PRD

CP+ and CP− D°→$K_S\pi\pi$ at CLEO-c

CLEO-c arXiv:0903.1681v1 [hep-ex], submitted to PRD



Exploiting Quantum Correlations at CLEO-c



PRL 100, 221801 (2008), PRD 78, 012001 (2008)

- CP-tagged rates

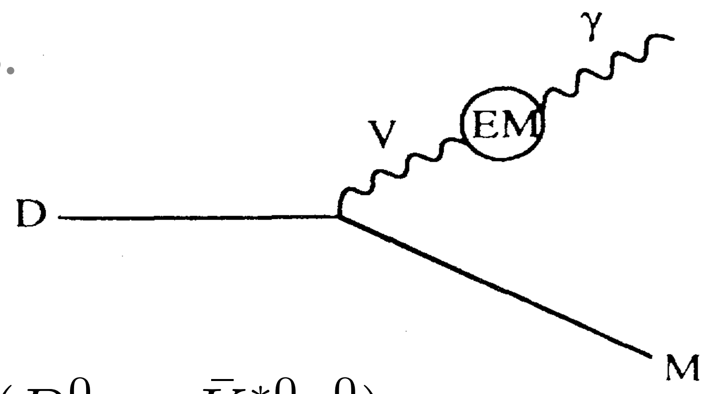
  $\propto (1 \pm 2\, r_D^{K\pi} \cos \delta_D^{K\pi} \pm y)$

- Combined analysis in many modes sensitive to $\delta_D^{K\pi}$ w/o ambiguity.
- Crucial input to charm mixing measurements, as well as helping measure γ
- Result: $\delta_D^{K\pi} = 22^{o}{}^{+11^o}_{-12^o}{}^{+9^o}_{-11^o}$

Analysis based on 1/3 of data set - update with full 818/fb soon.

VMD, D°→Vγ and D°→Vρ°

- Dominated by long-distance effects.



- Vector meson dominance (VMD): $A(D^o \to M\gamma) \approx (e/f_\rho)\, A(D \to M\rho^o)$ [1]

$$\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma) = \underline{(0.021} \pm 0.005)\, \mathcal{B}(D^0 \to \bar{K}^{*0}\rho^0)$$

$$\mathcal{B}(D^0 \to \phi\gamma) = \underline{(0.020} \pm 0.003)\, \mathcal{B}(D^0 \to \phi\rho^0)$$

- Using $(e/f_\rho) = 0.06$[2], expect:

$$\mathcal{B}(\mathrm{D}^0 \to \mathrm{V}\gamma) \approx \underline{0.0036} \cdot \mathcal{B}(\mathrm{D}^0 \to \mathrm{V}\rho^0)$$

- While proportionality predicted by VMD is seen, measured proportionality factor is a bit large.

[1] G. Burdman, E. Golowich, J. L. Hewett, and S. Pakvasa, Phys. Rev. , 6383 (1995) [2] E. Golowich and S. Pakvasa, Phys. Rev. D 51, 1215 - 1223 (1995)

Branching Fractions

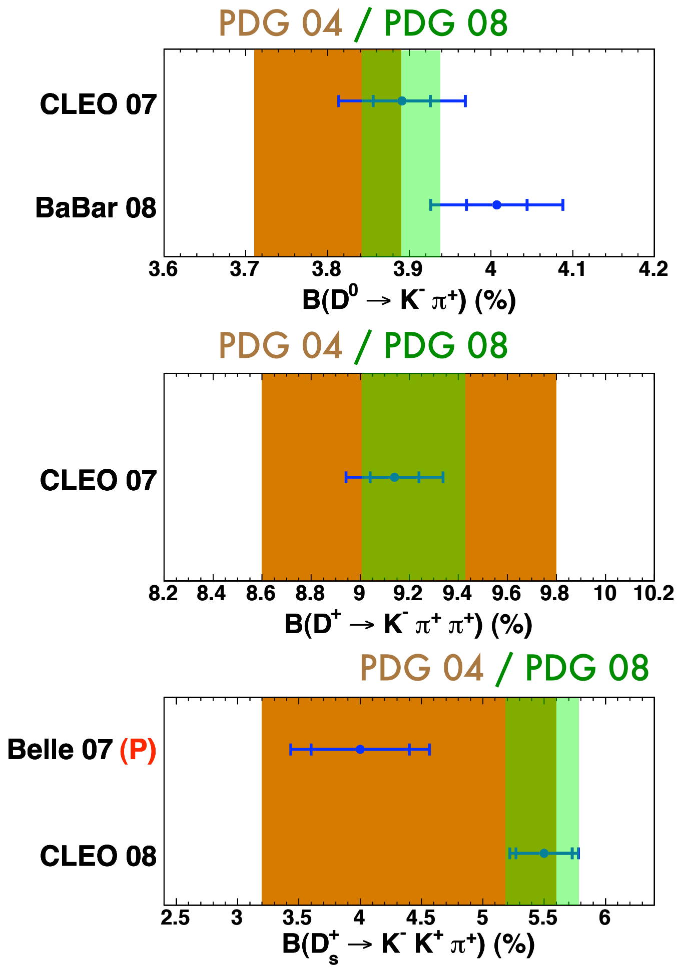
- Absolute BF: Progress in key reference modes.
- Comprehensive set of BF:

  $D_{(S)} \rightarrow PP$ with $P = K^{\pm}, K_S, K_L, \pi^{\pm}, \pi^0, \eta, \eta'$

  $D_{(S)} \rightarrow V\gamma$, $V\eta$, $V\varrho$

  $D_{(S)} \rightarrow$ baryons

- Recent addition: CLEO-c's new Ds*Ds data sample.

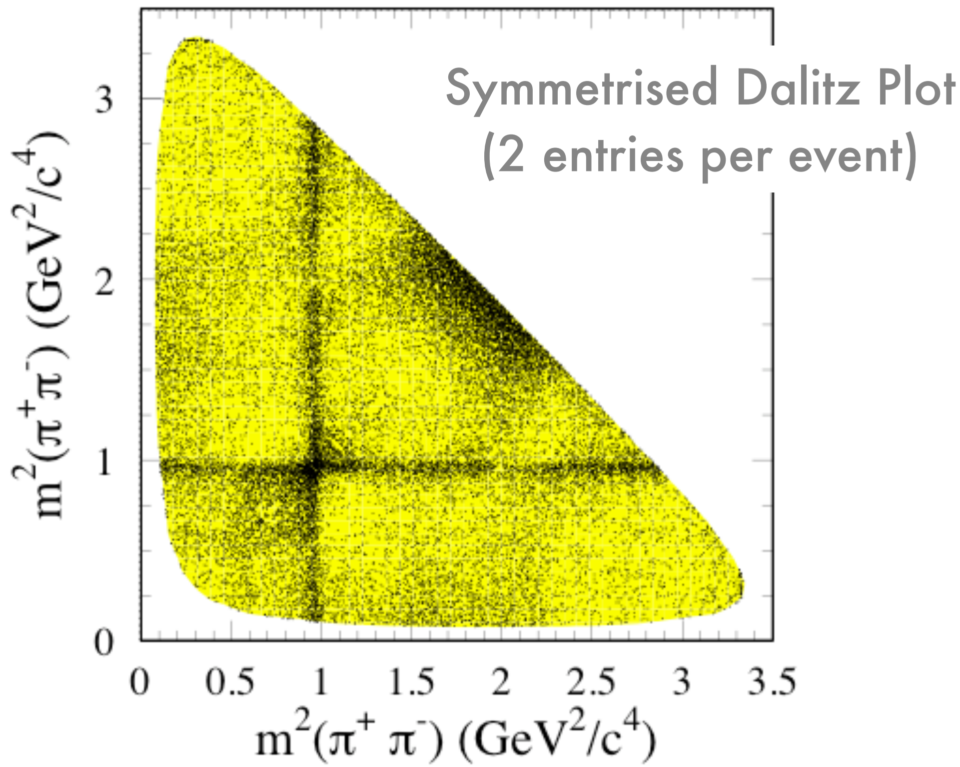


Belle 07: hep-ex/0701053 (Prel.) [552 fb^{-1}]
CLEO 07: PRD 76, 112001 [281 pb^{-1}]
BaBar 08: PRL 100, 051802 [210 fb^{-1}]
CLEO 08: PRL 100, 161804 [298 pb^{-1}]

$D_s^+ \to \pi^-\pi^+\pi^+$

10.5k signal events at BaBar, with 80% signal purity

- Dominated by S-wave (fit-fraction 83%).
- BaBar perform model-independent analysis of S-wave component [1], method pioneered by E791[2].

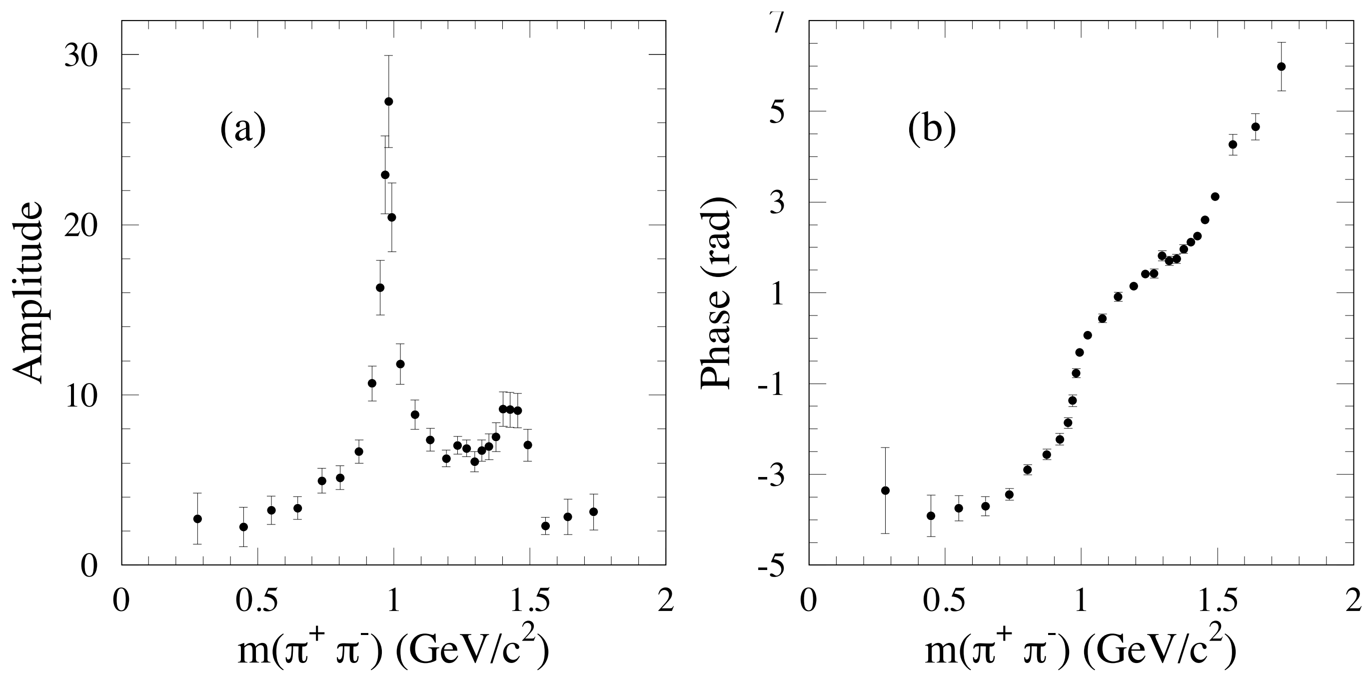


[1] BaBar: arXiv:0808.0971v3 [hep-ex], submitted to PRD
[2] E791: Phys. Rev. D 73, 032004 (2006).

$D_s^+ \to \pi^- \pi^+ \pi^+$

Model independent S-wave parameterisation

- Define 30 points in $m(\pi^+\pi^-)$.
- 2 fit parameters (magnitude & phase) for each point
- Interpolate between points*

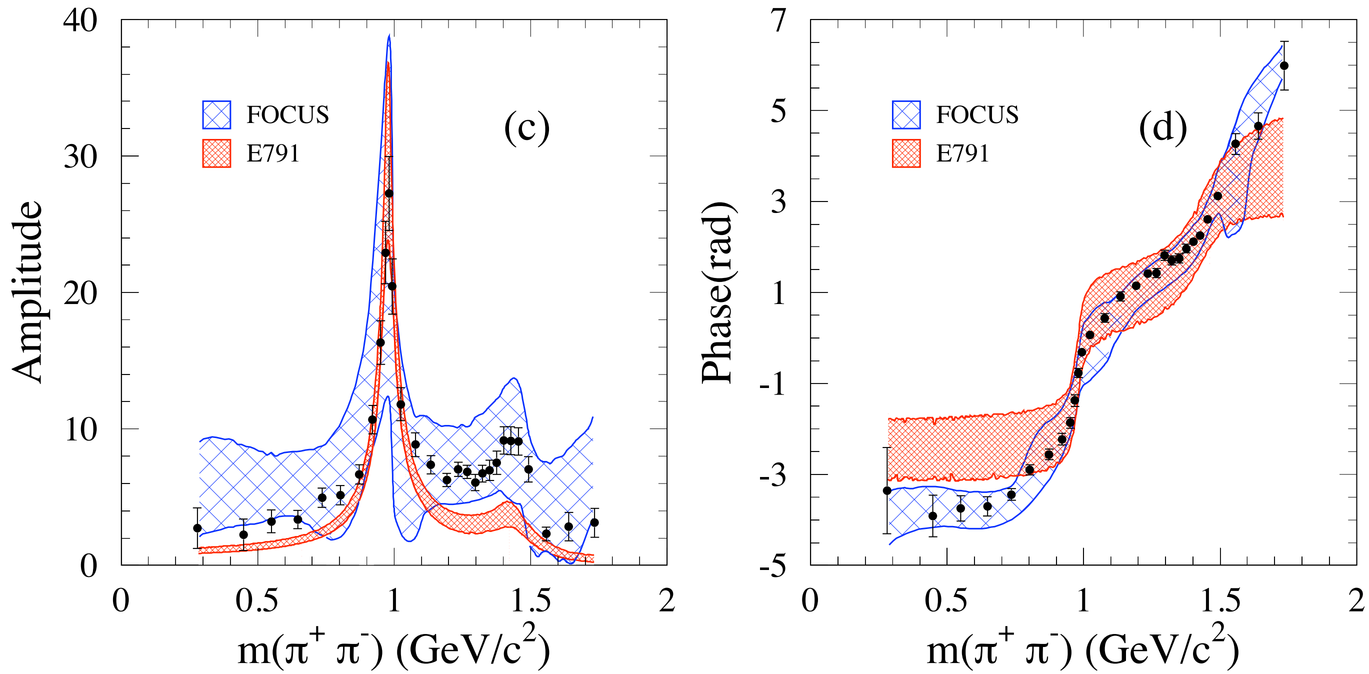


*)Relaxed Cubic Spline: K. S. Kölbig and H. Lipps, Cubic Splines and Their Integrals, CERN Program Library, E211.

BaBar: arXiv:0808.0971v3 [hep-ex], submitted to PRD

$D_s^+ \to \pi^-\pi^+\pi^+$

- Model-independent S-wave compatible with FOCUS (K-matrix) and E791 (isobar).



E791: Phys. Rev. Lett. 86, 765 (2001)
FOCUS: Phys. Lett. B 585, 200 (2004)
Dots and plots by:
BaBar: arXiv:0808.0971v3 [hep-ex], submitted to PRD

- Clear $f_0(980)$, signs of $f_0(1370)$, $f_0(1500)$
- Also: large D-wave contribution $f_2(1220)$

Direct CPV in D°, D+

- Plenty of results from BaBar, BELLE, CDF, CLEO, E791, FOCUS, averaged by HFAG
- Table shows averages for those results that received updates in 2007 or 2008.
- Plenty more modes
- Reaching per-mil precision.

	Mode	A_{CP}(%) Charm09	A_{CP}(%) Charm07
D^o	K^+K^-	-0.16±0.23	1.36±1.2
	$\pi^+\pi^-$	0.22 ± 0.37	1.27±1.25
	$\pi^+\pi^-\pi^o$	-0.23±0.42	1.0±9.0
	$K^-\pi^+\pi^o$	0.16±0.89	3.1±8.6
	$K^-K^+\pi^o$	0.16 ± 0.89	-
D^+	$K^-K^+\pi^+$	0.39 ± 0.61	0.7±0.8
	$K_S\pi^+$	-0.86 ± 0.90	-1.6±1.7
	$K_S\pi^+\pi^o$	0.3 ± 0.9 ± 0.3	-
	$K^-\pi^+\pi^+\pi^o$	1.0 ± 0.9 ± 0.9	-

Direct CPV in Ds

- CLEO-c's Ds data allowed for the first time a precise test of direct CP in the Ds system
- Plenty of modes, all results new since Charm 2007
- Many results at the few % level.

Mode	A_{CP}(%)
$\pi^+\eta$	-8.2 ± 5.2 ± 0.8
$\pi^+\eta'$	-5.5 ± 3.7 ± 1.2
$K_S\pi^+$	27 ± 11
$K_S\pi^o$	2 ± 29
$K^+\eta$	-20 ± 18
$K^+\eta'$	-17 ± 37
K^+K_S	4.9 ± 2.1 ± 0.9
$\pi^+\pi^-\pi^+$	2.0 ± 4.6 ± 0.7
$K^+\pi^+\pi^-$	11.2 ± 7.0 ± 0.9
$K_SK^-\pi^+\pi^+$	-0.7 ± 3.6 ± 1.1
$K^+K^-\pi^+\pi^0$	-5.9 ± 4.2 ± 1.2

Prospects for direct CPV

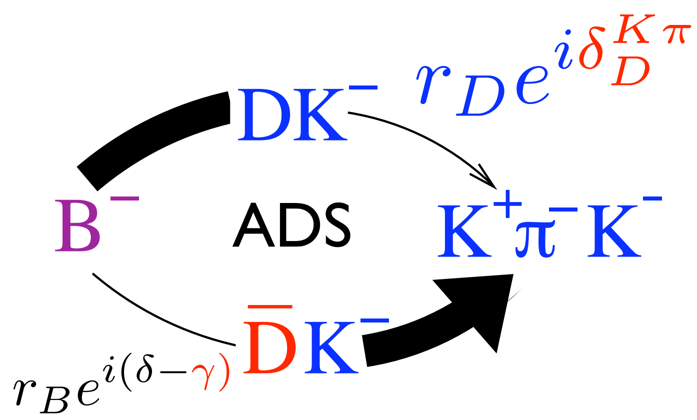
- Example: $D^o \rightarrow K^+ \overline{K}^-$
  - BaBar 2008: $+0.0000 \pm 0.0034 \pm 0.0013$
  - BELLE 2008: $-0.0043 \pm 0.0030 \pm 0.0011$
  - World average (HFAG): $+0.0022 \pm 0.0037$
- CDF has obtained its result of $+0.020 \pm 0.012 \pm 0.006$ with only 2% of its current data set. CDF could beat world stat precision now.
- LHCb, due to start this year, expects stat precision of 0.004% in 10/fb (ca 5 years, using charm from B decays, including prompt charm will improve this further).

γ from 2-body decays, ADS

- CLEO uses quantum coherence to measures $\delta_D^{K\pi}$ in decays such as

$$\Gamma(D_{CP+} \to K^+\pi^-) = \frac{1}{2}\left|A(D \to K^+\pi^-) + A(\overline{D} \to K^+\pi^-)\right|^2$$
$$\propto \left(1 + 2r_D^{K\pi}\cos\delta_D^{K\pi}\right) + \text{mixing terms}$$

- Result: $\delta_D^{K\pi} = 22^{o}{}^{+11^o}_{-12^o}{}^{+9^o}_{-11^o}$
- Also important input for D-mixing! *



PRL 100, 221801 (2008), PRD 78, 012001 (2008)

Analysis based on 1/3 of data set - update with full 818/fb and more tag modes, soon.

* Result shown includes external input on y, y′ from mixing measurements. Without external inputs: $\cos\delta = 1.03^{+0.31}_{-0.17} \pm 0.06$