Determination of Hadronic Branching Ratios and New Modes

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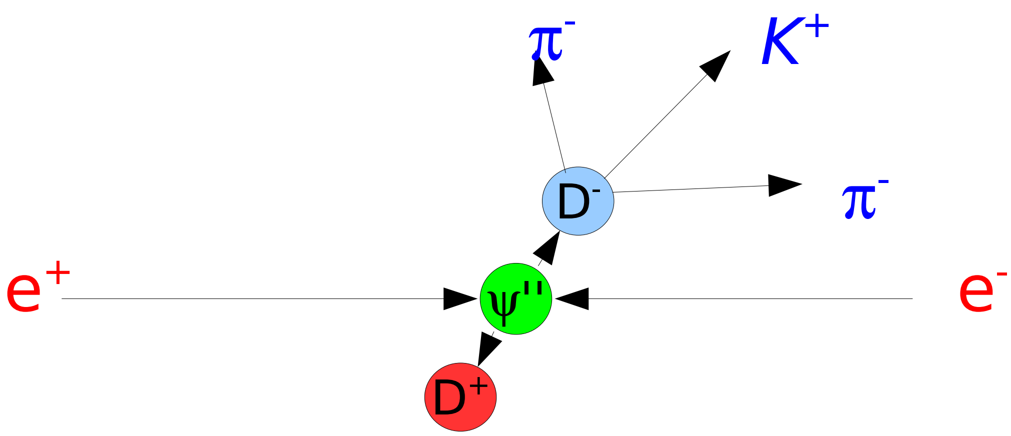
Outline:
- Absolute Charm Branching Fractions
  - D^0 and D^+
  - D_s
- Rare and inclusive modes
- Final states with K_S or K_L

Absolute Hadronic D^0 and D^+ Branching Fractions

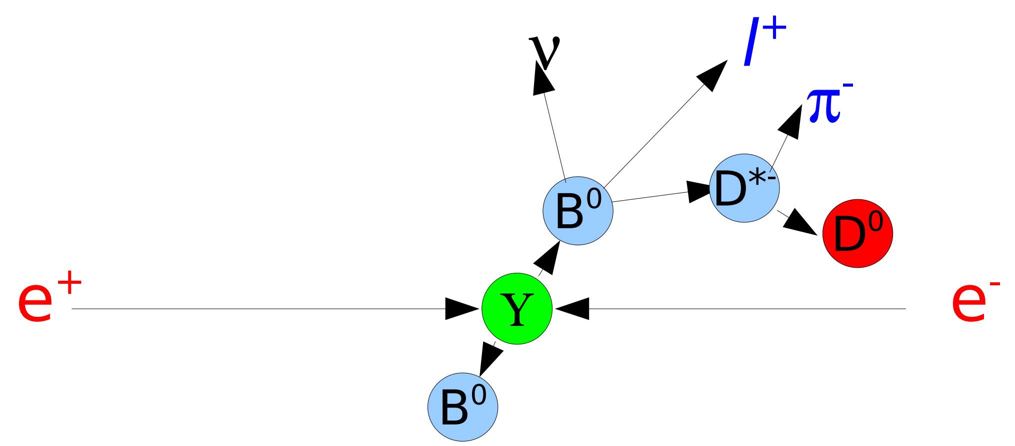
- Important to establish the branching fraction scale
  - Directly impact determination of *e.g.* V_{cb} from exclusive modes
- Need to 'count' the number of produced D mesons
  - Different techniques used

$c\bar{c}$-threshold



Tag by full reconstruction of one D

$\Upsilon(4S)$



Tag by partial reconstruction of lepton and slow pion (works only for D^0)

CLEO-c Hadronic *BrFr.*

- Use a 'double tag' technique, pioneered by MARK III

$$N_i = \epsilon_i B_i N_{D\overline{D}}$$

$$\overline{N}_j = \overline{\epsilon}_j B_j N_{D\overline{D}}$$

$$N_{ij} = \epsilon_{ij} B_i B_j N_{D\overline{D}}$$

$$N_{D\overline{D}} = \frac{N_i \overline{N}_j \epsilon_{ij}}{N_{ij} \epsilon_i \overline{\epsilon}_j} \qquad B_i = \frac{N_{ij} \epsilon_j}{N_j \epsilon_{ij}}$$

- The following final states are used
  D^0: $K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^-\pi^+$
  D^+: $K^-\pi^+\pi^+$, $K_s\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K_S\pi^+\pi^-\pi^+$, $K_S\pi^+\pi^0$, and $K^-K^+\pi^+$
- Determine separately the D and $\overline{D}$ yields
  - 18 single tag yields
  - 45 ($=3^2+6^2$) double tag yields
- In a combined χ^2 fit we extract 9 branching fractions and $D^0\overline{D}^0$ and D^+D^- yields. The fit includes the systematic errors.
- Many systematics cancel in the $D\overline{D}$ yield (*e.g.* tracking eff., PID eff.).

56 pb^{-1} (PRL 96, 092002)

Single Tag Yields (281 pb^{-1})

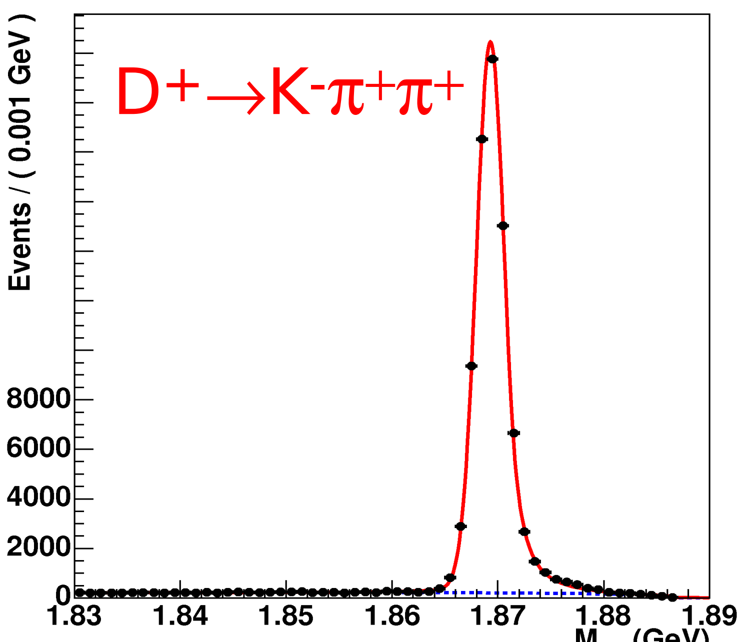
Extract yields from

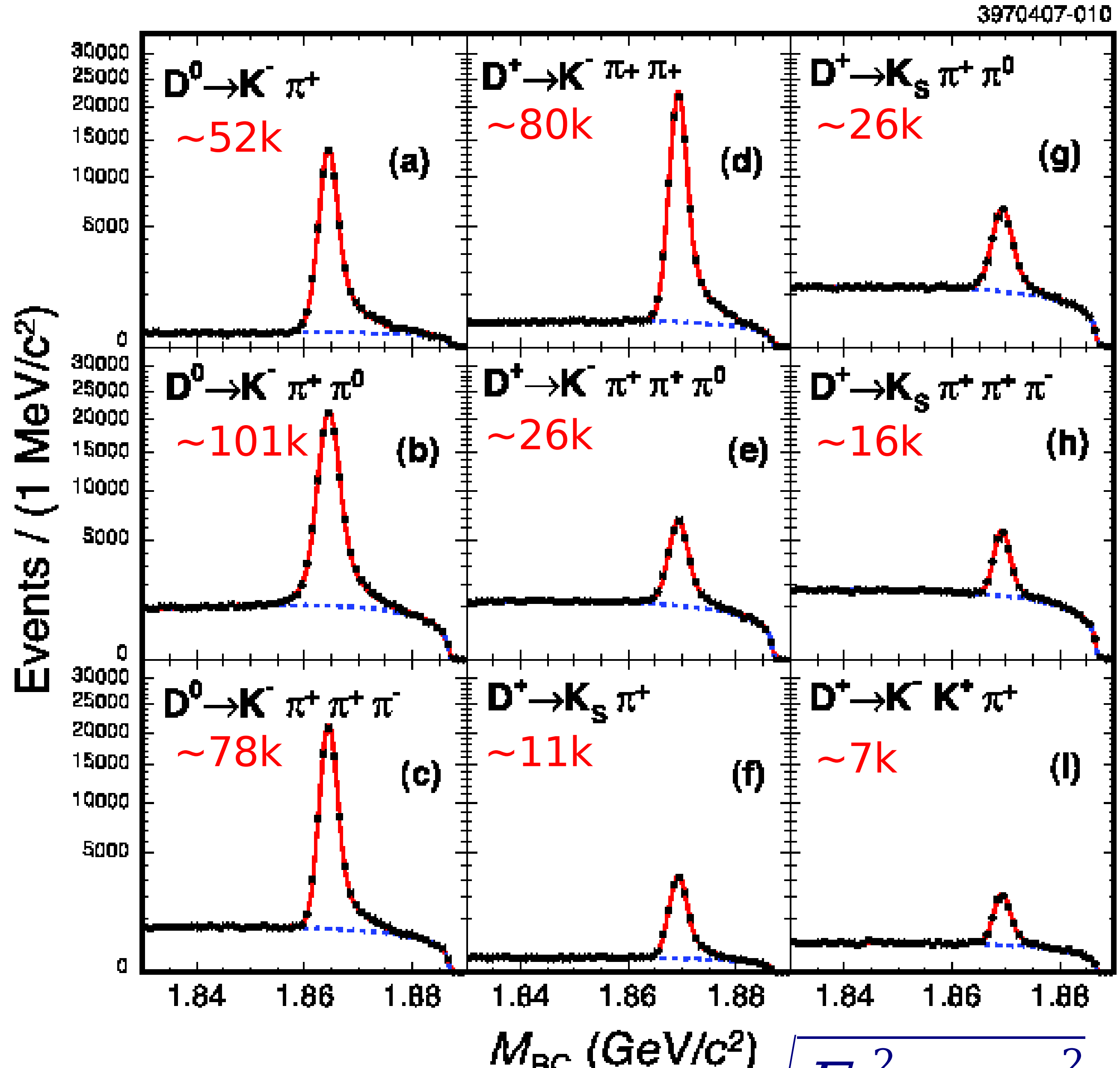
$$m_{BC} = \sqrt{E_{beam}^2 - P_D^2}$$

Lineshape includes

- Detector resolution
- ISR in $e^+e^- \to \psi(3770)$
- $\psi(3770)$ lineshape
- Beam energy spread

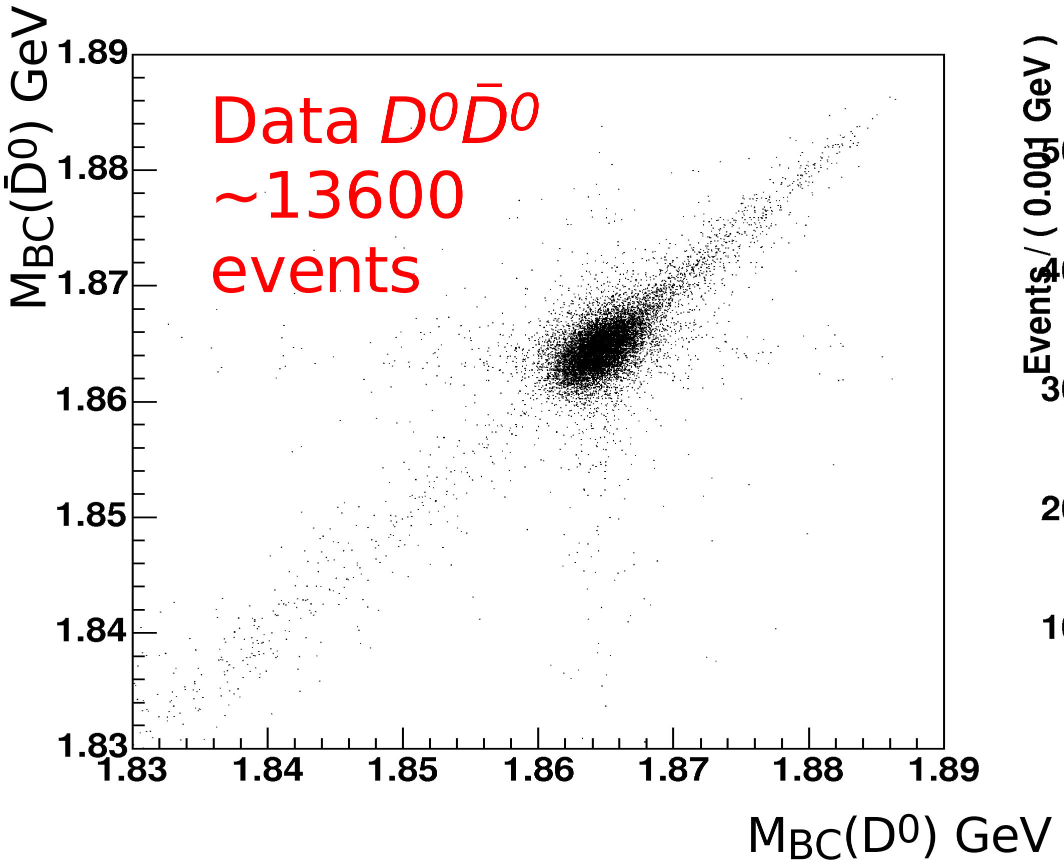
Linear scale

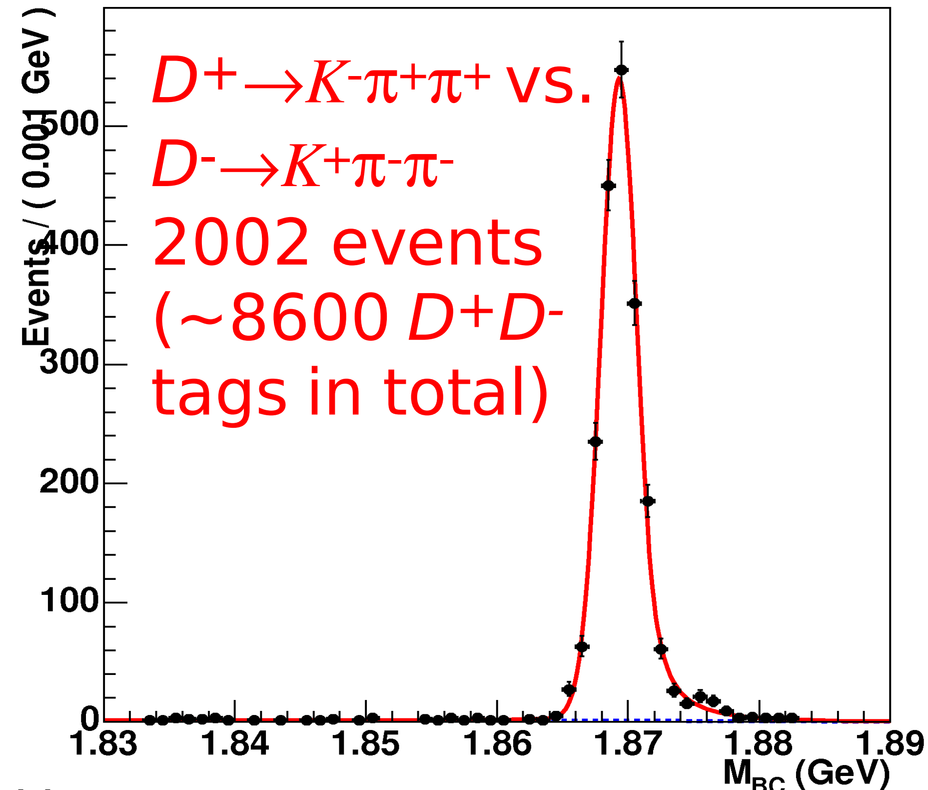




$$\sqrt{E_{beam}^2 - p_D^2}$$

Double Tag Yields (281 pb^{-1})

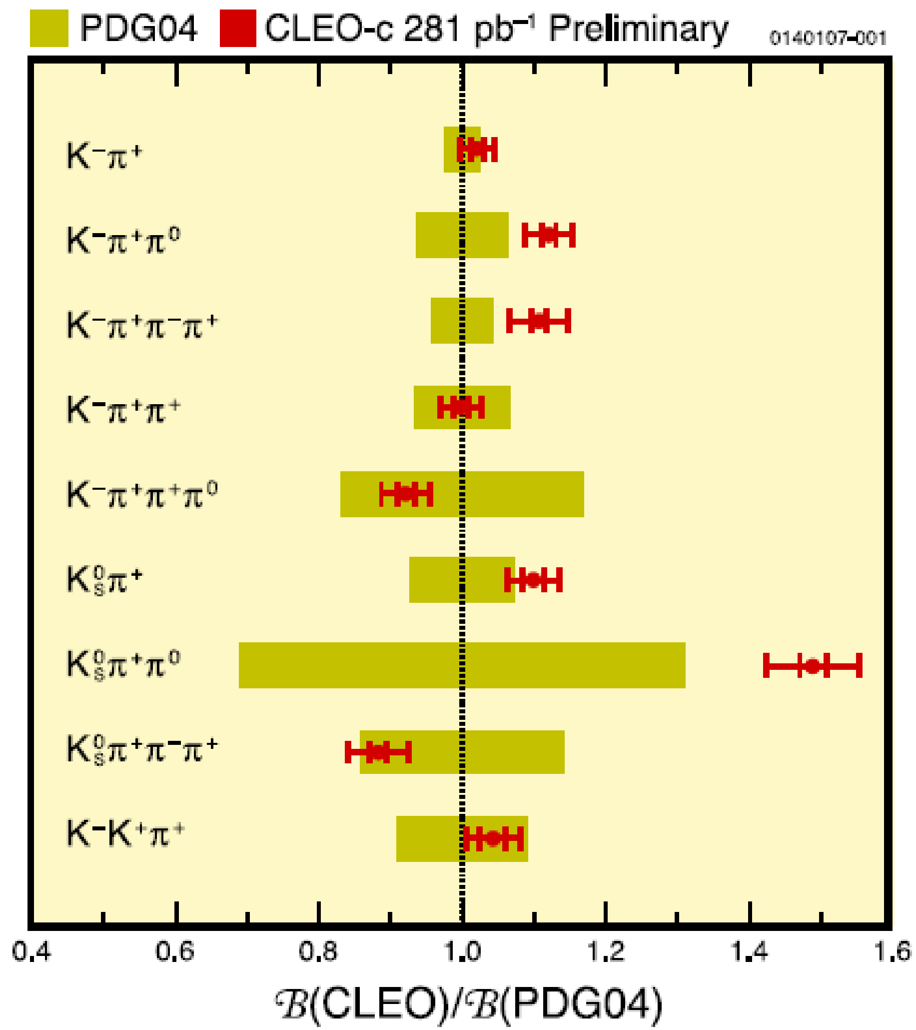




- Very clean signals in fully reconstructed events
- The statistical errors on the double tag yields set the scale of errors on the branching fractions

Preliminary Results for 281 pb^{-1}

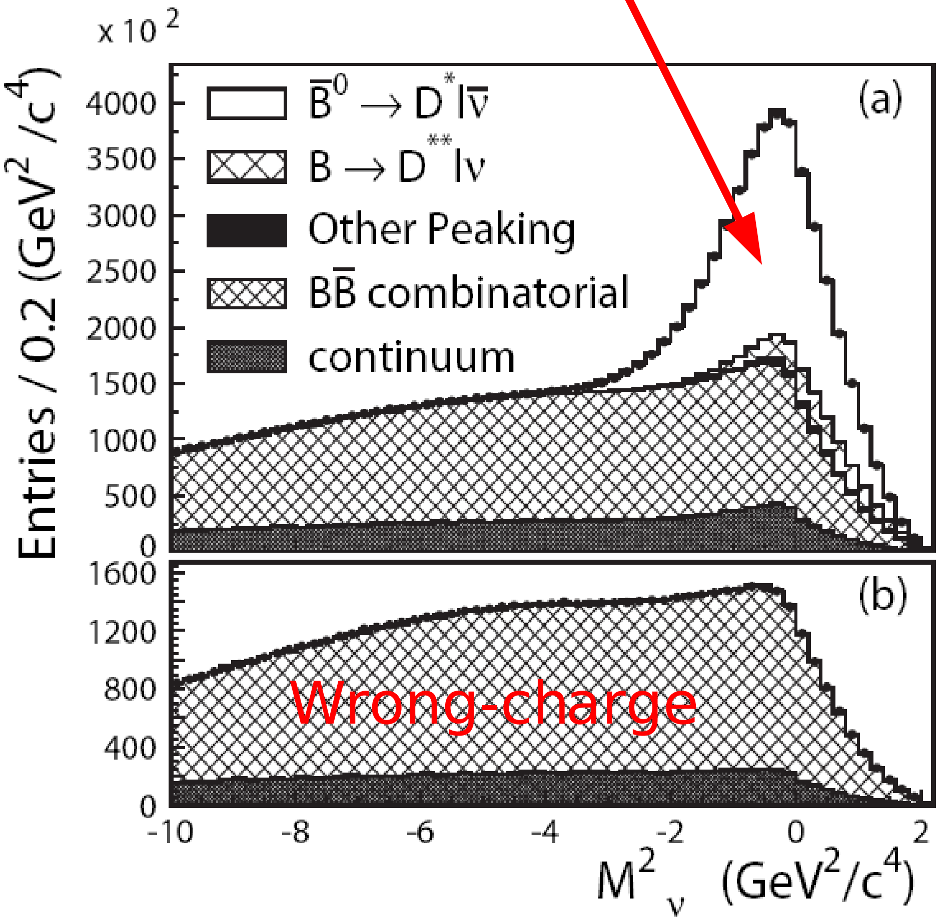
Mode	$\mathcal{B}$ (%)
$D^0 \to K^-\pi^+$	$3.87 \pm 0.04 \pm 0.08$
$D^0 \to K^-\pi^+\pi^0$	$14.6 \pm 0.1 \pm 0.4$
$D^0 \to K^-\pi^+\pi^-\pi^+$	$8.3 \pm 0.1 \pm 0.3$
$D^+ \to K^-\pi^+\pi^+$	$9.2 \pm 0.1 \pm 0.2$
$D^+ \to K^-\pi^+\pi^+\pi^0$	$6.0 \pm 0.1 \pm 0.2$
$D^+ \to K^0_S\pi^+$	$1.55 \pm 0.02 \pm 0.05$
$D^+ \to K^0_S\pi^+\pi^0$	$7.2 \pm 0.1 \pm 0.3$
$D^+ \to K^0_S\pi^+\pi^+\pi^-$	$3.13 \pm 0.05 \pm 0.14$
$D^+ \to K^+K^-\pi^+$	$0.93 \pm 0.02 \pm 0.03$

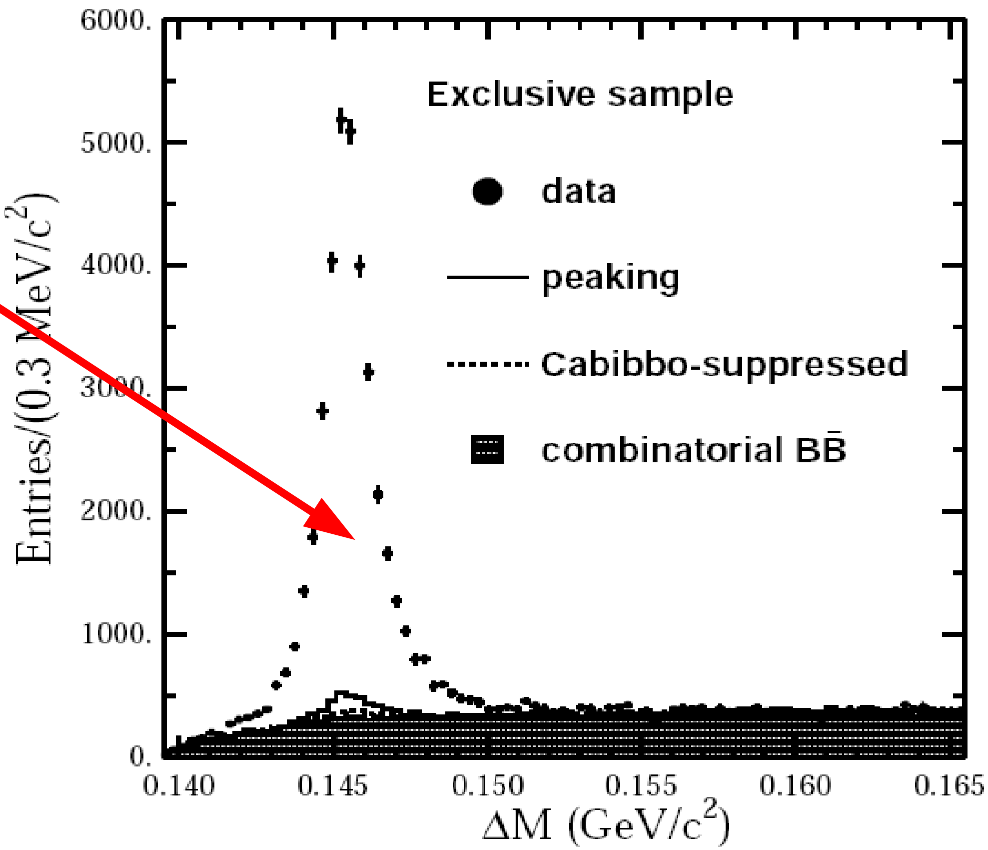


BABAR $D^0 \to K^- \pi^+$

arXiv:0704.2080
210 fb^{-1}

Source	Inclusive	Exclusive
Data	4412390 ± 2100	47270 ± 220
Continuum	460030 ± 2090	3090 ± 170
Combinatorial $B\overline{B}$	1781720 ± 680	8190 ± 50
Peaking	–	1630 ± 80
Cabibbo-suppressed	–	550 ± 10
Signal	2170640 ± 3040	33810 ± 290



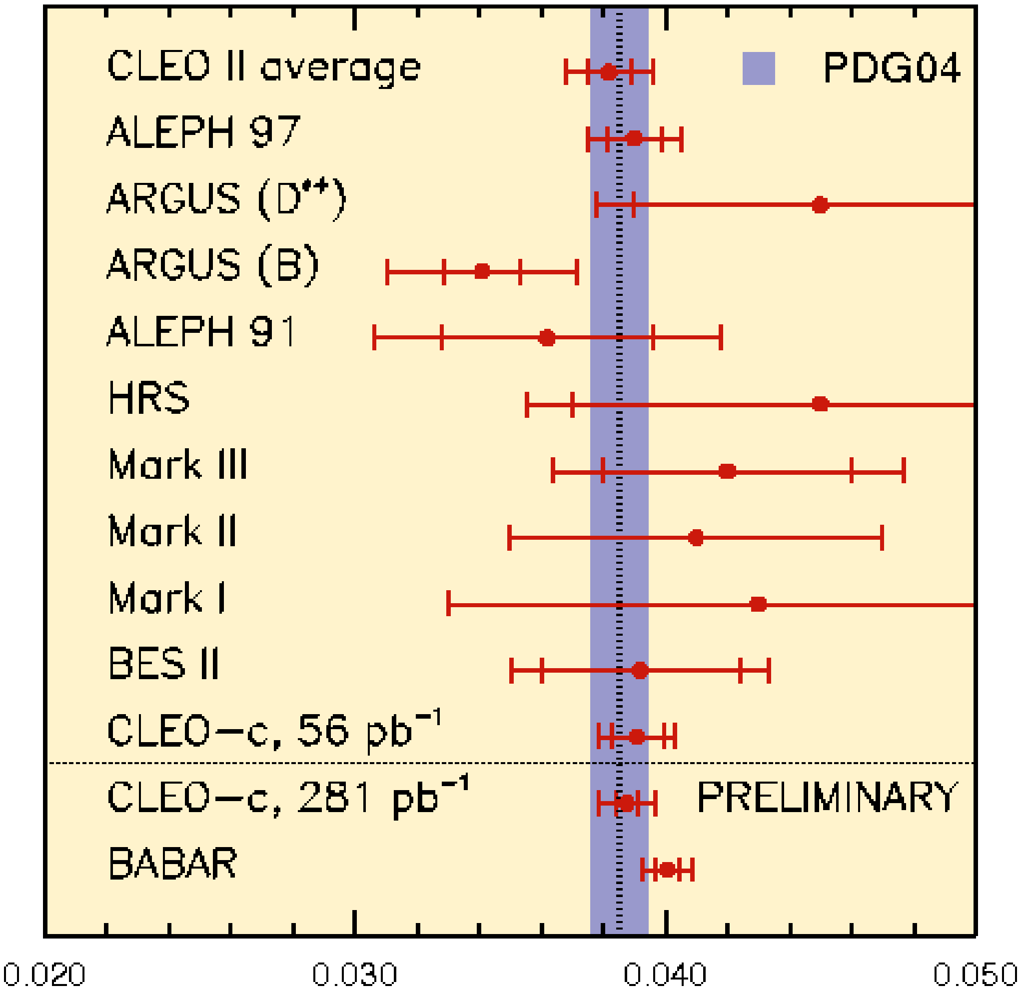


With $\varepsilon(K\pi)=39.96\%$

$\mathcal{B}(D^0 \to K^- \pi^+) = (4.007 \pm 0.037 \pm 0.070)\%$

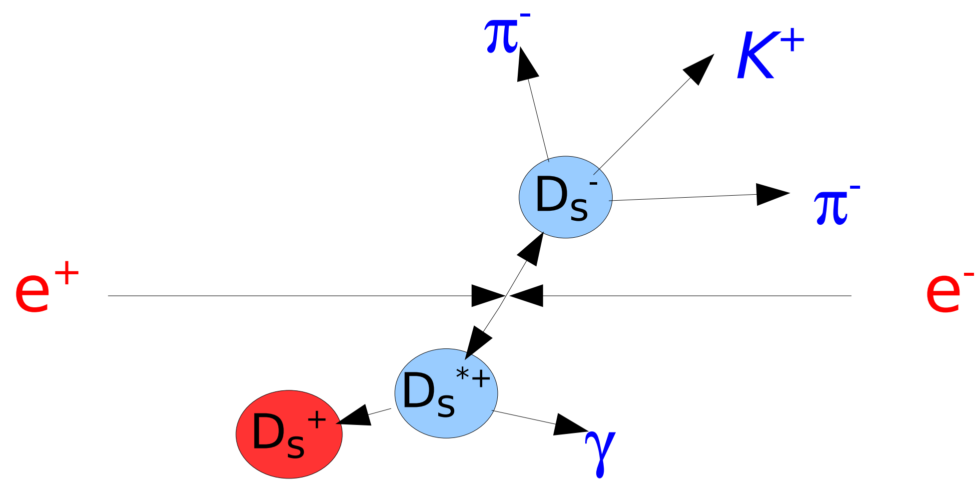
$D \rightarrow K\pi$ Summary

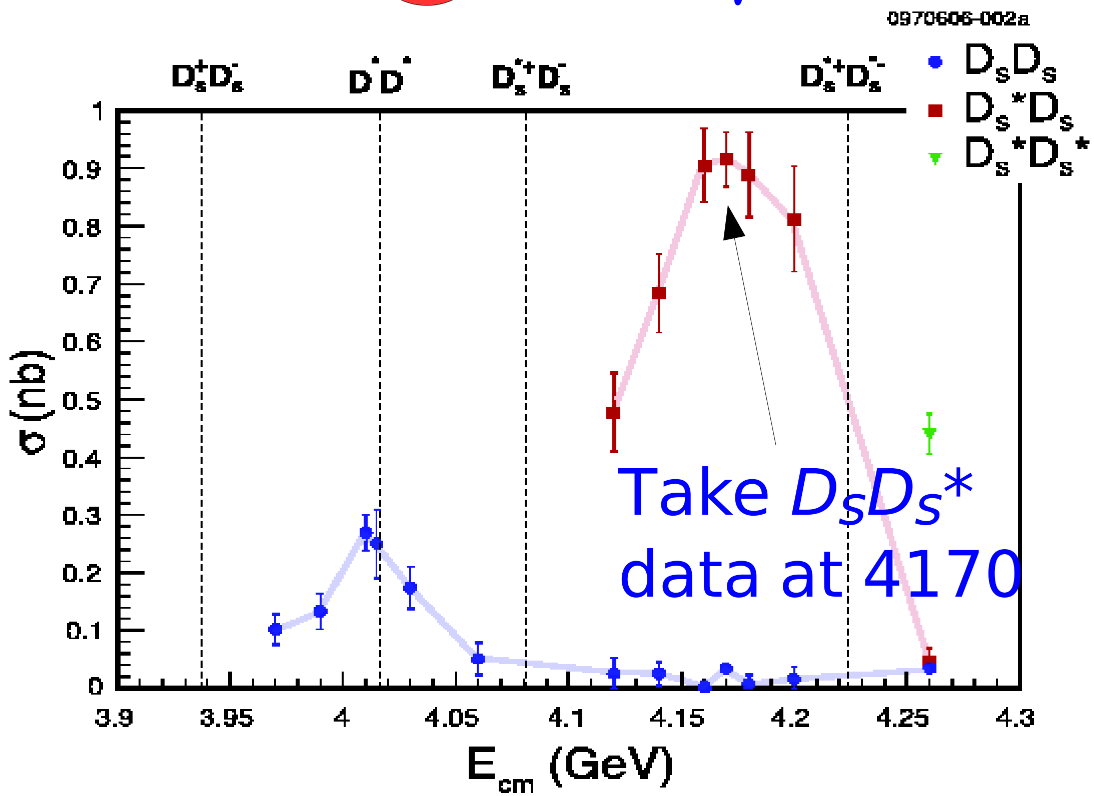
- Systematics limited:
  - Statistical: ~1%
  - Systematic: 1.5-2.0%
- Many systematic uncertainties at 1% level
- Some uncertainties that are determined in data will improve with more statistics, *e.g.,* tracking efficiencies and particle identification.
- CLEO-c doubly double Cabibbo suppressed decays
- Final state radiation is a 2-3% effect, rely on MC simulations.
- BABAR needs to understand background shapes very well.



CLEO-c D_s Branching Fractions

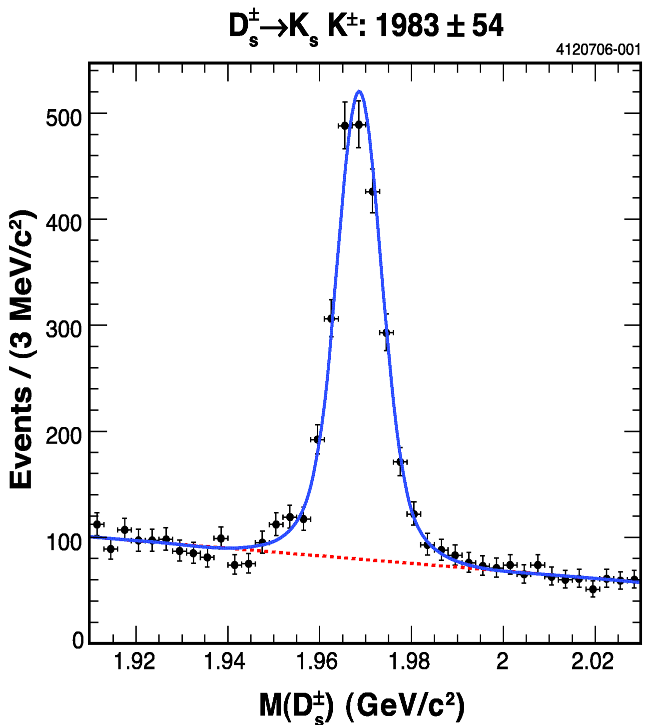
- Use same technique as for the D^0 and D^+ branching fractions
  - Pairs of D_s and D_s*
- Used 195 pb^{-1} of data recorded at (or near) E_{cm}=4170 MeV
- We study the final states:
  - $K_S K^+$
  - $K^+ K^- \pi^+$
  - $K^+ K^- \pi^+ \pi^0$
  - $\pi^+ \pi^- \pi^+$
  - $\eta \pi^+$
  - $\eta' \pi^+$

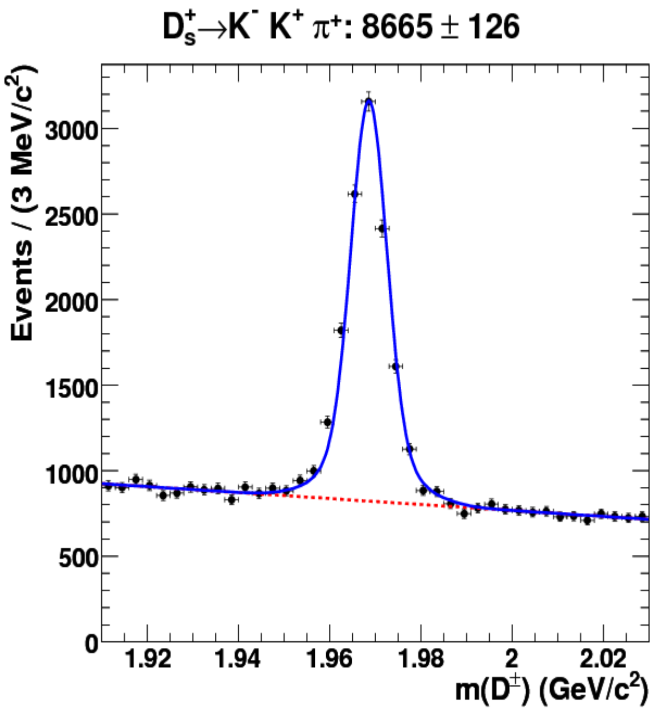


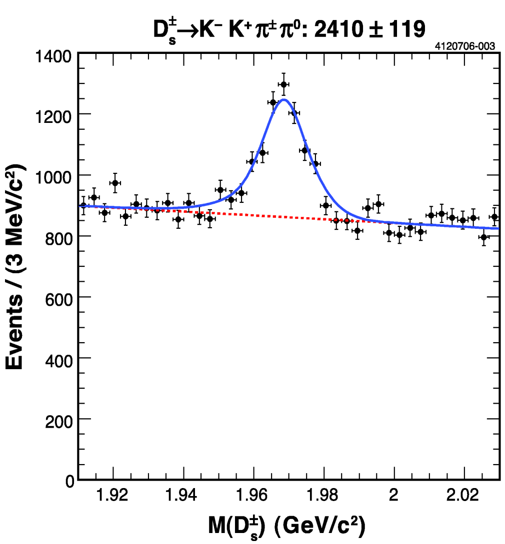


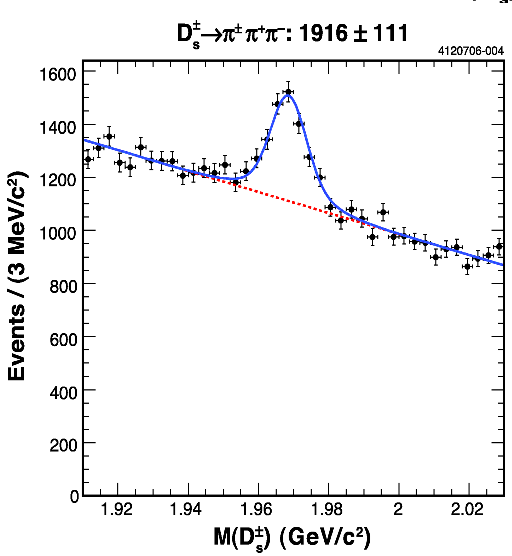
Single Tag Yields (195 pb^{-1})

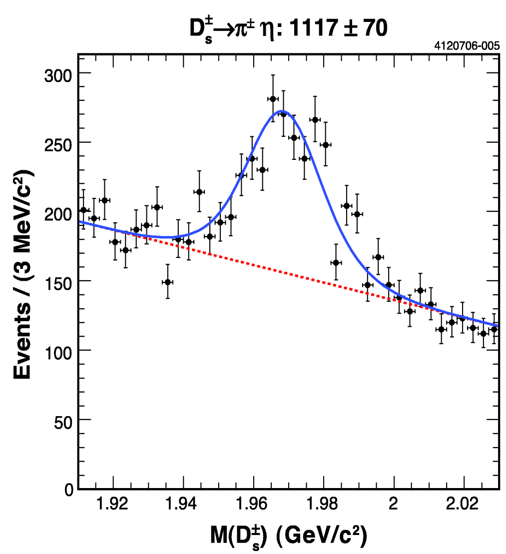
Mode	D_s+	D_s-
K_sK^+	1055±39	928±37
$K^+K^-\pi^+$	4316±89	4350±89
$K^+K^-\pi^+\pi$	1160±85	1251±84
$\pi^+\pi^-\pi^+$	970±80	947±78
$\eta\pi^+$	547±50	570±50
$\eta'\pi^+$	362±23	372±24

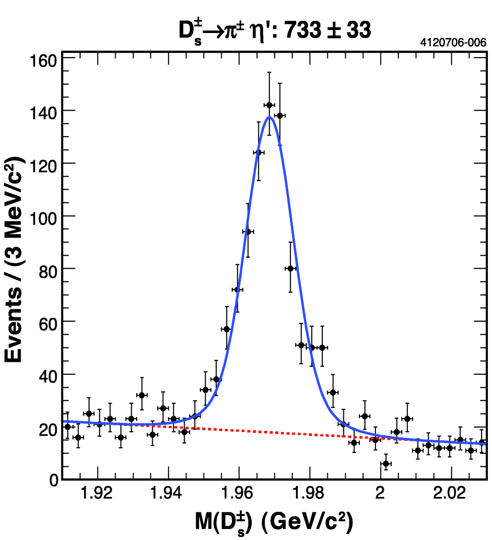




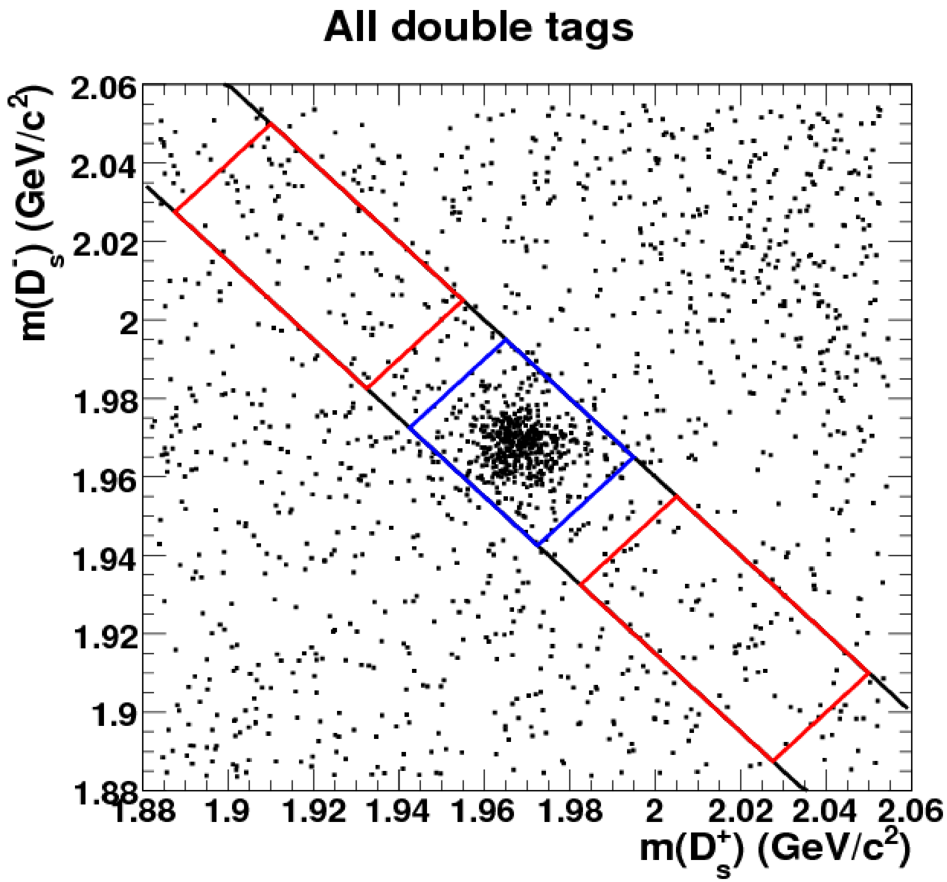


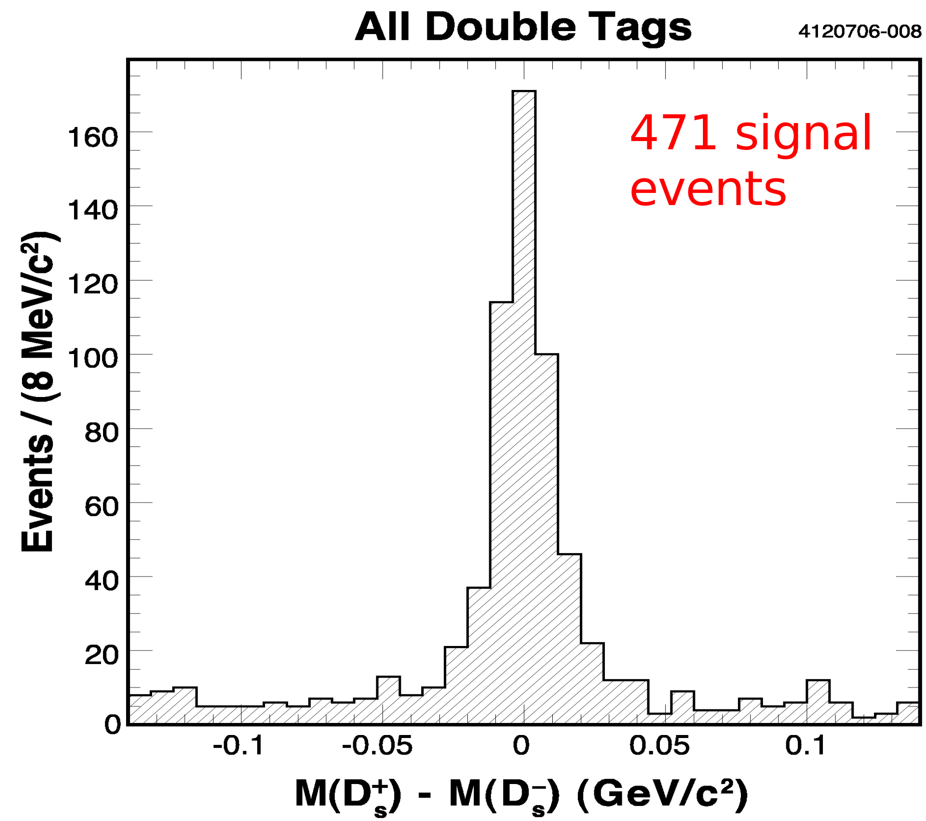






Double Tag Yields

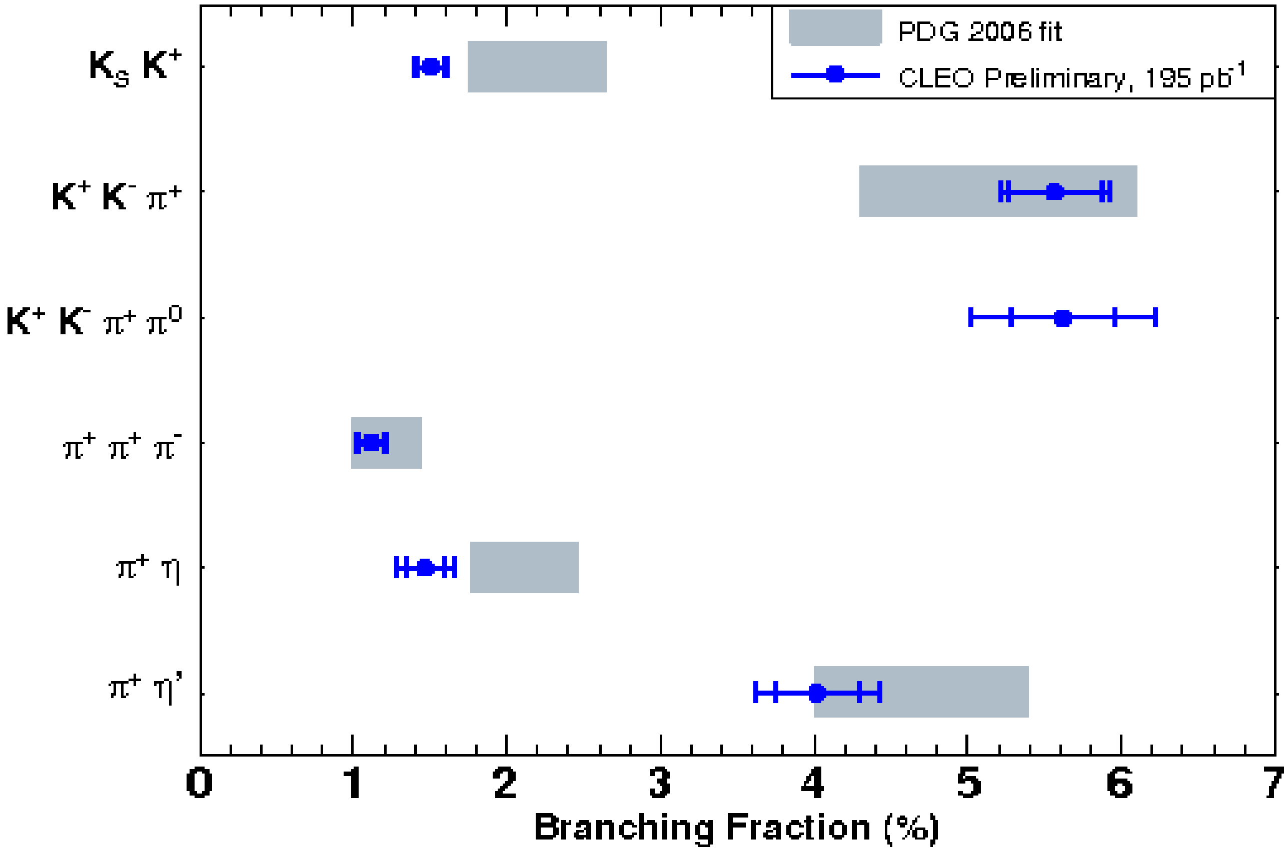




Yields from cut-and-count in blue signal region

	$K_S K^-$	$K^+K^-\pi^-$	$K^+K^-\pi^-\pi^0$	$\pi^-\pi^-\pi^+$	$\pi^-\eta$	$\pi^-\eta'$
$K_S K^+$	7.7	27.0	18.7	7.3	4.0	5.0
$K^-K^+\pi^+$	18.0	104.7	43.7	30.7	12.0	8.0
$K^-K^+\pi^+\pi^0$	8.7	35.7	14.0	13.3	1.0	5.7
$\pi^+\pi^+\pi^-$	3.3	22.7	16.0	13.3	4.7	4.0
$\pi^+\eta$	0.0	10.0	2.7	6.0	1.0	1.7
$\pi^+\eta'$	3.0	10.0	3.0	3.7	1.0	0.0

D_s Hadronic Branching Fractions



Mode	195 pb^{-1} (%)
$\mathcal{B}(K_S K^+)$	$1.50 \pm 0.09 \pm 0.05$
$\mathcal{B}(K^- K^+ \pi^+)$	$5.57 \pm 0.30 \pm 0.19$
$\mathcal{B}(K^- K^+ \pi^+ \pi^0)$	$5.62 \pm 0.33 \pm 0.51$
$\mathcal{B}(\pi^+ \pi^+ \pi^-)$	$1.12 \pm 0.08 \pm 0.05$
$\mathcal{B}(\pi^+ \eta)$	$1.47 \pm 0.12 \pm 0.14$
$\mathcal{B}(\pi^+ \eta')$	$4.02 \pm 0.27 \pm 0.30$

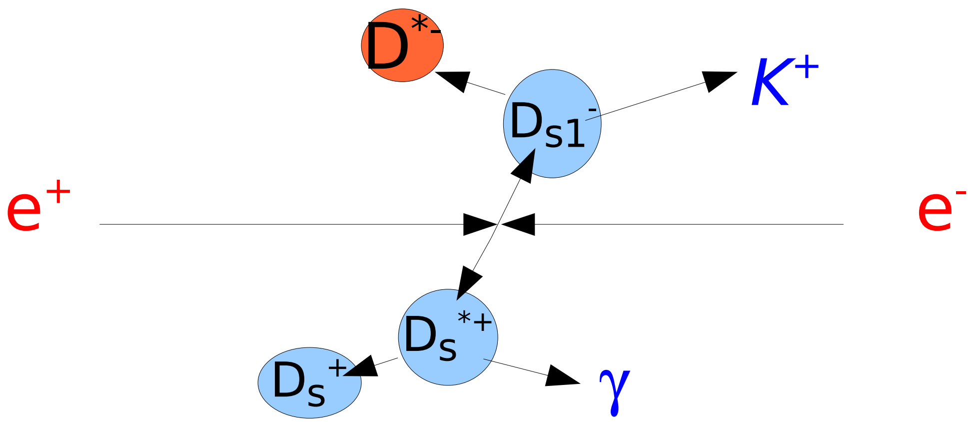
- Analysis is statistics limited
  - We have 300 pb^{-1} on tape
    - Final results this summer
- Plan to take ~300 pb^{-1} before CLEO-c running ends

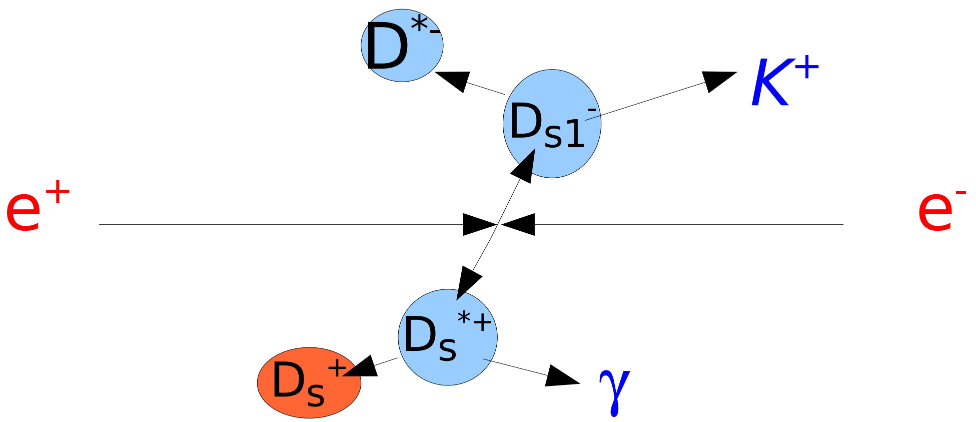
Belle $D_s^+ \to K^+K^-\pi^+$

- Using 0.55 ab^{-1} Belle partially reconstructs $e^+e^- \to D_s^* D_{s1}$

$N(D_s^{*+}) = N(e^+e^- \to D_s^* D_{s1})\,\varepsilon(D_s,\gamma,K)\,Br(D_s)$

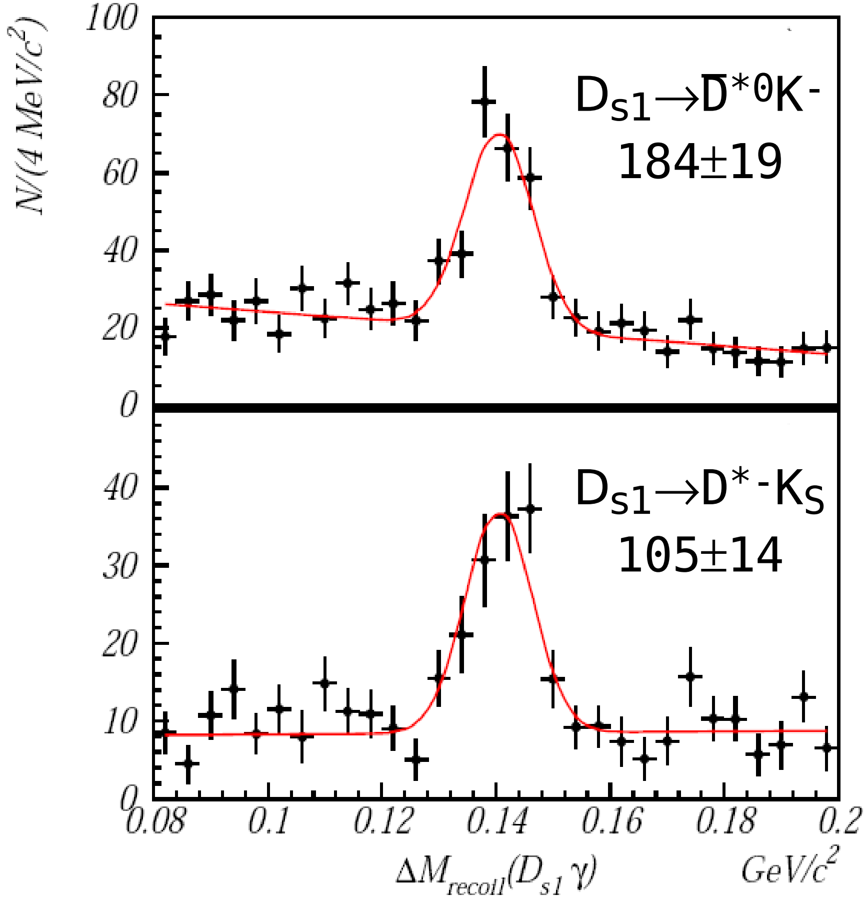
$N(D_{s1}^-) = N(e^+e^- \to D_s^* D_{s1})\,\varepsilon(D^*,\gamma,K)\,Br(D^*)$

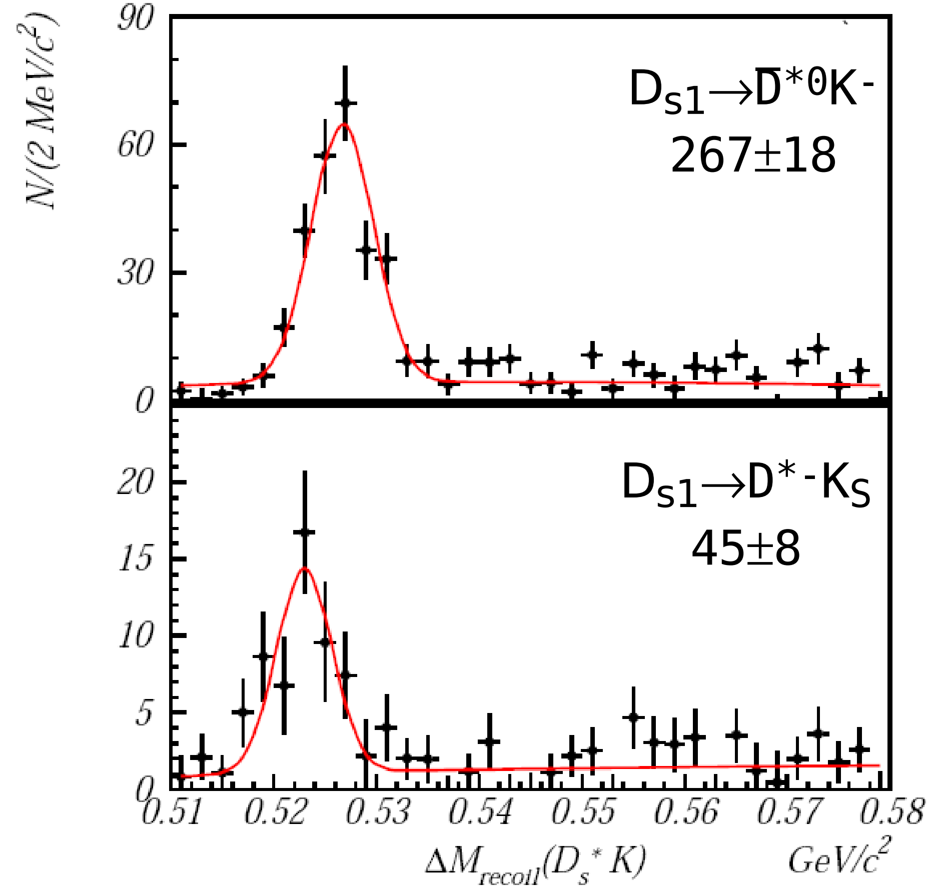




$$\mathcal{B}(D_s^+ \to K^+K^-\pi^+) = \frac{N(D_s^{*+})}{N(D_{s1}^-)} \cdot \frac{\epsilon(D_{s1}^-)}{\epsilon(D_s^{*+})} \cdot \mathcal{B}(\overline{D}^{(*)})$$

Belle $D_s \to KK\pi$





$B(D_s^+ \to K^+ K^- \pi^+) = (4.0 \pm 0.4 \pm 0.4)\%$

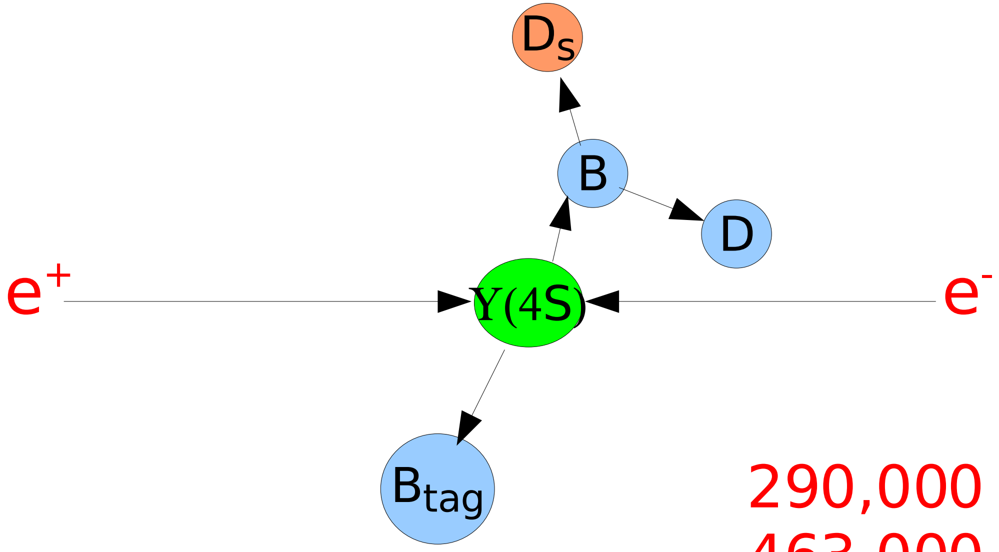
CLEO-c (preliminary):
$B(D_s^+ \to K^+ K^- \pi^+) = (5.57 \pm 0.30 \pm 0.19)\%$

BABAR $D_s \to \phi\pi$

- Using $B \to D^* D_s^*$ BABAR has previously measured
  $\mathcal{B}(D_s \to \phi\pi) = (4.81 \pm 0.52 \pm 0.38)\%$

PRD 71 091104 (2005)

- Using events in which one B meson is fully reconstructed and and either a $D^{(*)}$ or $D^{(*)}_{s(J)}$ is reconstructed they use a missing mass technique to identify the final states

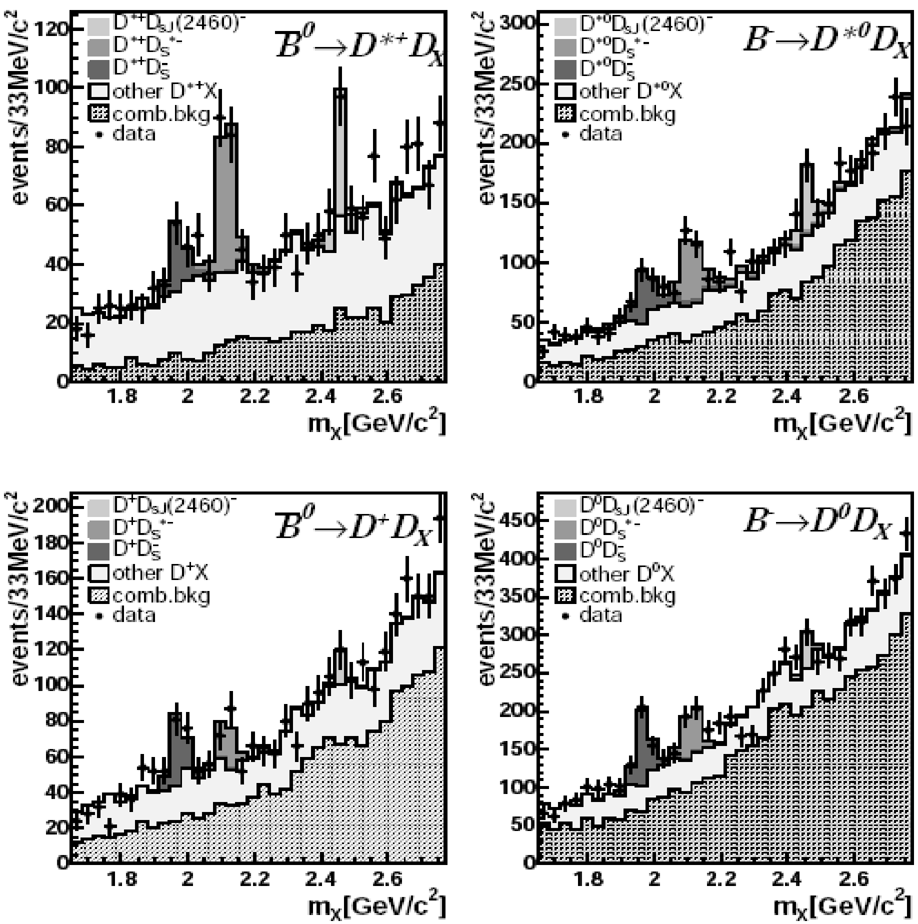


arXiv:hep-ex/0605036v2
210.5 fb^{-1}

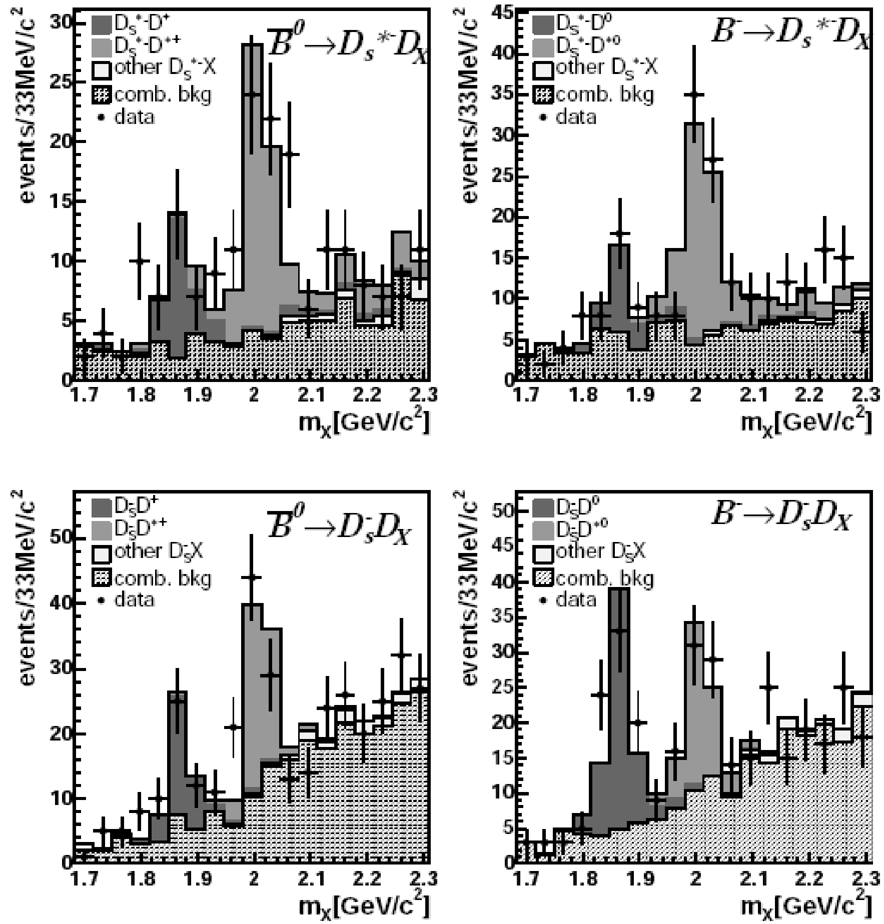
290,000 B^0 tags
463,000 B^+ tags

BABAR $D_s \to \phi\pi$

Recoil mass against *D* or *D**



Recoil mass against D_s or D_s*



$$\mathcal{B}(D_{sJ}(2460)^- \to D_s^{*-}\pi^0) = (56 \pm 13_{\text{stat.}} \pm 9_{\text{syst.}})\%,$$

$$\mathcal{B}(D_{sJ}(2460)^- \to D_s^-\gamma) = (16 \pm 4_{\text{stat.}} \pm 3_{\text{syst.}})\%,$$

$$\mathcal{B}(D_s^- \to \phi\pi^-) = (4.62 \pm 0.36_{\text{stat.}} \pm 0.50_{\text{syst.}})\%.$$

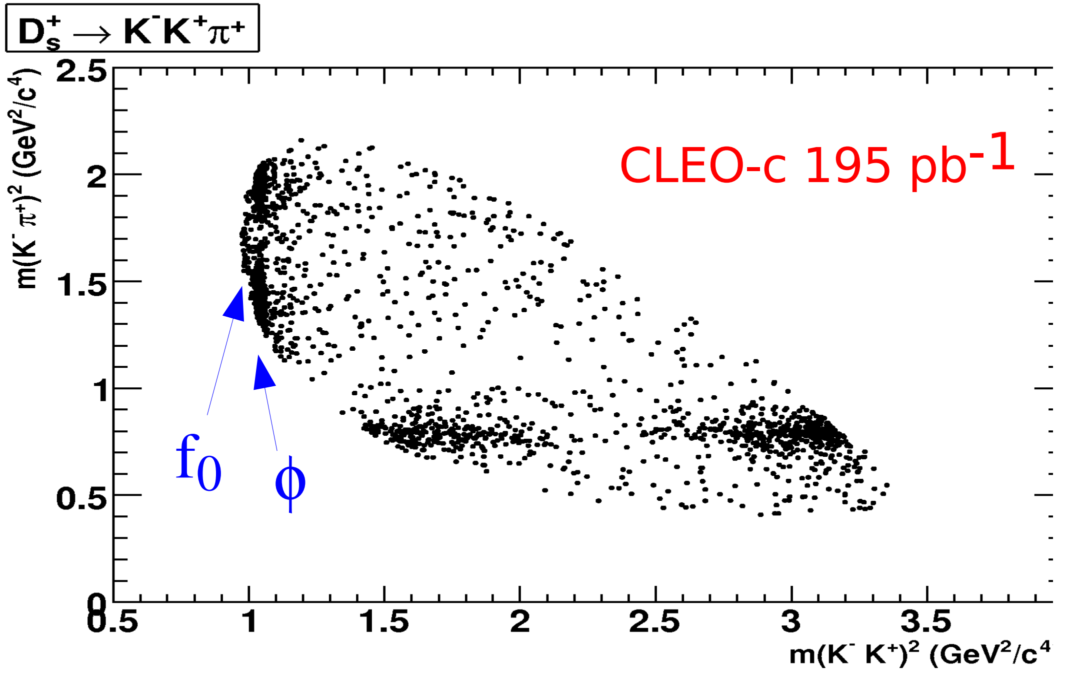
What about $D_s \to \phi\pi$?

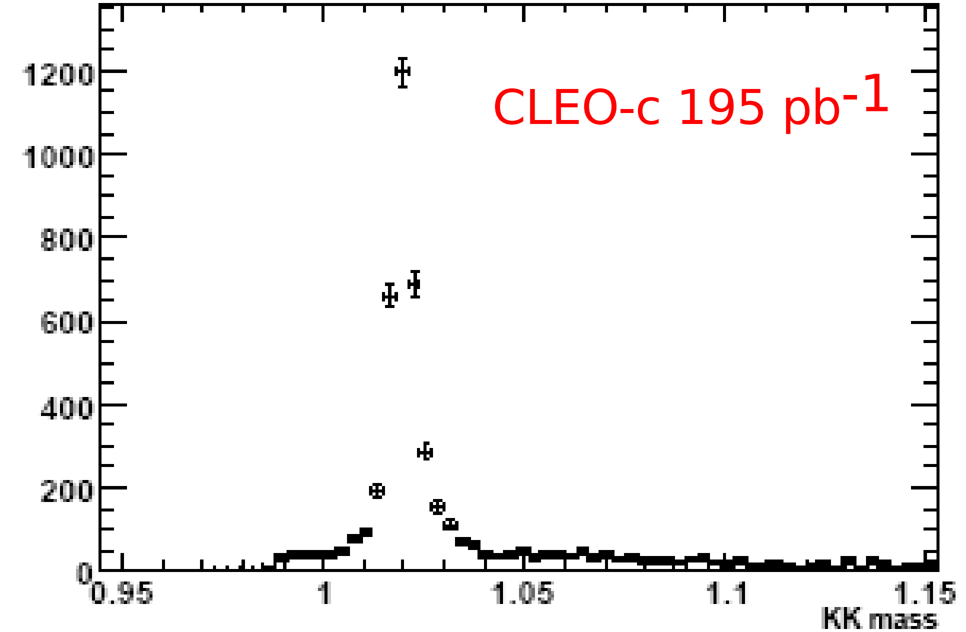
- The ϕ resonance is not well defined
  - $D_s \to \phi\pi$ interferes with $D_s \to f_0\pi$
- $B(D_s \to \phi\pi)$ is not well defined and CLEO-c are not quoting it.
- We calculate a partial br. fr. in a m_{KK} window around the ϕ mass
- A detailed Dalitz study needed to separate out the D_s fit fractions

$D_s \to K^+K^-\pi^+$ partial BF:

CLEO-c (±10 MeV around ϕ)
1.98±0.12±0.09
CLEO-c (±20 MeV around ϕ)
2.25±0.13±0.12
(Preliminary)

For reference: $D_s \to \phi\pi^+$
PDG06: 4.4±0.6
BaBar: 4.62±0.38±0.50
(1.008<M(K+K-)<1.035 GeV)





Inclusive η, η', and ϕ Production in *D* and D_s Decays at CLEO-c

- Tag one *D* or D_S and look at rest of event
  - 281 pb^{-1} for D^0 and D^+
  - 195 pb^{-1} for D_S
- As expected, we see that the production of η, η', and ϕ is larger in D_S decays than in *D* decays.
- Important branching fractions for studying B_S decays.

B	η (%)	PDG
D^0	9.5 ± 0.4 ± 0.8	<13%
D^+	6.3 ± 0.5 ± 0.5	<13%
D_s^+	23.5 ± 3.1 ± 2.0	-

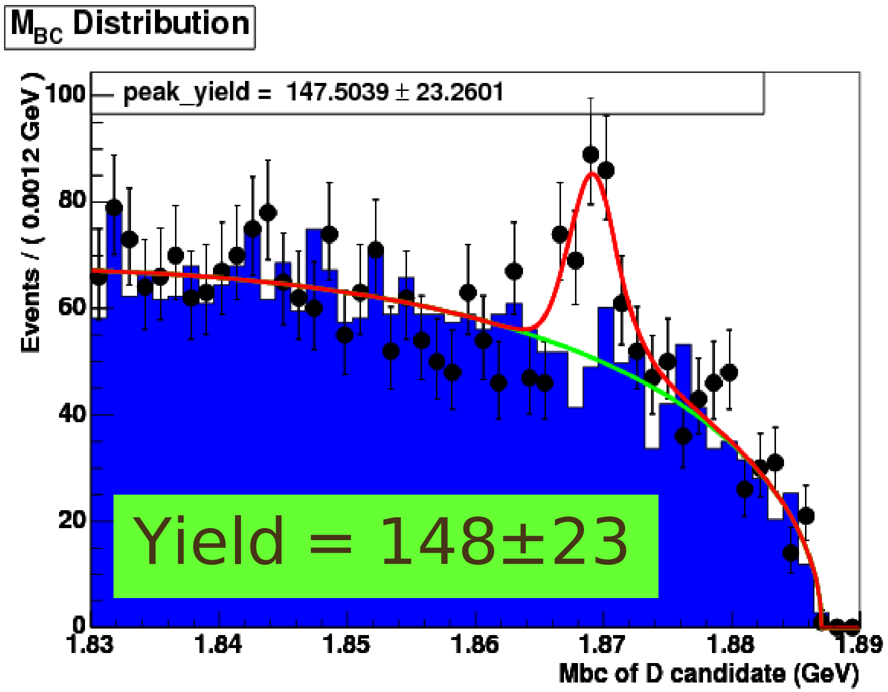
B	η' (%)	PDG
D^0	2.48 ± 0.17±0.21	-
D^+	1.04 ± 0.16±0.09	-
D_s^+	8.7 ± 1.9 ± 1.1	-

B	ϕ (%)	PDG
D^0	1.05 ± 0.08±0.07	1.7 ± 0.8
D^+	1.03 ± 0.10±0.07	<1.8
D_s^+	16.1 ± 1.2 ±1.1	-

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

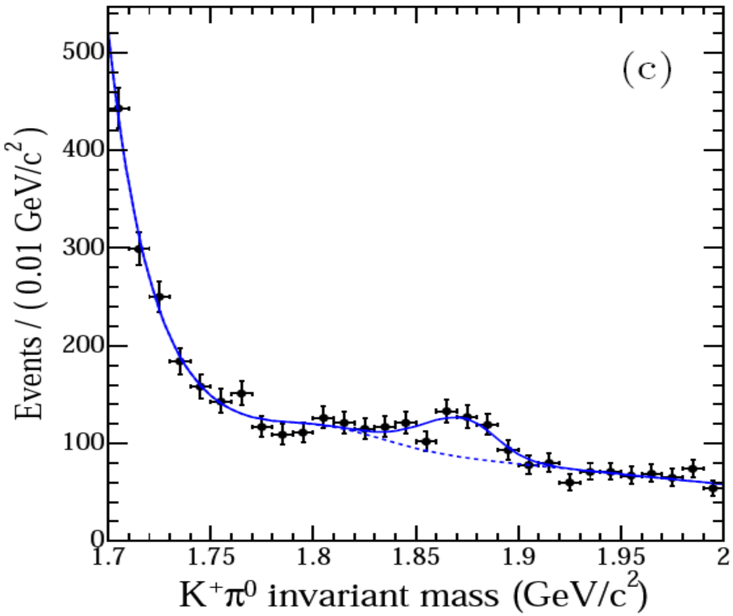
- CLEO-c and BABAR has measured this doubly Cabibbo suppressed decay
- Normalize to $D^+ \to K^-\pi^+\pi^+$

CLEO-c (281 pb^{-1})



$B(D^+ \to K^+\pi^0) = (2.24 \pm 0.36 \pm 0.15 \pm 0.08) \times 10^{-4}$

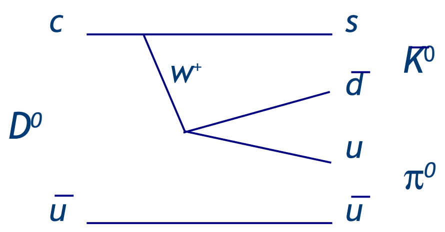
BaBar (124 fb^{-1})



$B(D^+ \to K^+\pi^0) = (2.52 \pm 0.46 \pm 0.24 \pm 0.08) \times 10^{-4}$

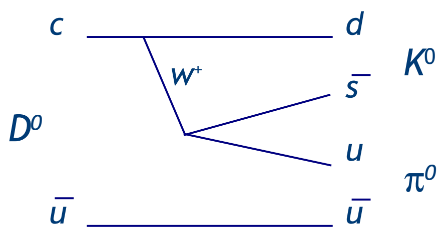
$D \to K_S \pi$ and $D \to K_L \pi$

- It is often assumed that $\Gamma(D \to K_S X) = \Gamma(D \to K_L X)$, but this is not strictly true due to interference effects.



Cabibbo-allowed

$$\bar{K}^0 = \frac{1}{\sqrt{2}}\left(K_S^0 - K_L^0\right)$$



Cabibbo-suppressed

$$K^0 = \frac{1}{\sqrt{2}}\left(K_S^0 + K_L^0\right)$$

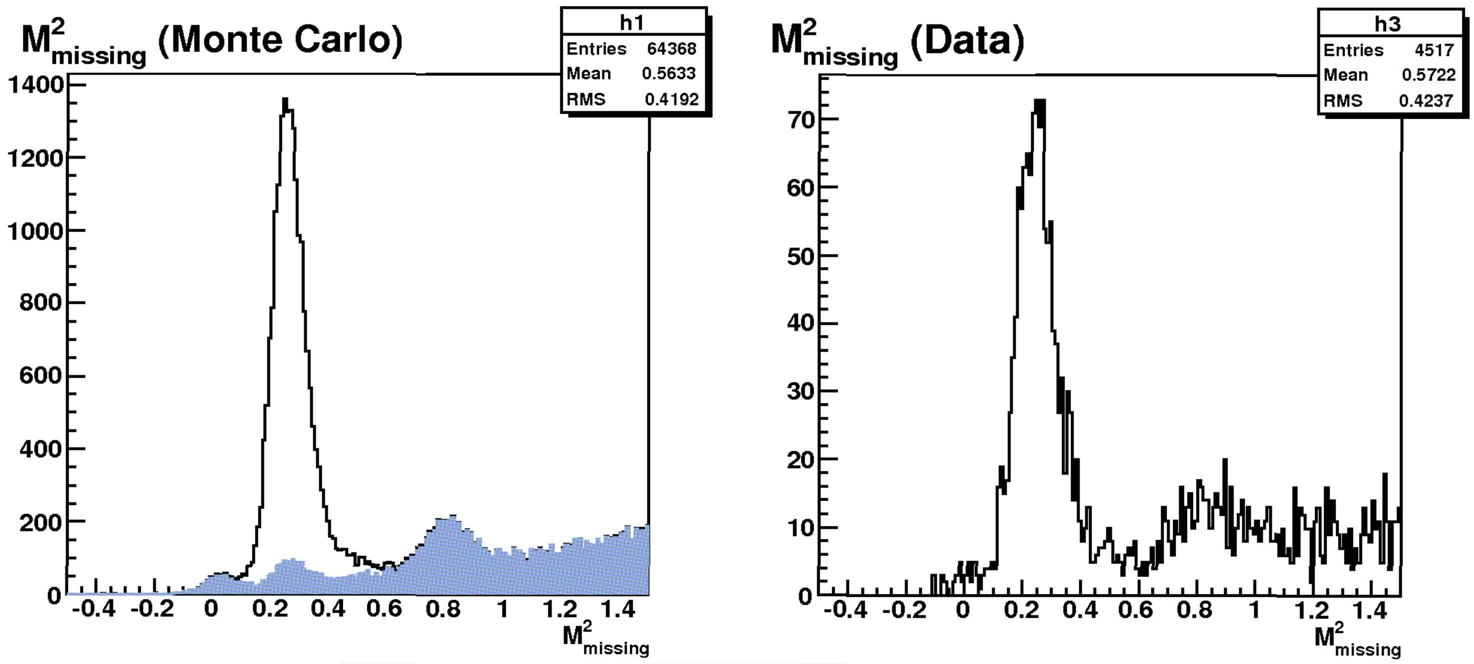
The physical states of the K_S and K_L have different rates due to interference

Based on factorization Bigi and Yamamoto (PLB 349, 363 (1995))
Predict

$$\frac{\Gamma(D^0 \to K_S\pi^0) - \Gamma(D^0 \to K_L\pi^0)}{\Gamma(D^0 \to K_S\pi^0) + \Gamma(D^0 \to K_L\pi^0)} \approx 2\tan\theta_C^2 \approx 0.10$$

Measuring $D^0 \to K_L \pi^0$ Preliminary

- CLEO-c is uniquely positioned to measure $D^0 \to K_L \pi^0$
- In tagged events, look at recoil against π^0 and veto K_S



- Correcting for Quantum Correlations
- $B(D^0 \to K_L^0 \pi^0) = (0.940 \pm 0.046 \pm 0.032)\%$
- $B(D^0 \to K_S^0 \pi^0) = (1.212 \pm 0.016 \pm 0.039)\%$

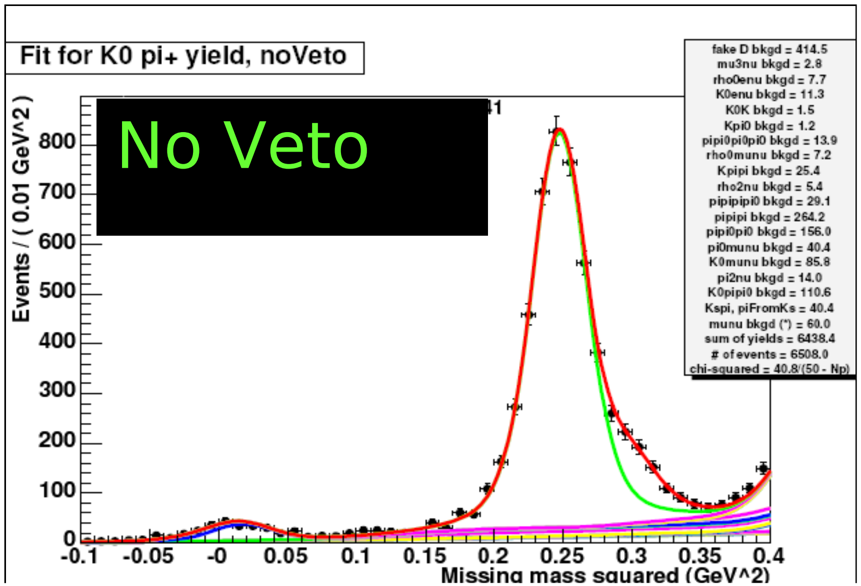
$$\frac{\Gamma(D^0 \to K_S) - \Gamma(D^0 \to K_L)}{\Gamma(D^0 \to K_S) + \Gamma(D^0 \to K_L)} = 0.122 \pm 0.024 \pm 0.030$$

In agreement with theory (factorization)

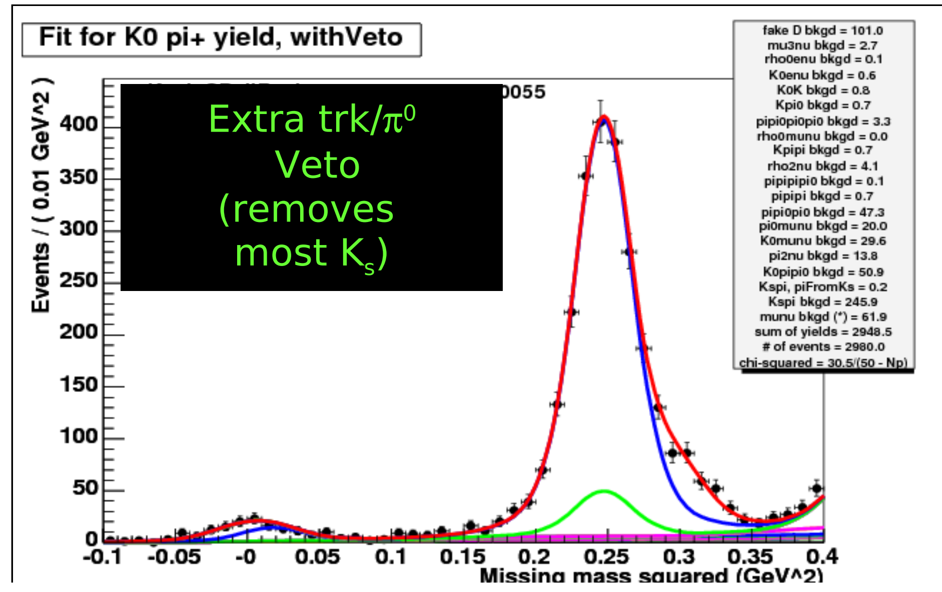
$D^+ \to K_L \pi^+$ vs. $D^+ \to K_S \pi^+$

Preliminary

- Look for recoil mass against pion in tagged events



Missing Mass Squared



Missing Mass Squared

	Yield	Efficency	BF (%)
$K_{S,L}\pi^+$	4428±79	85.2±0.1	3.095±0.056
$K_L\pi^+$	2023±54	81.8±0.1	1.456±0.040

$$R(D^+)=\frac{\Gamma(D^+\to K_S)-\Gamma(D^+\to K_L)}{\Gamma(D^+\to K_S)+\Gamma(D^+\to K_L)}=0.030\pm0.023\pm0.025$$

Dao-Neng Gao
arXiv:hep-ph/0610389v2

Predicts:
$R(D^+)$=0.035 to 0.044

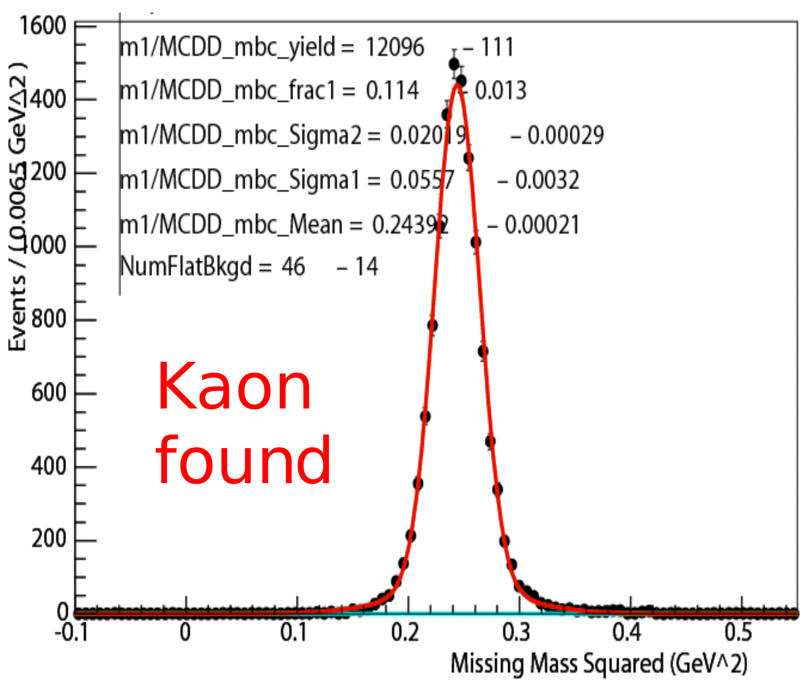
Conclusion

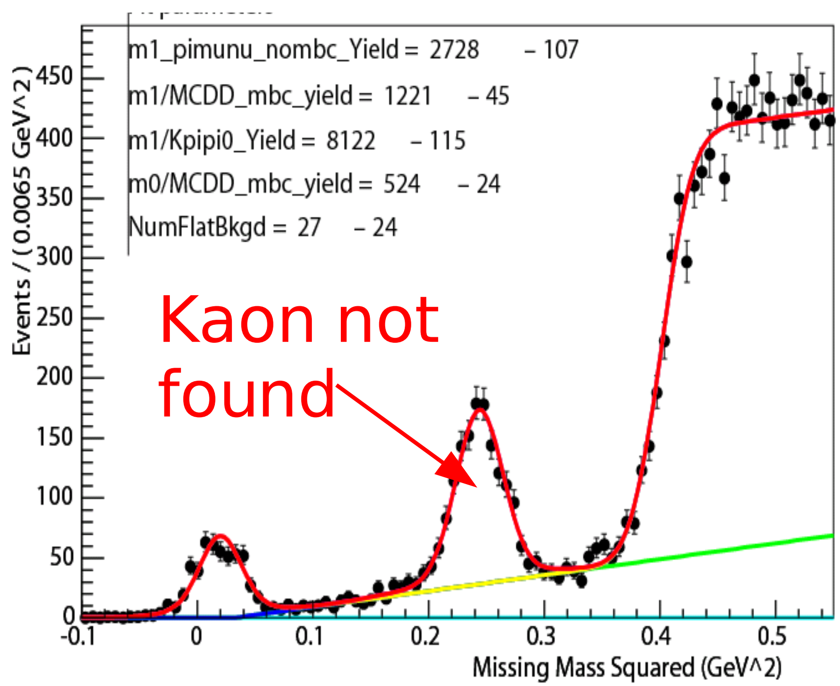
- For D^0 mesons new measurements from both Υ(4S) and the $\Psi(3770)$ are making improvements to the understanding of the absolute branching fractions.
  - Systematics are limiting the measurements at both energies now.
- For the D^+ branching fractions measured with tags at the $\Psi(3770)$ provides the cleanest measurements. Also limited by systematics.
- The D_s branching fractions at CLEO are not yet systematics limited.
- The clean environment at CLEO allows studies of modes with K_L.

Backup Slides

Tracking Efficiencies

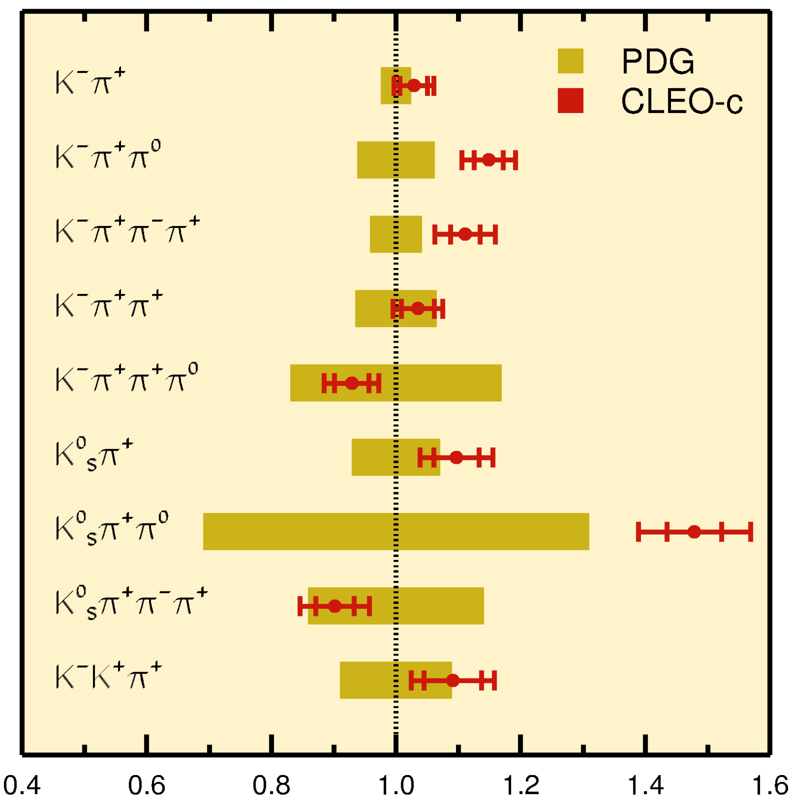
- Events that can be fully reconstructed can be used for very clean studies of tracking efficiencies
- Look at recoil mass against D^0-tag and pion – see how often kaon is found
  - In data we find $\varepsilon=(90.8\pm0.4)\%$





Results from 56 pb^{-1}
(PRL 95, 121801)

Parameter	Fitted Value	Δ_{FSR}
$N_{D^0\bar{D}^0}$	$(2.01 \pm 0.04 \pm 0.02) \times 10^5$	-0.2%
$\mathcal{B}(D^0 \to K^-\pi^+)$	$(3.91 \pm 0.08 \pm 0.09)\%$	-2.0%
$\mathcal{B}(D^0 \to K^-\pi^+\pi^0)$	$(14.9 \pm 0.3 \pm 0.5)\%$	-0.8%
$\mathcal{B}(D^0 \to K^-\pi^+\pi^+\pi^-)$	$(8.3 \pm 0.2 \pm 0.3)\%$	-1.7%
$N_{D^+D^-}$	$(1.56 \pm 0.04 \pm 0.01) \times 10^5$	-0.2%
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	$(9.5 \pm 0.2 \pm 0.3)\%$	-2.2%
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+\pi^0)$	$(6.0 \pm 0.2 \pm 0.2)\%$	-0.6%
$\mathcal{B}(D^+ \to K^0_S\pi^+)$	$(1.55 \pm 0.05 \pm 0.06)\%$	-1.8%
$\mathcal{B}(D^+ \to K^0_S\pi^+\pi^0)$	$(7.2 \pm 0.2 \pm 0.4)\%$	-0.8%
$\mathcal{B}(D^+ \to K^0_S\pi^+\pi^+\pi^-)$	$(3.2 \pm 0.1 \pm 0.2)\%$	-1.4%
$\mathcal{B}(D^+ \to K^+K^-\pi^+)$	$(0.97 \pm 0.04 \pm 0.04)\%$	-0.9%



Our branching fractions are corrected for FSR (so they include γ's)

Using our measured luminosity of $55.8 \pm 0.6\,\mathrm{pb}^{-1}$ we obtain:

$$\sigma(e^+e^- \to D^0\bar{D}^0) = (3.60 \pm 0.07 \pm 0.07)\,\mathrm{nb} \qquad \sigma(e^+e^- \to D^+D^-) = (2.79 \pm 0.07 \pm 0.10)\,\mathrm{nb}$$

$$\sigma(e^+e^- \to D\bar{D}) = (6.39 \pm 0.10 \pm 0.17)\,\mathrm{nb}$$

CLEO-c inclusive: $\sigma(e^+e^- \to \psi(3770) \to \mathrm{hadrons}) = (6.38 \pm 0.08^{+0.41}_{-0.30})\,\mathrm{nb}$

BABAR Systematics

Sample	Source	$\delta(\mathcal{B})/\mathcal{B}$ (%)
	Selection bias	±0.35
N^{incl}	Non-peaking combinatorial background	±0.89
	Peaking combinatorial background	±0.34
	Soft pion decays in flight	±0.10
	Fake leptons	±0.08
	Cascade decays	±0.08
	Monte Carlo events shape	±0.08
	Continuum background	±0.05
	D^{**} production	±0.02
	Photon radiation	±0.02
N^{excl}	Tracking efficiency	±1.00
	K^- identification	±0.70
	D^0 invariant mass	±0.56
	Combinatorial background shape	±0.30
	Combinatorial background normalization	±0.16
	Soft pion decay	±0.12
	Cabibbo-suppressed decays	±0.10
	Photon radiation in D^0 decay	±0.07
Total		±1.74

Quantum Correlations

PRD 73 034024 (2006)
Asner and Sun

The two D^0 mesons are correlated: C=-1

	f	$l+$	$CP+$	$CP-$
f	$R_M(1+r^2(2-z^2))$			
$\bar{f}$	$1+r^2(2-z^2)$			
$l-$	1	1		
$CP+$	$1+rz$	1	0	
$CP-$	$1-rz$	1	2	0
X	$1+rzy$	1	$1-y$	$1+y$

Correction to BR as compared to incoherent decay

$$x = \frac{\Delta m}{\Gamma}$$

$$y = \frac{\Delta \Gamma}{2\Gamma}$$

$$R_M = (x^2 + y^2)/2$$

$$r e^{i\delta} = \frac{\langle \bar{D}^0 | K^- \pi^+ \rangle}{\langle D^0 | K^- \pi^+ \rangle}$$

$$z = 2\cos\delta$$

- For *CP vs CP* eigenstates the correlation is a large effect
- *E.g* the decay $D^0 \to K_S \pi^0$ where the other *D* decays generically (single tag)

$$N(D^0 \to K_S^0 \pi^0) = 2 N_{D^0 \bar{D}^0} B(D^0 \to K_S^0 \pi^0)(1+y)$$

- Where the other *D* is a flavor tag $D \to f$

$$N(D^0 \to K_S^0 \pi^0) = N_{D^0 \bar{D}^0} B(D^0 \to K_S^0 \pi^0)(1 - 2 r_f \cos\delta_f)$$