Hadronic Charm Decays

Jonas Rademacker on behalf of CLEO-c

June 2010, FCPC, Turino

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Correlated charm for γ covered by Chris Thomas, yesterday

Mixing and CP violation in charm covered in dedicated session tomorrow

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Plenty of good stuff left:
Very comprehensive sets of absolute and relative branching fractions (incl. results from CLEO-c's full D and Ds dataset), symmetries of the strong interaction, strong phases, Dalitz analyses.

Correlated charm for γ covered by Chris Thomas, yesterday

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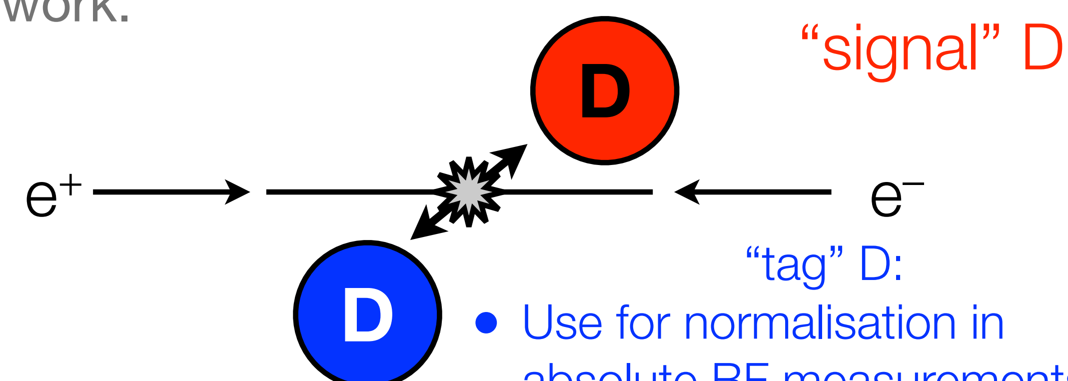
Facilities

- Most hadronic charm decays are found when looking for B mesons: By the B factories (ca 3 billion D mesons), by CDF's hadronic B trigger (even larger amounts, only a small fraction analysed). LHCb will reconstruct unprecedented amounts and has a dedicated charm programme.

- But: Quantity is not everything. FOCUS, a fixed-target charm experiment, is responsible for many world-leading charm results. CLEO-c has only ~0.3% of the amount of charm that the B factories have produced, but delivers unique and competitive results due to the special properties of threshold production. BES-III to continue the good work.

Threshold production:

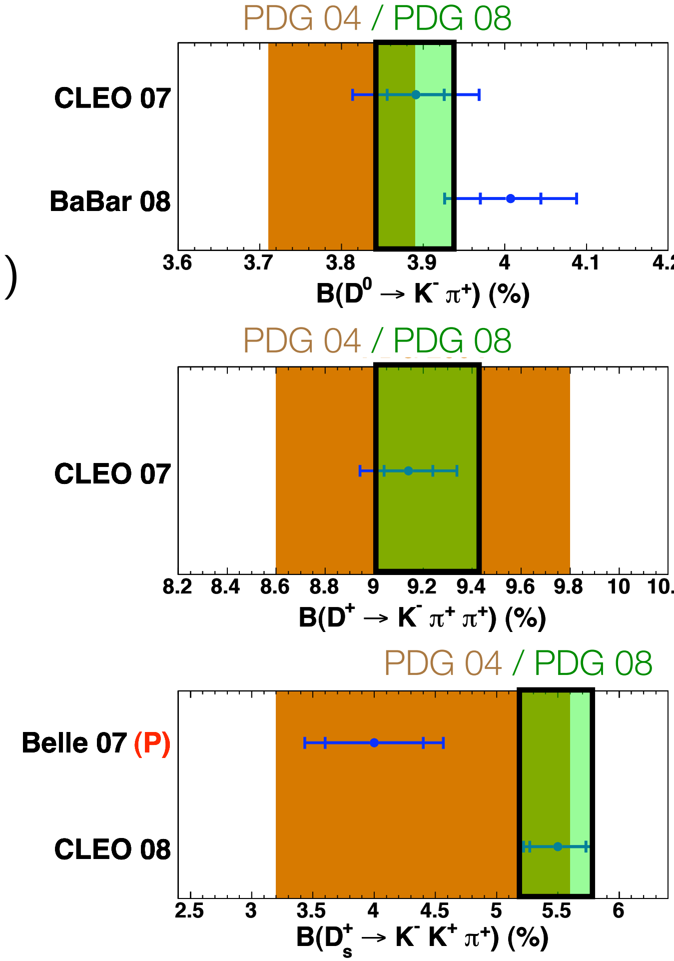


- Use for normalisation in absolute BF measurements.
- Fixes quantum numbers of signal D

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: $e^+e^- \to \overline{D}^{(*)}_{(s)}\, D_{(s)}$



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}]

Branching Fractions of D,D$_{(S)}$→PP

CLEO-c, full data set

818/pb at ψ(3770)

3 ·10^6 D^{o}D^o

2.4 ·10^6 D$^+$D$^-$

586/pb at

$\sqrt{s}$=4170 MeV

5.4 ·10^5 Ds$^+$ Ds$^-$

PhysRevD.81.052013 (2009)

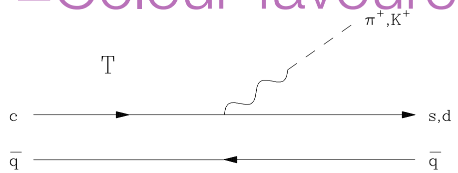
TABLE II: Ratios of branching fractions to the corresponding normalization modes $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, anc $D_s \to K^0_S K^+$, branching fractions results from this analysis, and charge asymmetries $\mathcal{A}_{CP}$. Uncertainties are statistical error systematic error, and the 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	
$D^0 \to K^0_S K^0_S$	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
$D^0 \to K^0_S\pi^0$	31.0495 ± 0.2964 ± 0.7467	1.2081 ± 0.0115 ± 0.0291 ± 0.0239	
$D^0 \to K^0_S\eta$	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	
$D^0 \to K^0_S\eta'$	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
$D^+ \to K^0_S K^+$	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
$D^+ \to K^0_S\pi^+$	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
$D_s^+ \to K^0_S K^+$	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.)	
$D_s^+ \to K^0_S\pi^+$	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

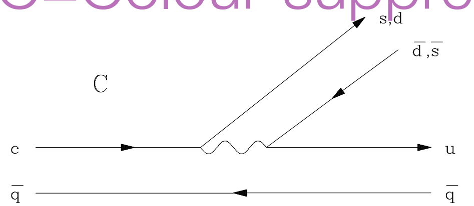
Some results I’ll show later use only part the data set.

Diagrammatic Approach

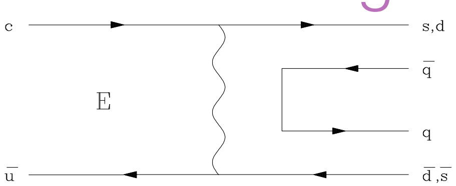
T=Colour-favoured Tree



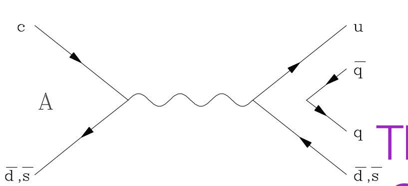
C=Colour-suppressed tree



E=Exchange



A=Annihilation



Express CF decays in terms of SU(3)-invariant diagrams, fit to measured BFs

Meson	Decay mode	$\mathcal{B}$ [10] (%)	Rep.
D^0	$K^-\pi^+$	3.891±0.077	$T+E$
	$\overline{K}^0\pi^0$	2.380±0.092	$(C-E)/\sqrt{2}$
	$\overline{K}^0\eta$	0.962±0.060	$\frac{C}{\sqrt{2}}\sin(\theta_\eta+\phi_1)-\frac{\sqrt{3}E}{\sqrt{2}}\cos(\theta_\eta+2\phi_1)$
	$\overline{K}^0\eta'$	1.900±0.108	$-\frac{C}{\sqrt{2}}\cos(\theta_\eta+\phi_1)-\frac{\sqrt{3}E}{\sqrt{2}}\sin(\theta_\eta+2\phi_1)$
D^+	$\overline{K}^0\pi^+$	3.074±0.097	$C+T$
D_s^+	$\overline{K}^0K^+$	2.98±0.17	$C+A$
	$\pi^+\eta$	1.84±0.15	$T\cos(\theta_\eta+\phi_1)-\sqrt{2}A\sin(\theta_\eta+\phi_1)$
	$\pi^+\eta'$	3.95±0.34	$T\sin(\theta_\eta+\phi_1)+\sqrt{2}A\cos(\theta_\eta+\phi_1)$

$$\begin{aligned}
T &= 3.003 \pm 0.023 \\
C &= (2.565 \pm 0.030)\ \exp\left[i(-152.11 \pm 0.57)^\circ\right] \\
E &= (1.372 \pm 0.036)\ \exp\left[i(123.62 \pm 1.25)^\circ\right] \\
A &= (0.452 \pm 0.058)\ \exp\left[i(19^{+15}_{-14})^\circ\right]
\end{aligned}$$

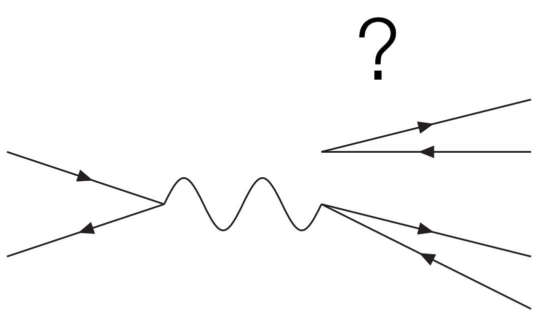
These are not Feynman diagrams. All QCD effects to all orders are implied

Applying the diagrammatic approach to SCS

- Using the results from the CF analysis to predict SCS decay rates results in reasonable qualitative agreement with some notable exceptions.

Meson	Decay mode	$\mathcal{B}$[1] (10^{-3})	Predicted $\mathcal{B}$ (10^{-3}) $\lvert T\rvert < \lvert C\rvert$	$\lvert T\rvert > \lvert C\rvert$
D^0	$\pi^+\pi^-$	1.45 ± 0.05	2.24	2.24
	$\pi^0\pi^0$	0.81 ± 0.05	1.36	1.35
	K^+K^-	4.07 ± 0.10	1.92	1.93
	$K^0\overline{K}^0$	0.32 ± 0.02	0	0
D^+	$\pi^+\pi^0$	1.18 ± 0.06	0.88	0.89
	$K^+\overline{K}^0$	6.12 ± 0.22	0.73	6.15
D_s^+	π^+K^0	2.52 ± 0.27	0.37	3.08
	π^0K^+	0.62 ± 0.23	0.86	0.85

- For decays involving η or η', there is some indication of the presence of an additional contribution from the singlet-annihilation diagram:

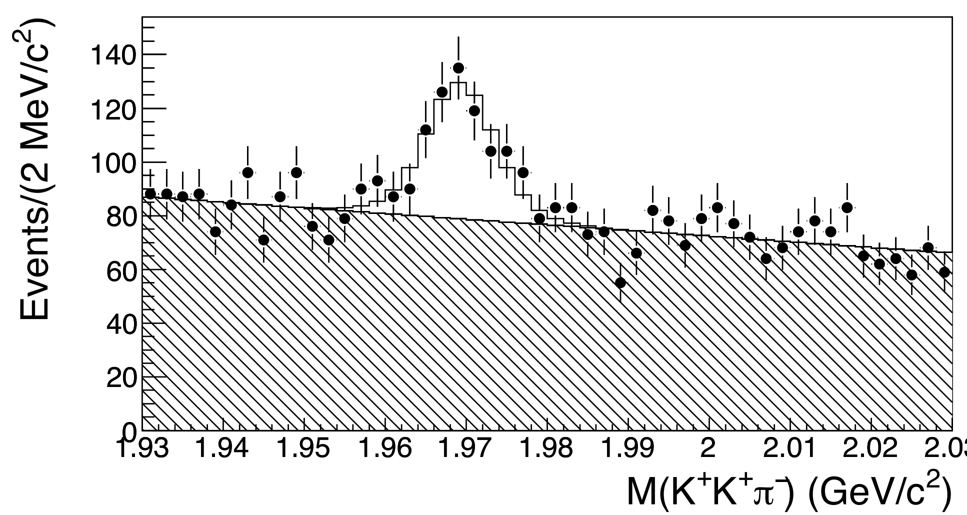


PhysRevD.81.014026 2010

1st observation and SU(3) test

	Expect from SU(3)	get
$\frac{\Gamma(D^+ \to K^+K^+\pi^-)\,\Gamma(D^+ \to K^+\pi^+\pi^-)}{\Gamma(D^+ \to K^+K^-\pi^+)\,\Gamma(D^+ \to K^-\pi^+\pi^+)}$	$\tan^8\theta$ H. J. Lipkin, Nucl. Phys. B, Proc. Suppl. 115, 117 (2003).	$(1.57 \pm 0.21)\times\tan^8\theta$ BELLE: Phys. Rev. Lett. 102, 221802 (2009)

1st Observation of $D_s^+ \to K^+K^+\pi^-$ (BELLE 2009)



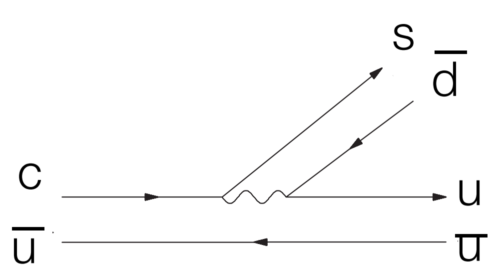
U-spin and $D^o \to K_{S,L}\pi^o$

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

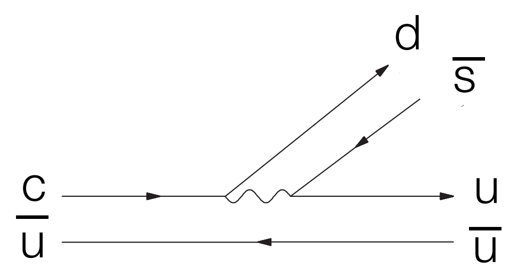
- $\Gamma(D^o \to K_S\pi^o) \neq \Gamma(D^o \to K_L\pi^o)$

- $\sqrt{2}\, A(D^o \to K_{S,L}\pi^o) = A(D \to K^o\pi^o) \pm A(D \to \overline{K^o}\pi^o)$

CF



±



DCS

U-spin* prediction

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

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

$D^o \rightarrow K_{L,S}\pi^0$ $D^+ \rightarrow K_{L,S}\pi^+$ experimentally

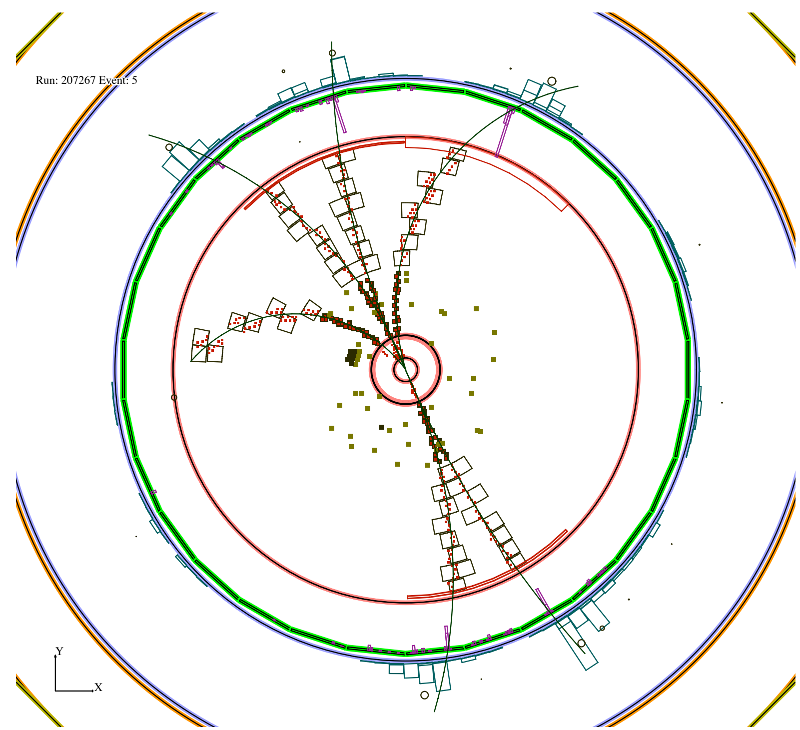
- Challenging: Invisible K_L, difficult π^o.

CLEAN-c

- CLEO-c:
  - e+ e– → $\psi(3770) \rightarrow DD$

    100% of beam energy converted to DD pair ⇒ kinematic constraints.

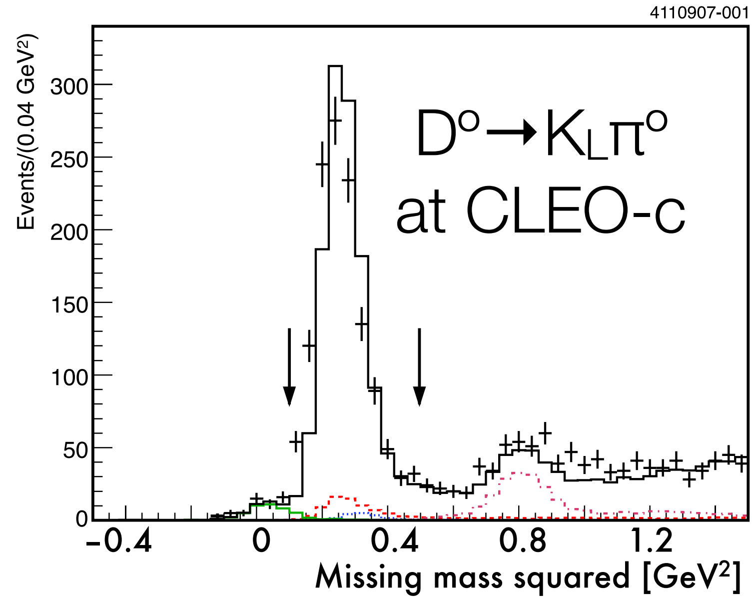
  - Extremely clean environment, good calorimeter



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

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

- Clean missing mass-squared peak at $m^2_{K^o} = 0.28 GeV^2$
- Lines: MC simulation. Crosses: Data.
- Result

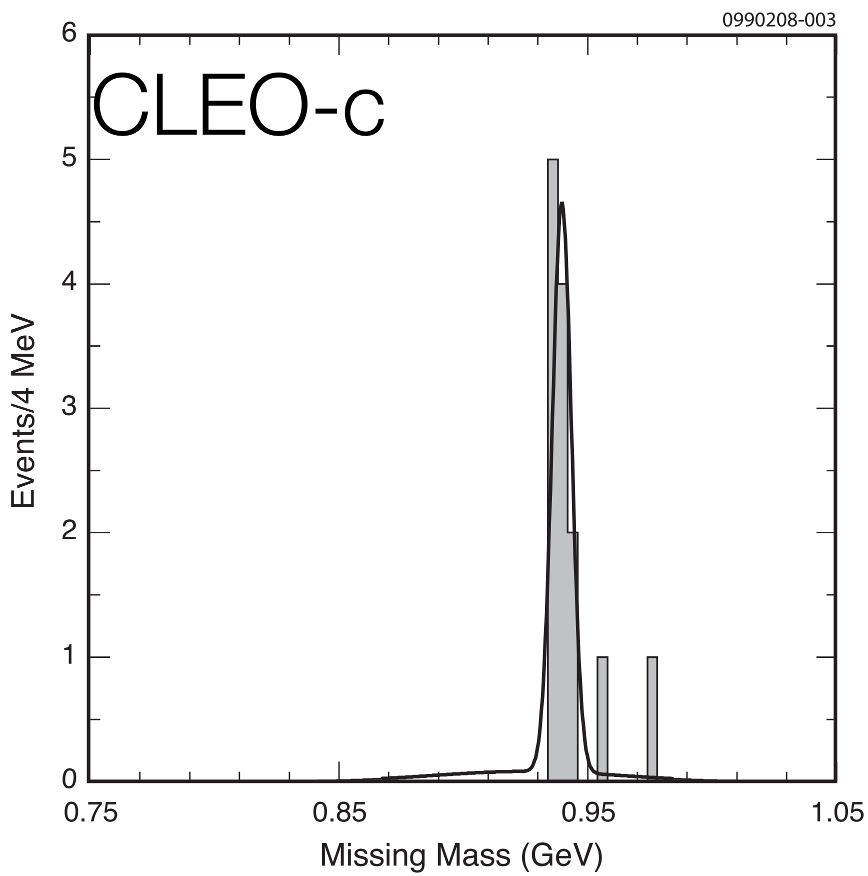


$$\frac{\Gamma\left(D^0 \rightarrow K_S \pi^0\right) - \Gamma\left(D^0 \rightarrow K_L \pi^0\right)}{\Gamma\left(D^0 \rightarrow K_S \pi^0\right) + \Gamma\left(D^0 \rightarrow K_L \pi^0\right)} = 0.108 \pm 0.025 \pm 0.024$$

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

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

First Observation of $D_s^+ \to pn$



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

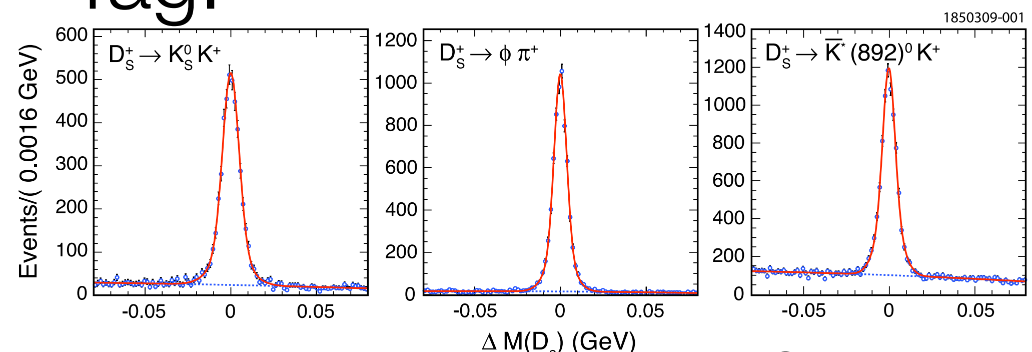
- Only baryonic state kinematically accessible to D^0 D^+ D_s^+
- Virtually background-free reconstruction at CLEO-c
- First observation of meson → 2 baryons plus nothing else.

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

Inclusive D_s BF

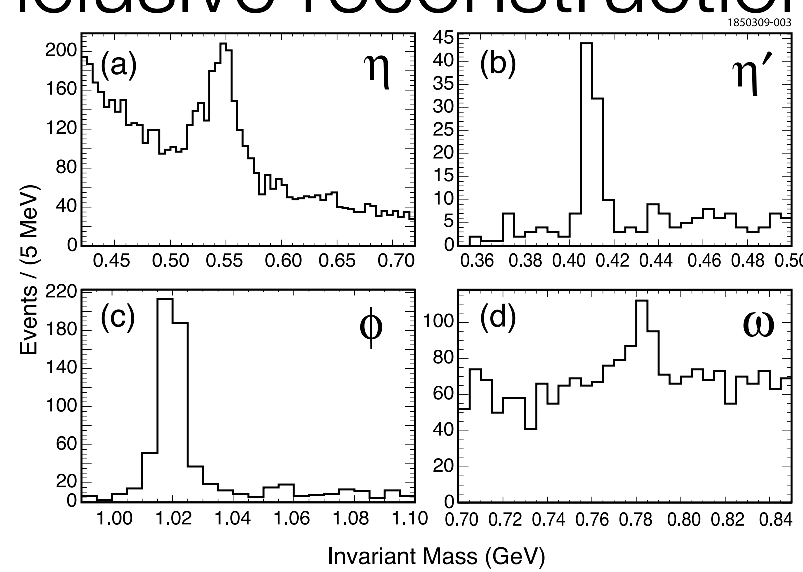
- $e^+e^- \to D_s^{+*} D_s^-$
- Fully reconstruct one Ds as tag
- Reconstruction of desired decay product on other side.

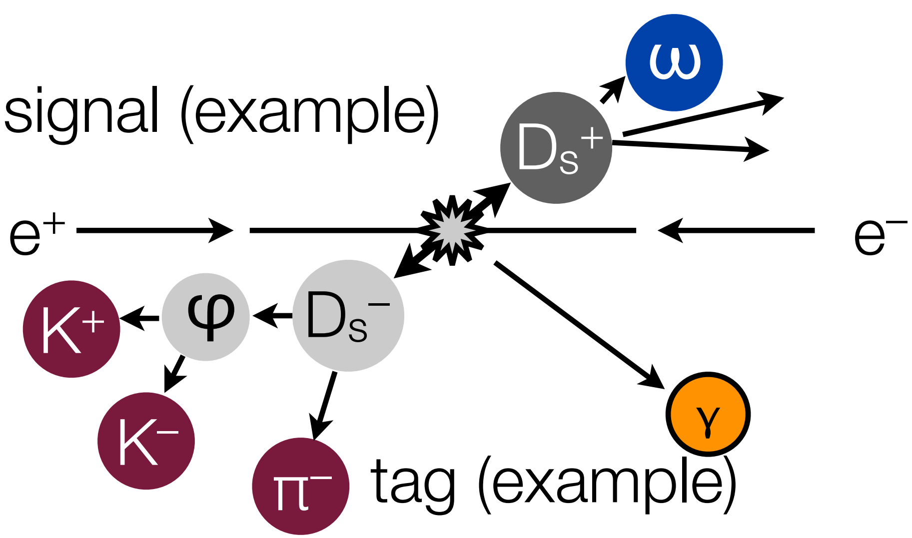
Tag:



reconstructed Ds mass minus PDG Ds mass

Inclusive reconstruction:





CLEO: PhysRevD.79.112008 (2009) (arXiv:0904.2417)

Inclusive Ds BF Results

Mode	Yield(%)	K_L^0 Mode	Yield(%)	$\mathcal{B}$(PDG)(%)	prediction based on excl. rates [1]
$D_s^+ \to \pi^+ X$	$119.3 \pm 1.2 \pm 0.7$				125.5 ±11.1
$D_s^+ \to \pi^- X$	$43.2 \pm 0.9 \pm 0.3$				46.6±6.8
$D_s^+ \to \pi^0 X$	$123.4 \pm 3.8 \pm 5.3$				112.5±8.0
$D_s^+ \to K^+ X$	$28.9 \pm 0.6 \pm 0.3$			$20\ ^{+18}_{-14}$	27.3 ± 1.4
$D_s^+ \to K^- X$	$18.7 \pm 0.5 \pm 0.2$			$13\ ^{+14}_{-12}$	18.4±0.7
$D_s^+ \to \eta X$	$29.9 \pm 2.2 \pm 1.7$				32.7 ± 2.9
$D_s^+ \to \eta' X$	$11.7 \pm 1.7 \pm 0.7$				18.2±2.1
$D_s^+ \to \phi X$	$15.7 \pm 0.8 \pm 0.6$				19.2±2.4
$D_s^+ \to \omega X$	$6.1 \pm 1.4 \pm 0.3$				0.8±0.1
$D_s^+ \to f_0(980) X, f_0(980) \to \pi^+\pi^-$	$< 1.3\%$ (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	K^0: 18.4±2.0, $\bar{K}^0$ 22.7± 2.2
$D_s^+ \to K_S^0 K_S^0 X$	$1.7 \pm 0.3 \pm 0.1$	$D_s^+ \to K_L^0 K_S^0 X$	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 inclusive Ds result: PhysRevD.79.112008 (2009) (arXiv:0904.2417),
[1] Prediction: Gronau and Rosner: PhysRevD.79.074022 (2009)

Inclusive D_s BF Results

Mode	Yield(%)	K_L^0 Mode	Yield(%)	$\mathcal{B}$(PDG)(%)	prediction based on excl. rates [1]
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$D_s^+ \to \pi^- X$	$43.2 \pm 0.9 \pm 0.3$				46.6±6.8
$D_s^+ \to \pi^0 X$	$123.4 \pm 3.8 \pm 5.3$				112.5±8.0
$D_s^+ \to K^+ X$	$28.9 \pm 0.6 \pm 0.3$			$20\ ^{+\ 18}_{-\ 14}$	27.3 ± 1.4
$D_s^+ \to K^- X$	$18.7 \pm 0.5 \pm 0.2$			$13\ ^{+\ 14}_{-\ 12}$	18.4±0.7
$D_s^+ \to \eta X$	$29.9 \pm 2.2 \pm 1.7$				32.7 ± 2.9
$D_s^+ \to \eta' X$	[illegible]				18.2±2.1
$D_s^+ \to \phi X$	$15.7 \pm 0.8 \pm 0.6$				19.2±2[illegible]
$D_s^+ \to \omega X$	$6.1 \pm 1.4 \pm 0.3$				0.8±0.1
$D_s^+ \to f_0(980)X, f_0(980) \to \pi^+\pi^-$	$< 1.3\%$ (90% CL)				
$D_s^+ \to K_S^0 X$	[illegible]	$D_s^+ \to K_L^0 X$	[illegible]	[illegible]	[illegible] 18.4±2.0, K^0 22.7± 2.2
$D_s^+ \to K_S^0 K_S^0 X$	$1.7 \pm 0.3 \pm 0.1$	$D_s^+ \to K_L^0 K_S^0 X$	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)				

$D_s^+ \to \omega X \quad 6.1 \pm 1.4 \pm 0.3 \qquad 0.8\pm0.1$

CLEO inclusive Ds result: PhysRevD.79.112008 (2009) (arXiv:0904.2417),
[1] Prediction: Gronau and Rosner: PhysRevD.79.074022 (2009)

Exclusive vs inclusive $D_S \rightarrow \omega X$

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

- A closer look at exclusive $D_S \rightarrow \omega X$ BR:

Mode	$\mathcal{B}_{\rm mode}(\%)$
$D_s^+ \to \pi^+\omega$	$0.21 \pm 0.09 \pm 0.01$
$D_s^+ \to \pi^+\pi^0\omega$	$2.78 \pm 0.65 \pm 0.25$
$D_s^+ \to \pi^+\pi^+\pi^-\omega$	$1.58 \pm 0.45 \pm 0.09$
$D_s^+ \to \pi^+\eta\omega$	$0.85 \pm 0.54 \pm 0.06$
	< 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)

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:

Mode	$\mathcal{B}_{\text{mode}}(\%)$
$D_s^+ \to \pi^+\omega$	$0.21 \pm 0.09 \pm 0.01$
$D_s^+ \to \pi^+\pi^0\omega$	$2.78 \pm 0.65 \pm 0.25$
$D_s^+ \to \pi^+\pi^+\pi^-\omega$	$1.58 \pm 0.45 \pm 0.09$
$D_s^+ \to \pi^+\eta\omega$	$0.85 \pm 0.54 \pm 0.06$
[illegible]	< 2.13 (90% CL)
$D_s^+ \to K^+\omega$	< 0.24 (90% CL)
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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±1.0)%, accounts for most of inclusive BR($D_s \to \omega X$) = (6.1±1.4)%

CLEO exclusive ω results: PhysRevD.80.051102 (2009)

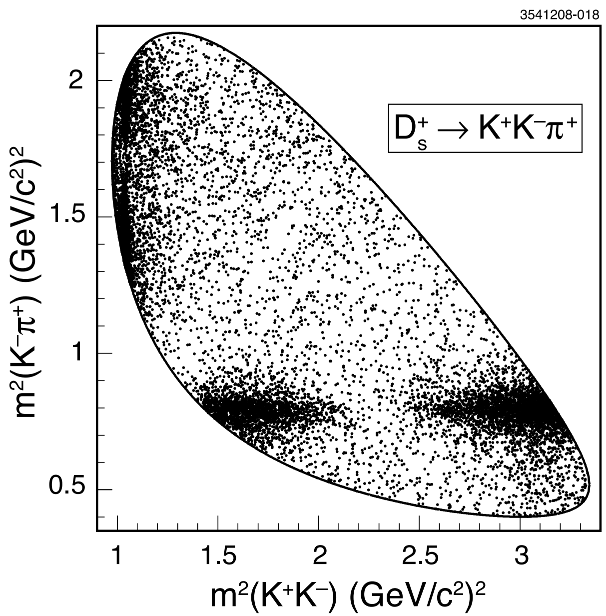
Dalitz Analyses

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

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

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

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



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

- Decay rates:

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

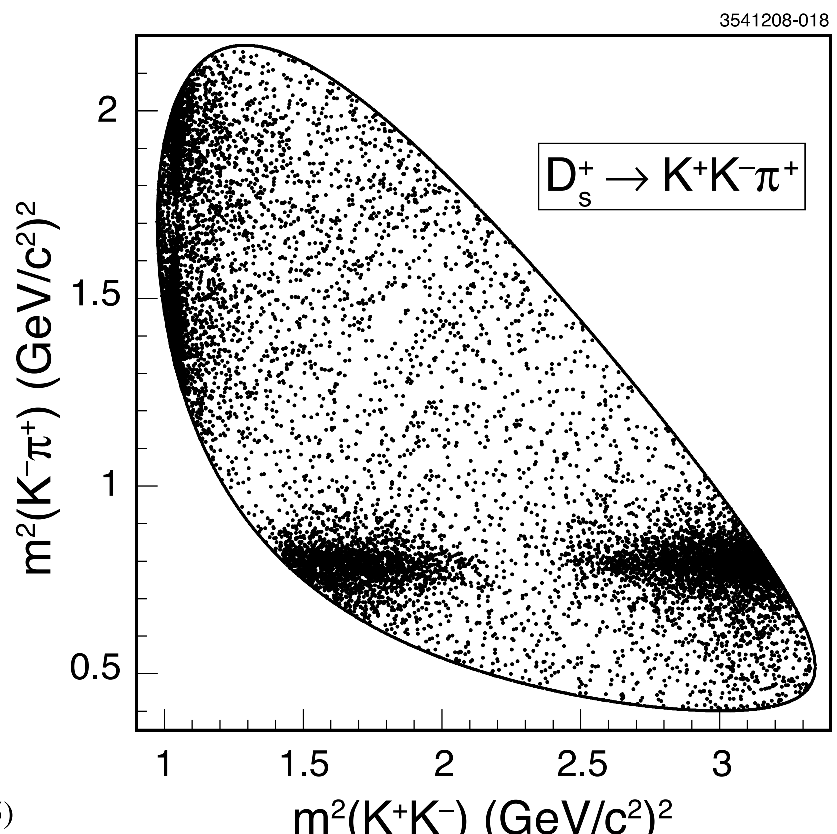
- Strength: Access to magnitudes AND phases of amplitudes.

Recent Results: $D_S^+ \to K^- K^+ \pi^+$ at CLEO

- 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)

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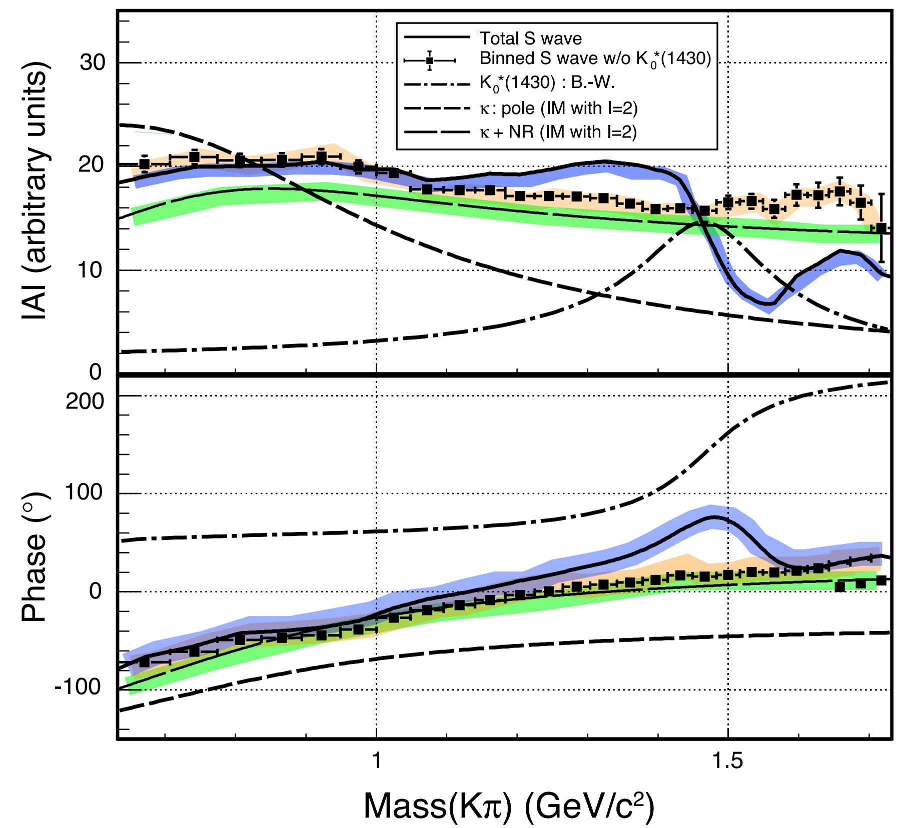
- General consensus: Isobar OK for (relatively narrow) P, D wave resonances, but problematic for (usually very broad) S-wave.
- Isobar S-wave usually modelled by a “non-resonant” component, plus, occasionally, $\sigma\to\pi\pi$ and $\kappa\to K\pi$ resonances (rather controversial).

$D^+ \to K^-\pi^+\pi^+$ (ca 80% $K\pi$ S-wave)

colours added for illustration, not error bands

- total Kπ S-wave
- Kπ S-wave w/o $K_0^*(1430)$
- isobar S-wave w/o $K_0^*(1430)$



CLEO: PhysRevD.78.052001 (2008)

E791 isobar analysis: Phys. Rev. Lett 89, 121801 (2002); *E791 model indep analysis:Phys. Rev. D73, 032004 (2006);
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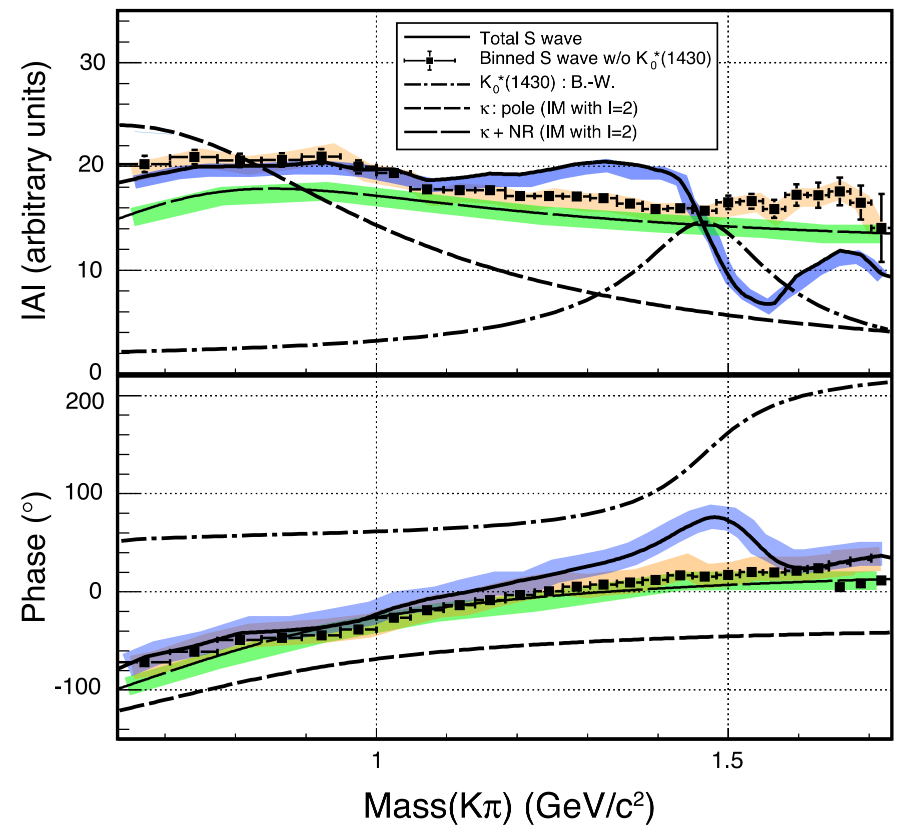

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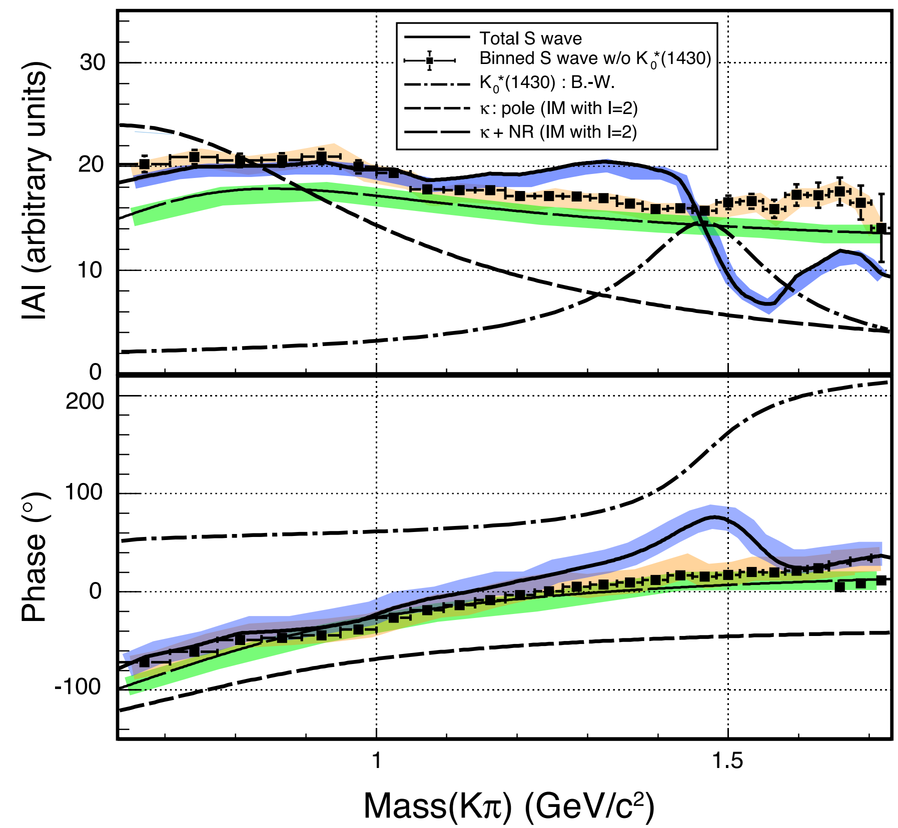

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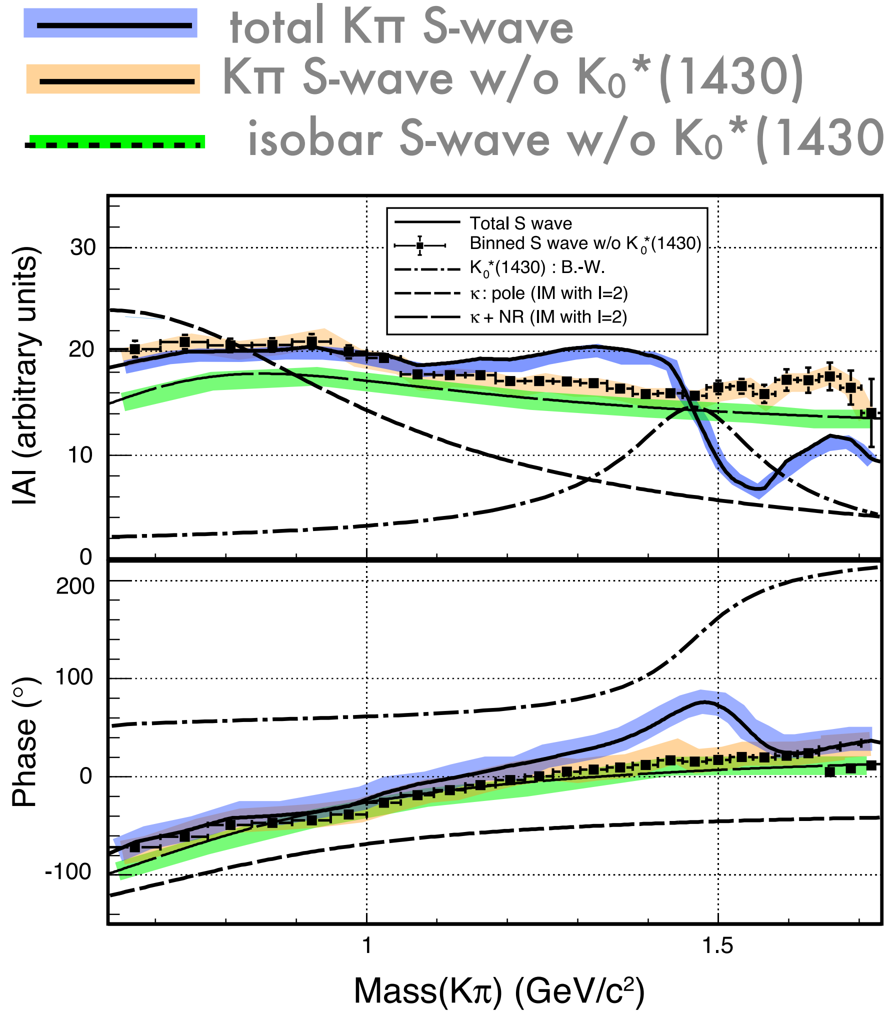

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- Result: binned magnitudes and phases. Plot compares model-indep. with isobar (incl κ)
- Also: Found that fit significantly improves when adding a I=2 $\pi^+\pi^+$ S-wave component.

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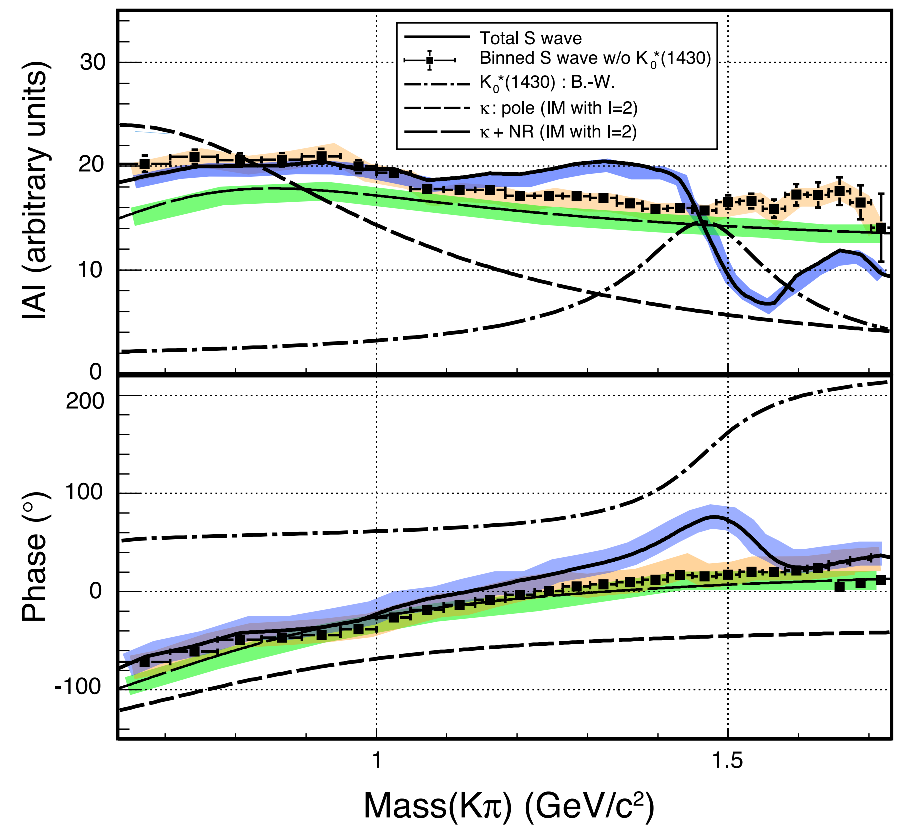
Kπ S-wave w/o $K_0^*(1430)$

isobar S-wave w/o $K_0^*(1430)$



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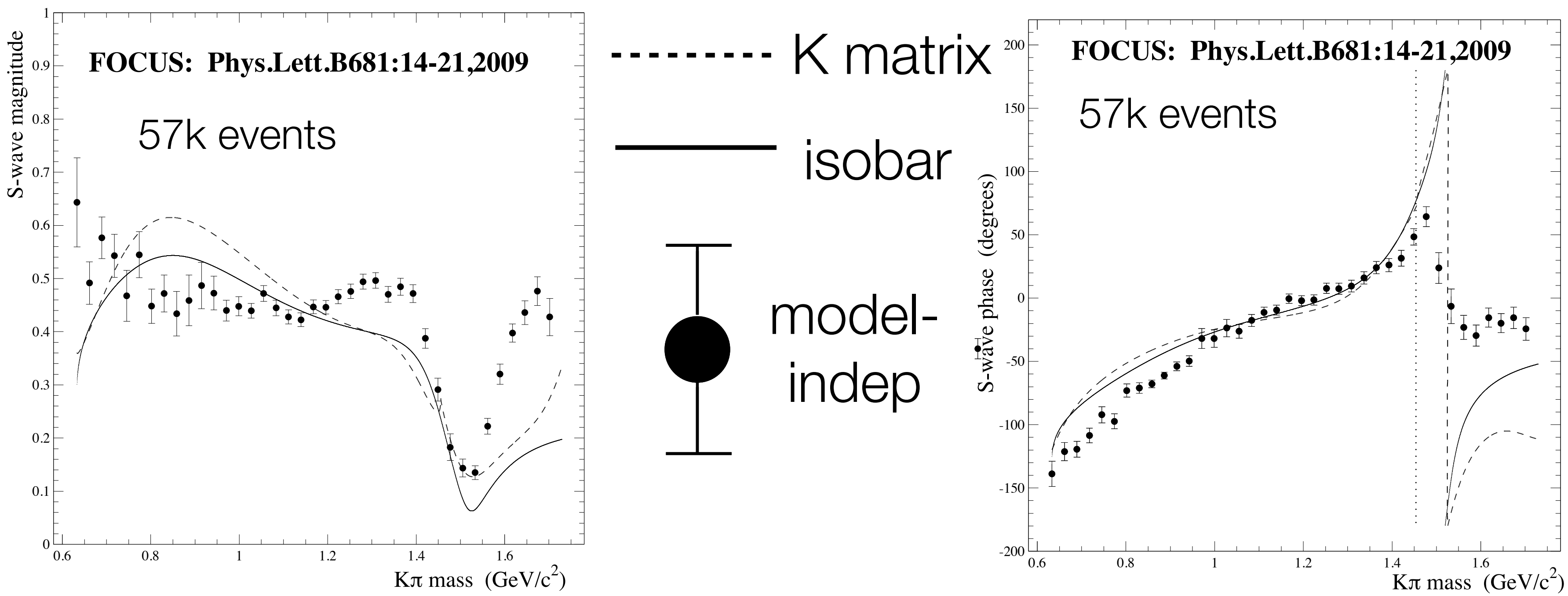
FOCUS Kπ S-wave in $D^+ \to K^-\pi^+\pi^+$

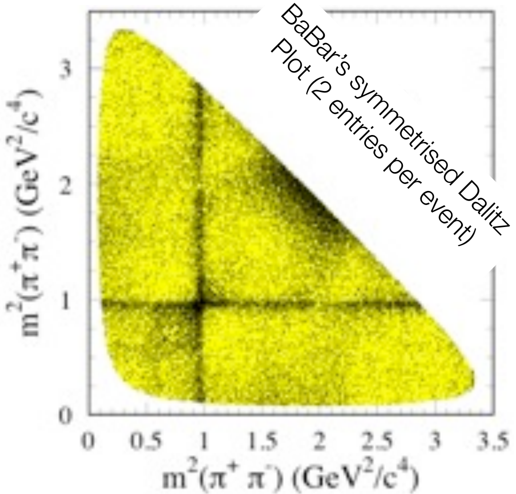
Focus recently re-analysed their data using a the model-independent analysis (57k evts, 1/3 of CLEO-c). Below: Comparison of FOCUS' three S-wave fits

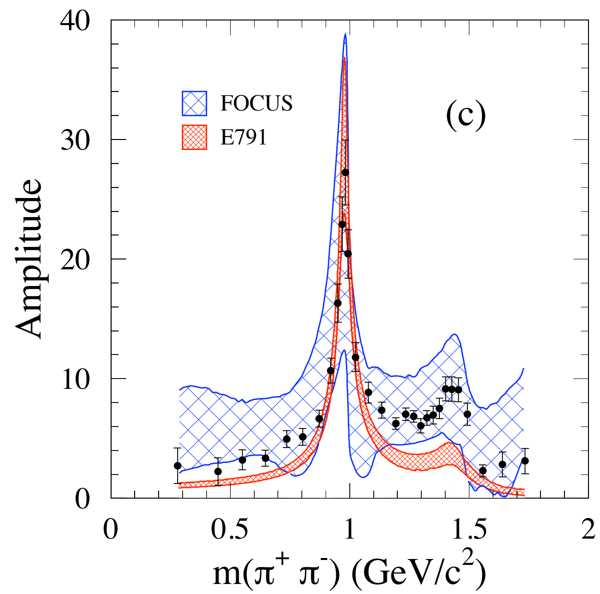


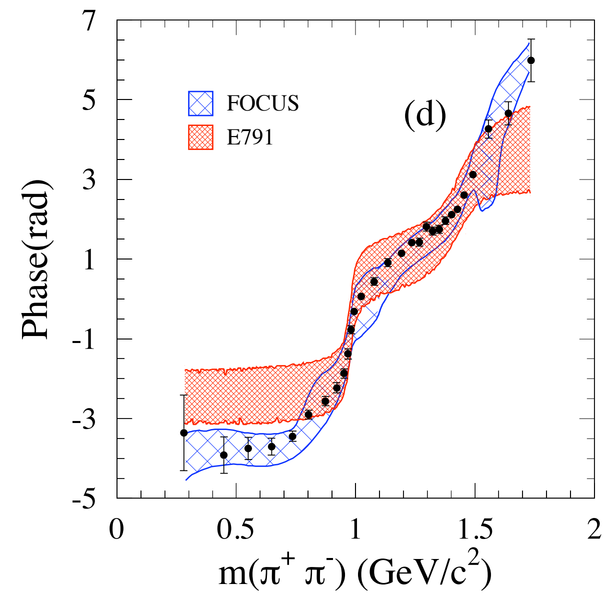
magnitude phase

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

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]

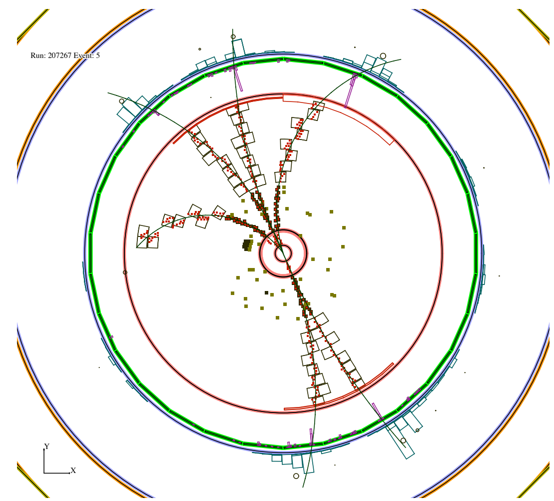
- Dominated by S-wave (fit fraction 83%).
- BaBar: model-independent analysis[1] of S-wave component. Result compatible with FOCUS (K-matrix) [2] and E791 (isobar) [3] analyses.
- Many more results in paper.

[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)

CLEO-c

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

- Threshold production of correlated DD.
- D mesons must have opposite CP and flavour.
- Gives access to different D-Dbar superpositions, and thus access to phases. E.g.:



"tag" D	signal D rate
CP+, eg KK	$\Gamma = \left\| (A_D - \overline{A}_D)/\sqrt{2} \right\|^2$
Flavour, e.g. $K^- e^+ \nu_e$	$\Gamma = \|A_D\|^2$

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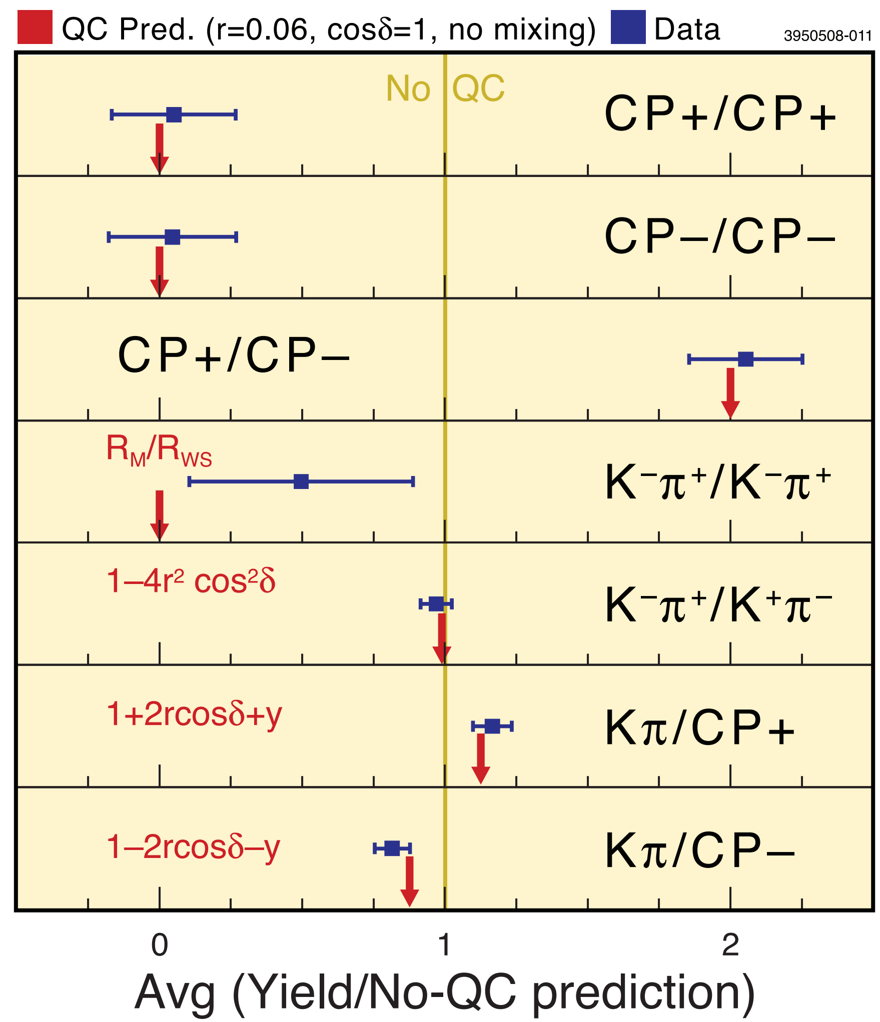
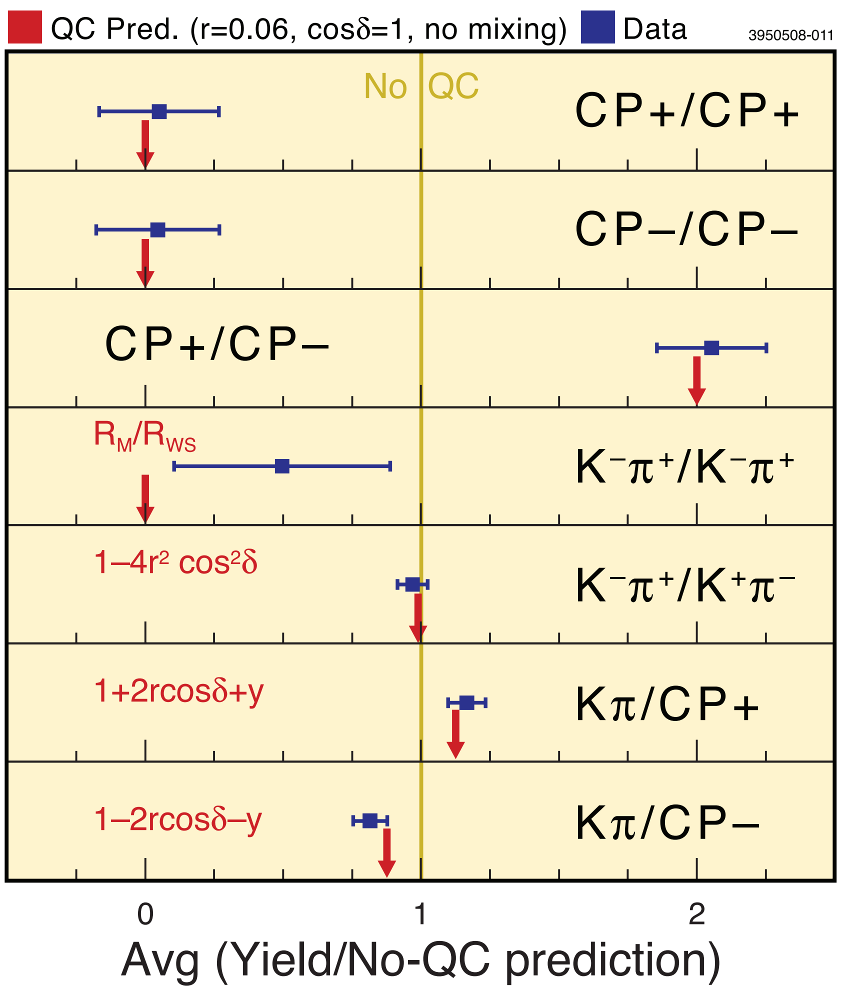


Exploiting Quantum Correlations at CLEO-c



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

See Chris Thomas' presentation

- 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.

New kids on the block

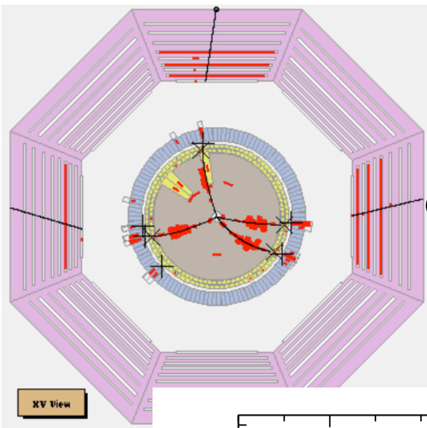
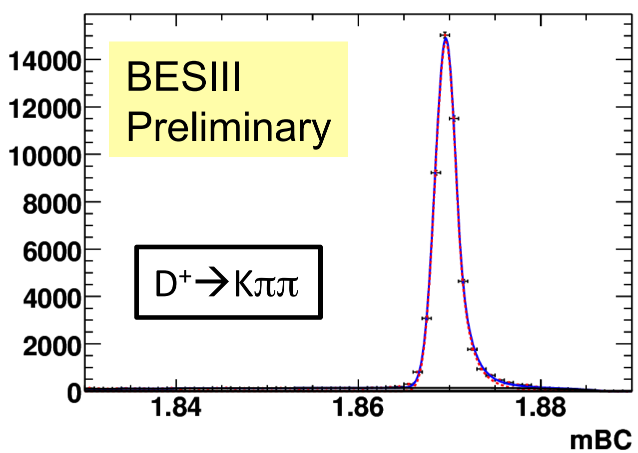


Fig. 2. The first event rec

BES-III at the charm threshold

Hai-Bo Li

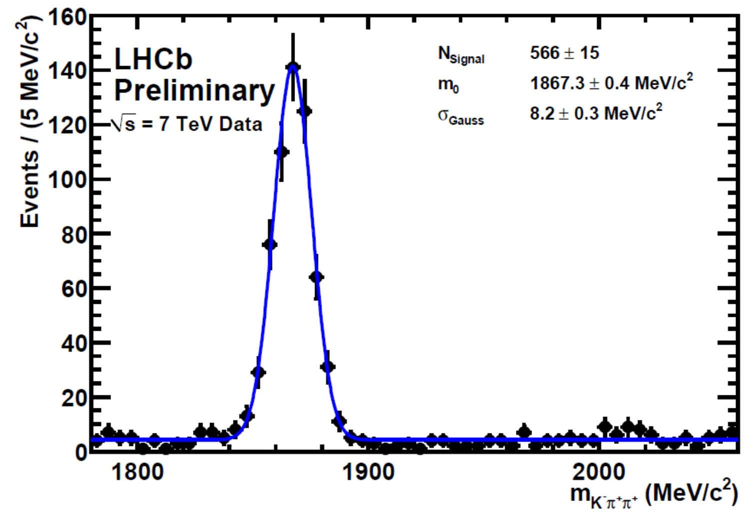


BES-III: Correllated D-Dbar pairs.
To collect ~20×CLEO-c statistics.
(already collected ca 1×CLEO-c)

LHCb: Unprecedented Statistics

Franz Muheim

$D^- \to K^+\pi^-\pi^-$ in LHCb's first 0.8/nb = 0.000008/fb.



First run (1-2 years): 1/fb. Expect huge charm samples.

Summary

- In this talk: A lot of new branching fractions, including recent results from CLEO-c's full D_s dataset • Several new modes • $SU(3)_F$ and U-spin tests • Dalitz analyses to study light resonances • Correlated D-Dbar pairs to measure phases.

- Dalitz analyses in charm are experiencing a renaissance as an important tool in charm and B physics, but we don't really understand them. What are those S-wave contributions? (Can we develop accurate, physically motivated models?)

- Expect lots of new data from LHCb (unprecedented statistics) and BES-III (charm threshold, ca 20x CLEO statistics); also, by far not all B-factory, CLEO and CDF charm data fully exploited.

Backup

D->Kpipi Dalitz fit comparison

FOCUS: Phys.Lett.B681:14-21,2009

TABLE II: Decay fractions (%) and phases, in degress, from the MIPWA Dalitz plot fit compared to E791 and CLEO-c.

mode	FOCUS MIPWA	E791	CLEO-c
$K^-\pi^+$ S-wave	80.24±1.38±0.23±0.25±0.26	78.6±2.3	83.8±3.8
$\overline{K}_0^*(1430)\pi^+$	-	-	13.3±0.62
	-	-	51 (fixed)
$\overline{K}^*(892)^0\pi^+$	12.36±0.34±0.19±0.16±0.23	11.9±2.0	9.88±0.46
	0 (fixed)	0 (fixed)	0 (fixed)
$\overline{K}^*(1680)^0\pi^+$	1.75±0.62±0.24±0.23±0.42	1.2±1.2	0.20±0.12
	67±6±2±2±3	43±17	113±14
$\overline{K}_2^*(1430)\pi^+$	0.58±0.1±0.04±0.03±0.04	0.2±0.1	0.20±0.04
	336±7±3±2±2	-12±29	15±9

Conclusion

- Crucial for B physics, especially for a high-precision measurement of CKM angle γ in B decays.
- Properties of the charm system such as mixing and CP violation. CPV in charm is highly sensitive to New Physics.
- Decay amplitudes and rates: important parameters that need to be measured, and provide a window to low-energy QCD, its symmetries (Isospin, U-spin, SU(3)-flavour, ...) and how they are broken.
- Properties of light meson resonances - important in its own right, but could become very revelant for precision charm and B physics Dalitz analyses.

B

↓

D

↓

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

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

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

CLEO-c's quantum correlations as input for others

- Measure phase difference between $D \to K^+\pi^-$ and $D \to K^+\pi^-$, $\delta^{K\pi}$. Needed for extracting the charm mixing parameters x, y from time-dependent analyses using $D \to K^+\pi^-$ which are sensitive to x', y':

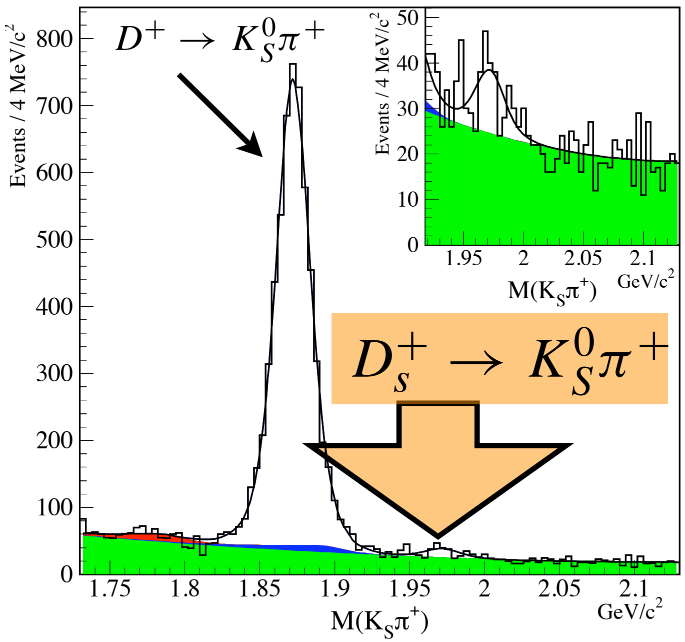
$$x' = x \cos(\delta^{K\pi}) + y \sin(\delta^{K\pi})$$

$$y' = y \cos(\delta^{K\pi}) - x \sin(\delta^{K\pi})$$

- Same for $D \to K^+\pi^-\pi^0$.

- Phase information from CLEO-c also provides important input to extracting the CPV phase γ from $B^\pm \to DK^\pm$ modes with various final states of the D, such as $K_S\pi\pi$, K_SKK, $K\pi\pi\pi$ (Chris Thomas' presentation).

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



Discovered by FOCUS

Phys.Lett.B660:147-153,2008

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

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

$D_S^+ \to K_S\pi^+$ confirmed by CLEO & BELLE

$\Gamma\left(D_S^+ \to K_S^0\pi^+\right) = (0.1263 \pm 0.0106 \pm 0.0026 \pm 0.0073)\ \%$ CLEO-c PhysRevD.81.052013 (2009)

$\Gamma\left(D_S^+ \to K_S^0\pi^+\right) = (0.120 \pm 0.009)\ \%$ BELLE PhysRevD.80.111101 (2009)

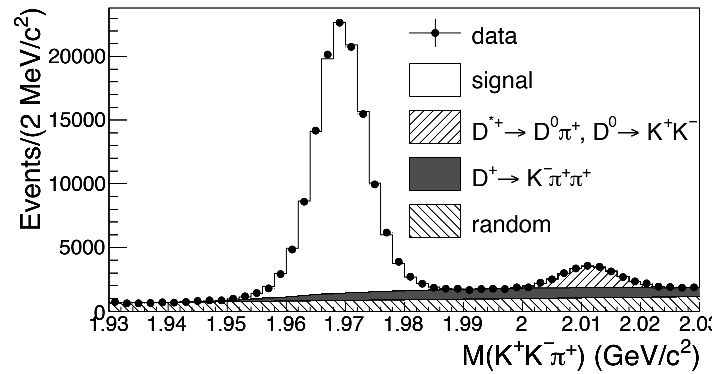
BELLE also use $D_S^+ \to K_S K^+$, $D_S^+ \to K_S\pi^+$ for CPV measurement* - see Anze Zupanc's talk

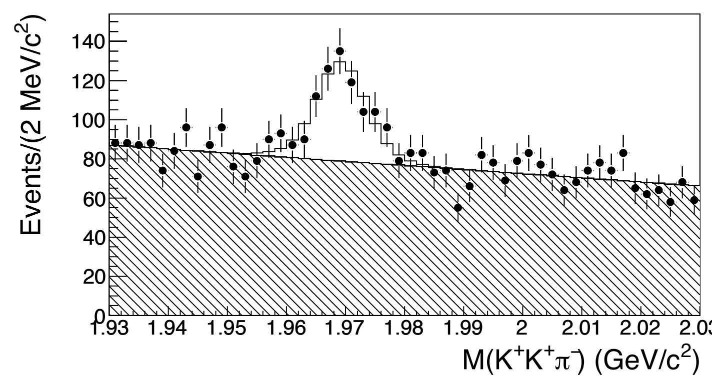
*)PhysRevLett.104.181602 (2010)

1st Observation of $D_s^+ \to K^+K^+\pi^-$ by BELLE

- BELLE made the first observation of DCS $D_s^+ \to K^+K^+\pi^-$. Use CF $D_s^+ \to K^+K^+\pi^-$. as normalisation.

- Repeat measurement with SU(3)-flavour related D+ modes.





Decay mode	$\mathcal{N}_{\text{signal}}$	$\mathcal{B}_{\text{rel}}$ (%)
$D^+ \to K^+\pi^+\pi^-$	2637.7 ± 84.4	$0.569 \pm 0.018 \pm 0.014$
$D^+ \to K^-\pi^+\pi^+$	482702 ± 727	100
$D_s^+ \to K^+K^+\pi^-$	281.4 ± 33.8	$0.229 \pm 0.028 \pm 0.012$
$D_s^+ \to K^+K^-\pi^+$	118127 ± 452	100

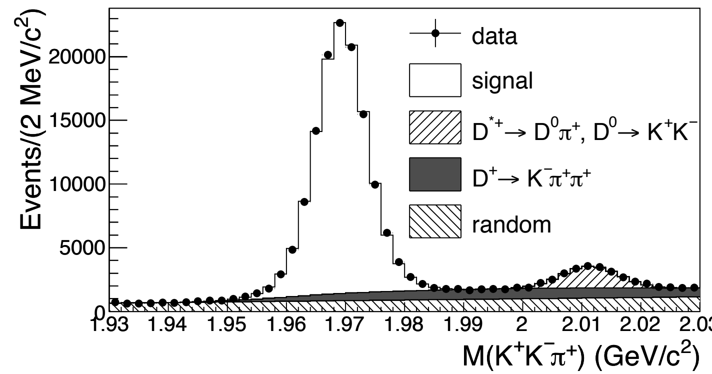
$$\frac{\mathcal{B}(D_s^+ \to K^+K^+\pi^-)}{\mathcal{B}(D_s^+ \to K^+K^-\pi^+)} \frac{\mathcal{B}(D^+ \to K^+\pi^+\pi^-)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = \tan^8\theta_C$$

H. J. Lipkin, Nucl. Phys. B, Proc. Suppl. 115, 117 (2003).

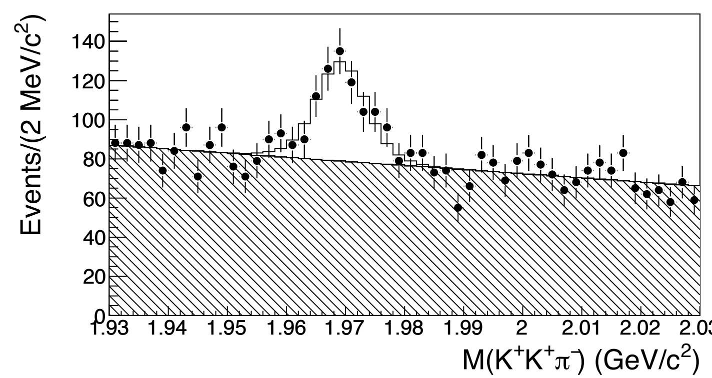
Phys. Rev. Lett. 102, 221802 (2009)

1st Observation of $D_s^+ \to K^+K^+\pi^-$ by BELLE

- BELLE made the first observation of DCS $D_s^+ \to K^+K^+\pi^-$. Use CF $D_s^+ \to K^+K^+\pi^-$. as normalisation.



- Repeat measurement with SU(3)-flavour related D+ modes.



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Phys. Rev. Lett. 102, 221802 (2009)

Recent first observations at the B factories

$D^0 \to \omega\eta$ $(2.21 \pm 0.08 \pm 0.22)\cdot 10^{-3}$

$D^0 \to K^{*0}\eta$ $(4.8 \pm 1.0 \pm 0.4)\cdot 10^{-5}$

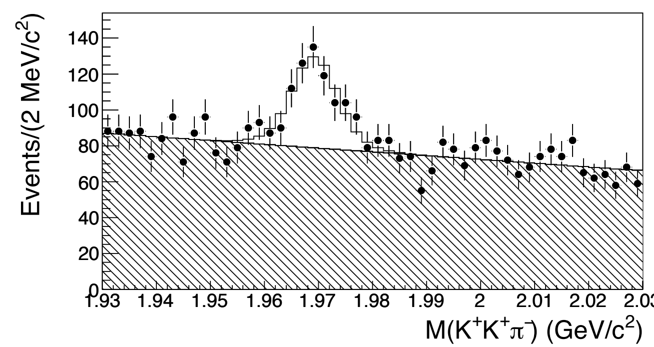
BaBar preliminary (2009)

Caitlin Malone on behalf of BaBar at APS April Meeting 2009

$D_s^+ \to K^+K^+\pi^-$ $(1.3 \pm 0.2 \pm 0.1)\cdot 10^{-4}$

BELLE 2009

BELLE: Phys. Rev. Lett. 102, 221802 (2009)



BELLE:	Expect from SU(3)	get
$\frac{\Gamma(D^+ \to K^+K^+\pi^-)}{\Gamma(D^+ \to K^+K^-\pi^+)} \frac{\Gamma(D^+ \to K^+\pi^+\pi^-)}{\Gamma(D^+ \to K^-\pi^+\pi^+)}$	$\tan^8\theta$ H. J. Lipkin, Nucl. Phys. B, Proc. Suppl. 115, 117 (2003).	$(1.57 \pm 0.21)\times\tan^8\theta$ BELLE: Phys. Rev. Lett. 102, 221802 (2009)

SU(3) tests

	Expect from SU(3)	get
$\frac{\Gamma(D^+ \to K_S\pi^+) - \Gamma(D^+ \to K_L\pi^+)}{\Gamma(D^+ \to K_S\pi^+) + \Gamma(D^+ \to K_L\pi^+)}$	≈ 0.4 D.-N. Gao, Phys. Lett. B **645**, 59 (2007)	$0.022 \pm 0.016 \pm 0.018$ 281/pb at CLEO: PRL **100,** 091801 (2008)
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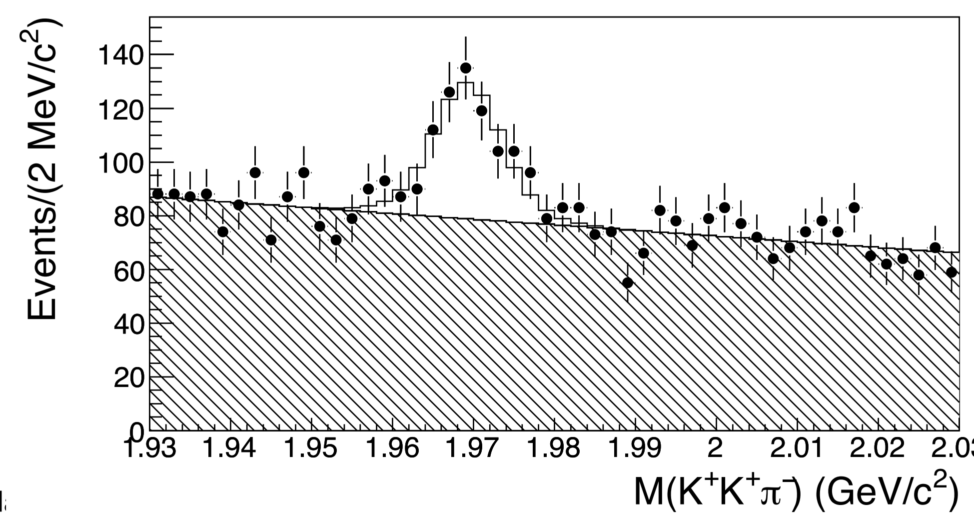
$\frac{\Gamma(D^+ \to K^+K^+\pi^-)\,\Gamma(D^+ \to K^+\pi^+\pi^-)}{\Gamma(D^+ \to K^+K^-\pi^+)\,\Gamma(D^+ \to K^-\pi^+\pi^+)}$	$\tan^8\theta$ H. J. Lipkin, Nucl. Phys. B, Proc. Suppl. 115, 117 (2003).	$(1.57 \pm 0.21)\times\tan^8\theta$ BELLE: Phys. Rev. Lett. 102, 221802 (2009)

1st Observation of $D_s^+ \to K^+K^+\pi^-$ (BELLE 2009)



Prospects for direct CPV

- Example: $D^o \rightarrow K^+K^-$
  - BaBar 2008: (0.00 ± 0.34 ± 0.13)%
  - BELLE 2008: (-0.43 ± 0.30 ± 0.11)%
  - World average (HFAG): (+0.22 ± 0.37)%
- CDF has obtained its result of (+2.0 ± 1.2 ± 0.6)% with only 2% of its current data set. CDF could beat world stat precision now.
- LHCb expects stat precision of ~0.1% in 1/fb

Charm Physics with the first LHCb data

- LHCb gets more charm than B. Charm measurements highly sensitive to New Physics:

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1$$

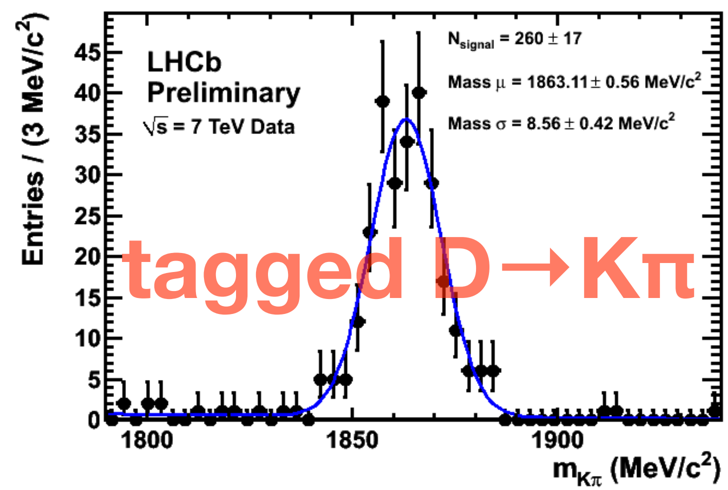
$$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)}$$

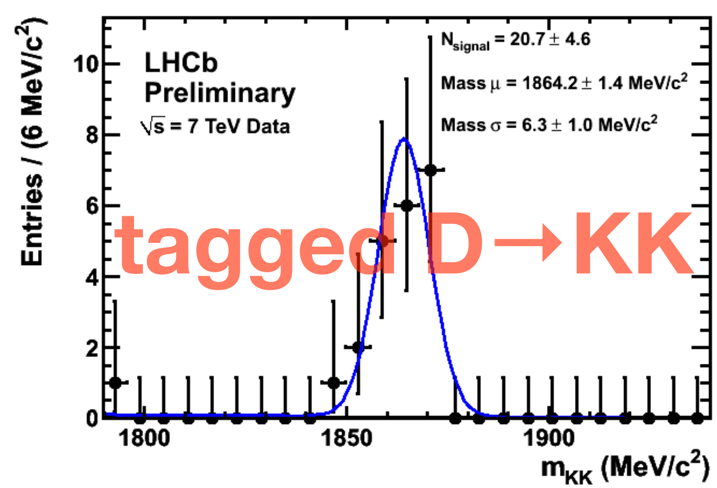
- Best measurement currently by BELLE who have ca 100,000 flavour-tagged (i.e. know if it's a D or a D-bar) D→KK in 540/fb.

- We expect a few million such events in the first 0.1/fb.

Charm in our first

0.8/nb = 0.000008/fb





$D^o \rightarrow V\eta$

Mode	Theory B.F. /10^{-3} B. Bhattacharya, J. L. Rosner, arXiv: 0812.3167v1 [hep-ph] (2008)		Experiment previously[1]	BaBar Results (preliminary) April 09 [2]	
	Sol A	Sol B		BF / 10^{-3}	yield
$D^o \rightarrow \varphi\eta$	0.93 ± 0.09	1.4 ± 0.1	0.14 ± 0.04	0.21 ± 0.01 ± 0.02	513 ± 26
$D^o \rightarrow \omega\eta$	1.4 ± 0.09	1.27 ± 0.09		2.21 ± 0.08 ± 0.22	4450 ± 103
$D^o \rightarrow K^{*o}\eta$	0.038 ± 0.004	0.037 ± 0.004		0.048 ± 0.010 ± 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

Dalitz Plot

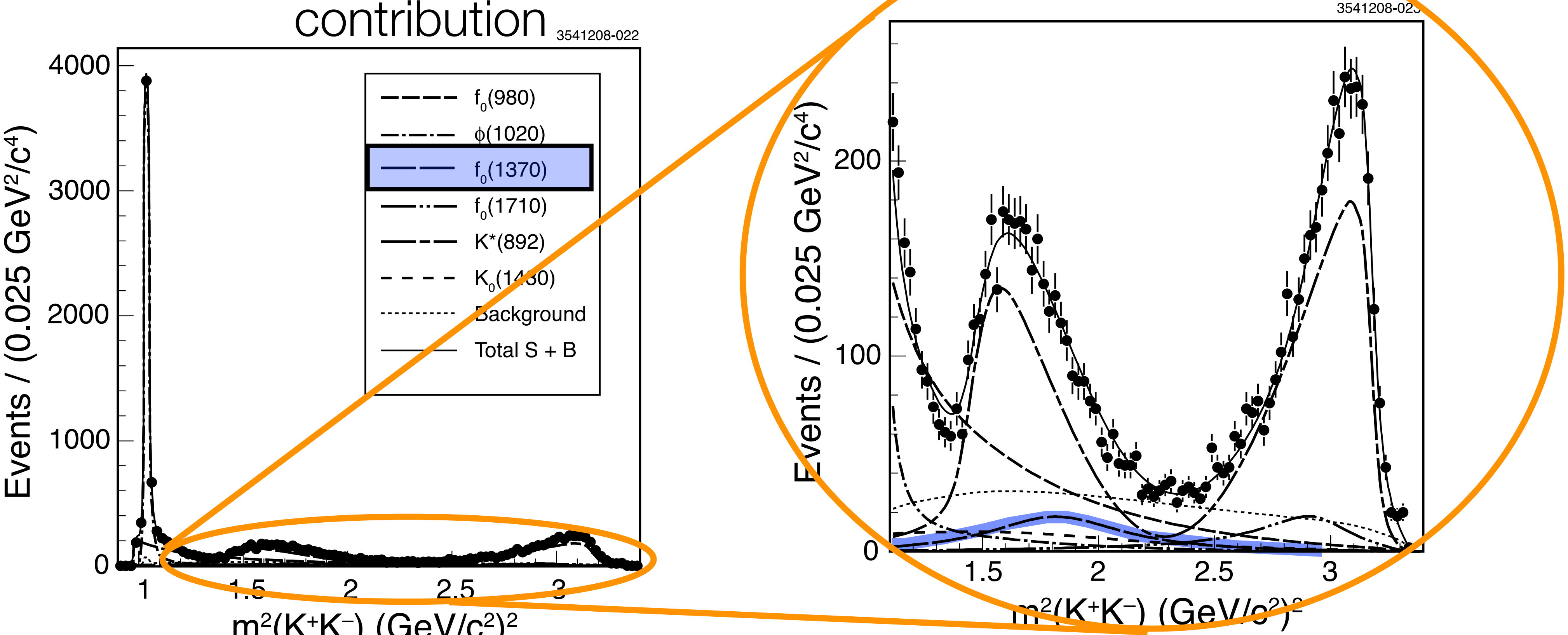
R.H. Dalitz, Philos. Mag. 44, 1068 (1953)

$D_S^+ \rightarrow K^- K^+ \pi^+$

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

$D_S^+ \rightarrow K^- K^+ \pi^+$ $M^2(KK)$ projections

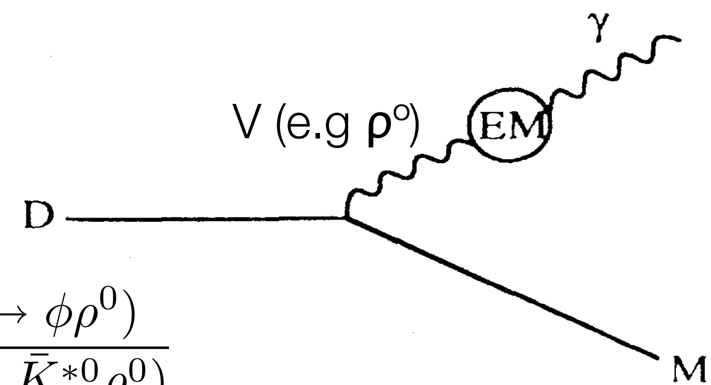
CLEO: arXiv:0903.1301v1 [hep-ex] (March 2009)



[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)

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

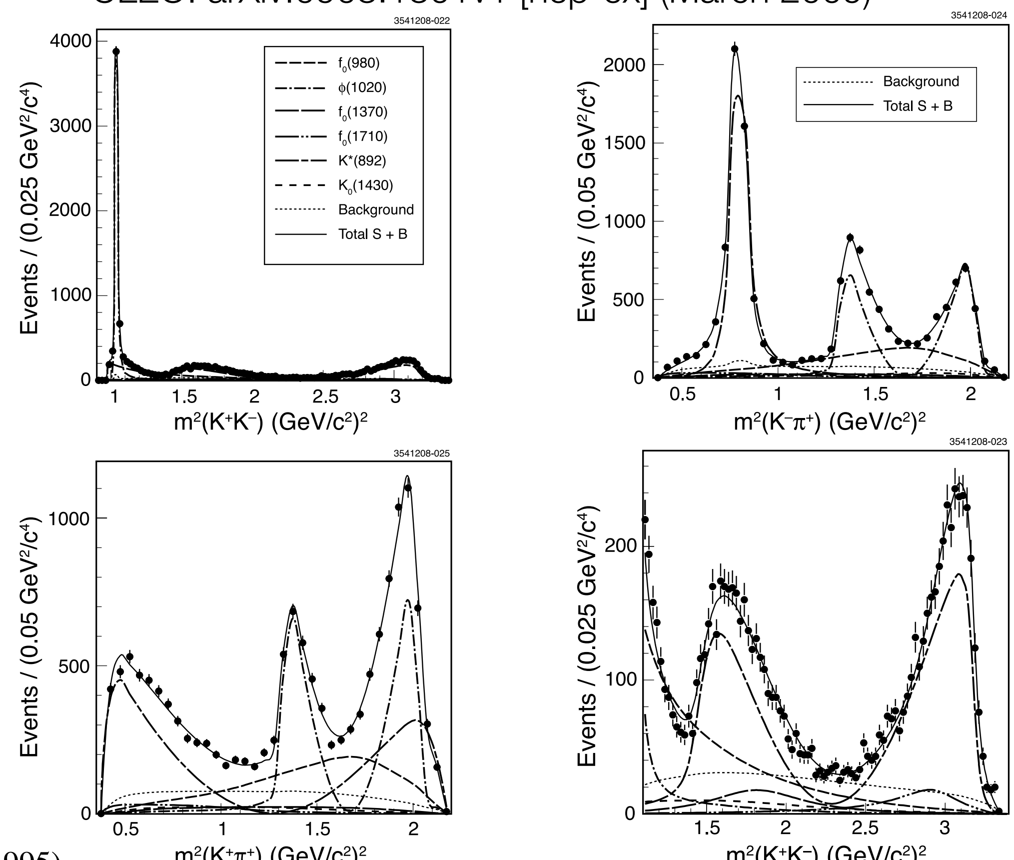
[1] G. Burdman, E. Golowich, J. L. Hewett, and S. Pakvasa, Phys. Rev. , 6383 (1995)

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

- 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 $f_0(1370)$

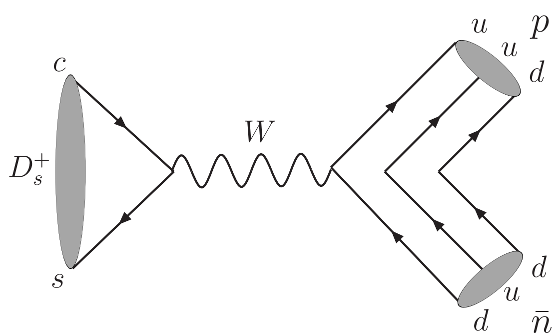
12k $D_S^+ \to K^- K^+ \pi^+$ fit projections

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



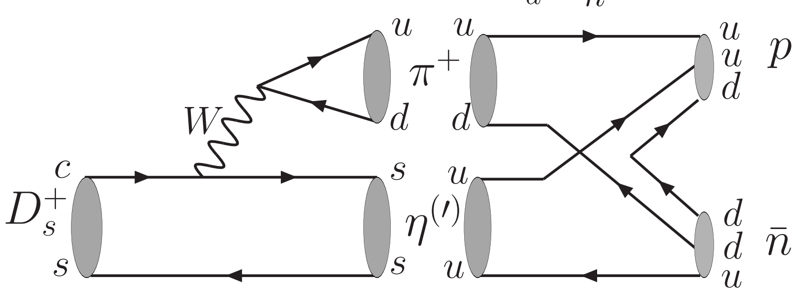
[1] P.L. Frabetti et al. (E687 Collaboration), Phys. Lett., B351, 591 (1995)
[2] [4]A.M. Rahimi, FERMILAB-THESIS-2000-13
[3] S. Malvezzi, AIP Conf. Proc. 549, 569 (2002)

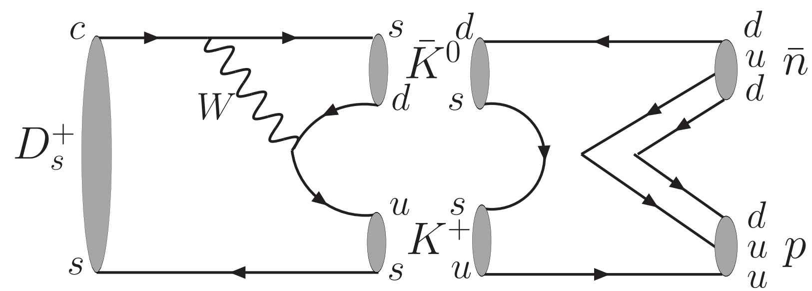
Theory of $D_s^+ \to pn$



- Short Distance:

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



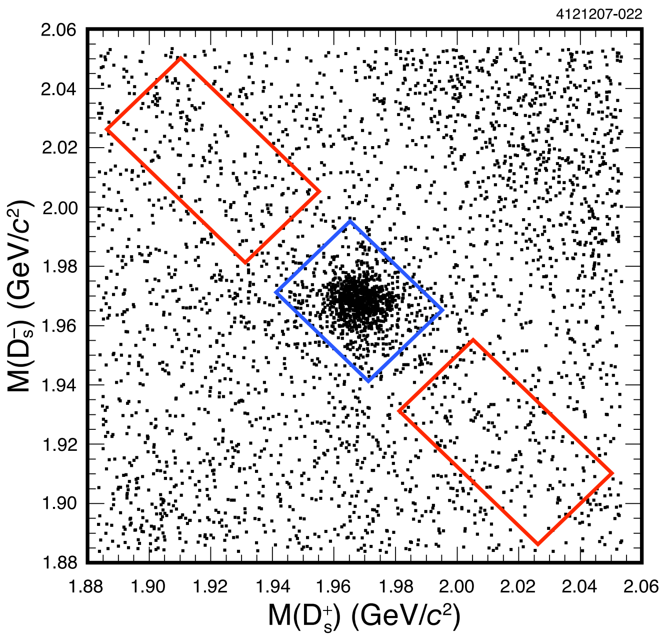


- Long Distance $\mathcal{B}(D_s^+ \to p\bar{n}) \approx \left(0.8^{+2.4}_{-0.6}\right) \times 10^{-3}$
- Measured $\mathcal{B}(D_s^+ \to p\bar{n}) = (1.30 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$

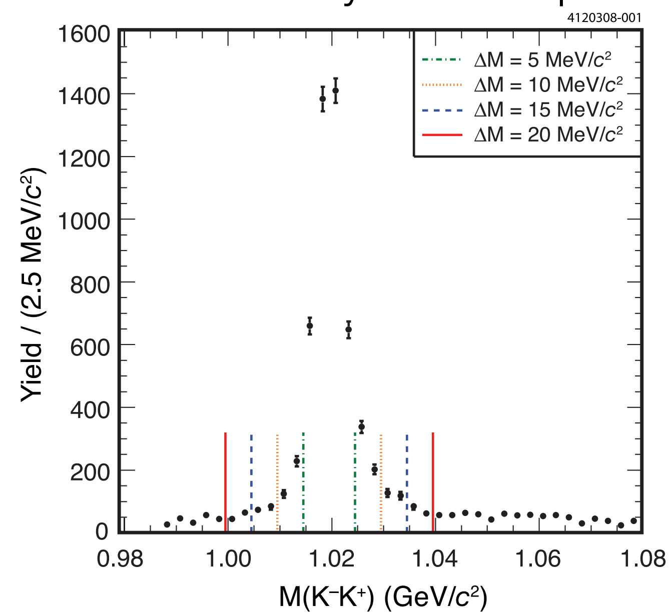
Chen, Cheng, Hsiao: Phys.Lett.B663:326-329,2008

Absolute Ds→KKπ BF at CLEO-c

M(D_s^-) vs M(D_s^+)



KK pair mass - full phase space (not just **φ**) included in analysis (see also Sheldon Stone's talk why this is important)



298 /pb of CLEO-c data at E_{cm} = 4.17 GeV

$B(D_s \to K^- K^+ \pi^+) = (5.50 \pm 0.23 \pm 0.16)\%$

Phys.Rev.Lett.100:161804,2008 (arxiv)

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

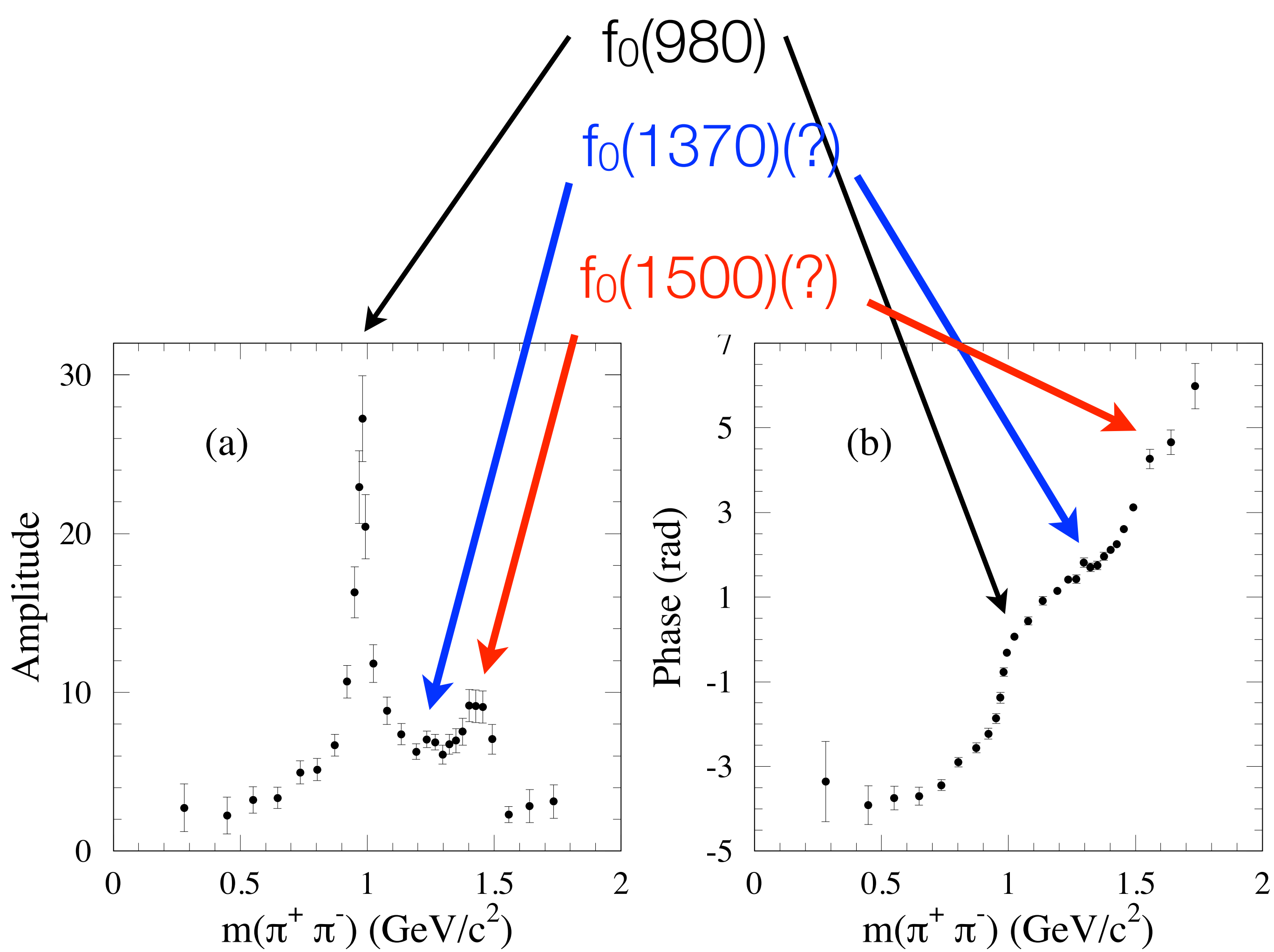
- $D_S^+ \to (\pi^+\pi^-)_{S\text{-wave}}\ \pi^+$ dominates.
- Model-independent S-wave fit compatible with $f_0(980)$ resonance.
- Also with FOCUS's K-matrix and E791's isobar fit
- Signs of something going on near $f_0(1370)$, $f_0(1500)$.
- Large D-wave component with $f_2(1270)$

Fit Fractions

Decay Mode	Decay fraction(%)
$f_2(1270)\pi^+$	$10.1\pm1.5\pm1.1$
$\rho(770)\pi^+$	$1.8\pm0.5\pm1.0$
$\rho(1450)\pi^+$	$2.3\pm0.8\pm1.7$
$\mathcal{S}$-wave	$83.0\pm0.9\pm1.9$
Total	$97.2\pm3.7\pm3.8$
χ^2/NDF	$\frac{437}{422-64} = 1.2$

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

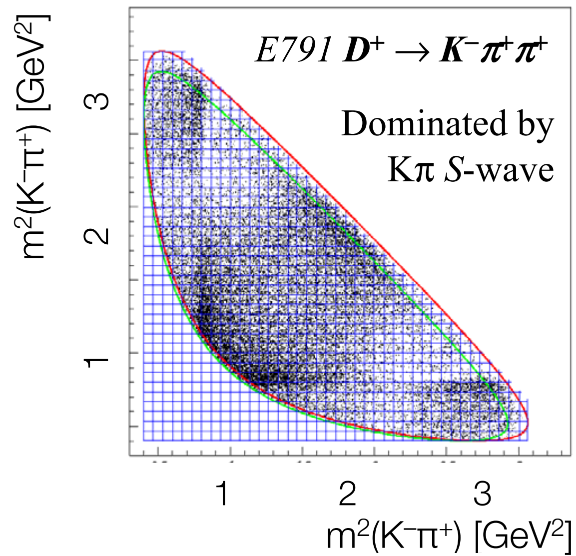
$D_S^+ \to \pi^-\pi^+\pi^+$
Model independent S-wave parameterisation



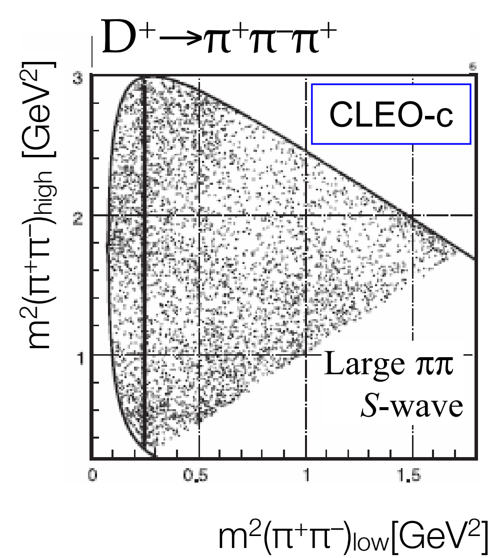
BaBar: arXiv:0808.0971v3 [hep-ex], submitted to PRD

S-wave

- S-wave resonances $\sigma \rightarrow \pi^+\pi^-$, $\kappa \rightarrow K^+\pi^-$: are they real?
  - needed in isobar fits to $D^+ \rightarrow \pi^+\pi^-\pi^+$, $D^0 \rightarrow K_S\pi^+\pi^-$, $D^+ \rightarrow K^-\pi^+\pi^+$
  - unclear if compatible with LASS scattering data
  - not required in $D^0 \rightarrow K^-\pi^+\pi^0$, $D^0 \rightarrow \pi^+\pi^-\pi^0$ isobar fits (BaBar, PhysRevD.74.091102).
- K-matrix Models don't explicitly require σ, κ.



Phys. Rev. Lett 89, 121801 (2002)



P. Naik on behalf of CLEO at HADRON 07

Hadronic Charm decays

- Crucial for B physics, especially for a high-precision measurement of CKM angle γ in B decays.
- Properties of the charm system such as mixing and CP violation. CPV in charm is highly sensitive to New Physics.
- Decay amplitudes and rates: important parameters that need to be measured, and provide a window to low-energy QCD, its symmetries (Isospin, U-spin, SU(3)-flavour, ...) and how they are broken.
- Properties of light meson resonances - important in its own right, but could become very revelant for precision charm and B physics Dalitz analyses.

B

↓

D

↓

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

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

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B

↓

D

↓

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

BR($D^+_{(s)}$ →K_SK^+), BR($D^+_{(s)}$ →$K_S\pi^+$) at BELLE

- Precise Ratio of BR recently measured at BELLE (using CF modes $D^+ \to K_S\pi^+$, $D_s^+ \to K_SK^+$ for normalisation)

$$\mathcal{B}(D^+ \to K_S^0 K^+) = (2.75 \pm 0.08) \times 10^{-3}$$

$$\mathcal{B}(D_s^+ \to K_S^0 \pi^+) = (1.20 \pm 0.09) \times 10^{-3}$$

- Ratio not what you'd expect from SU(3).

$$\mathcal{B}(D^+ \to K_S^0 K^+)/\mathcal{B}(D_s^+ \to K_S^0 \pi^+) = 2.29 \pm 0.18$$

- $D_s^+ \to K_SK^+$, $D_s^+ \to K_S\pi^+$ also used for CPV measurement - see Anze Zupanc's talk

PhysRevLett.104.181602 (2010)

PhysRevD.80.111101 (2009)