Open Charm Physics at CLEO-c

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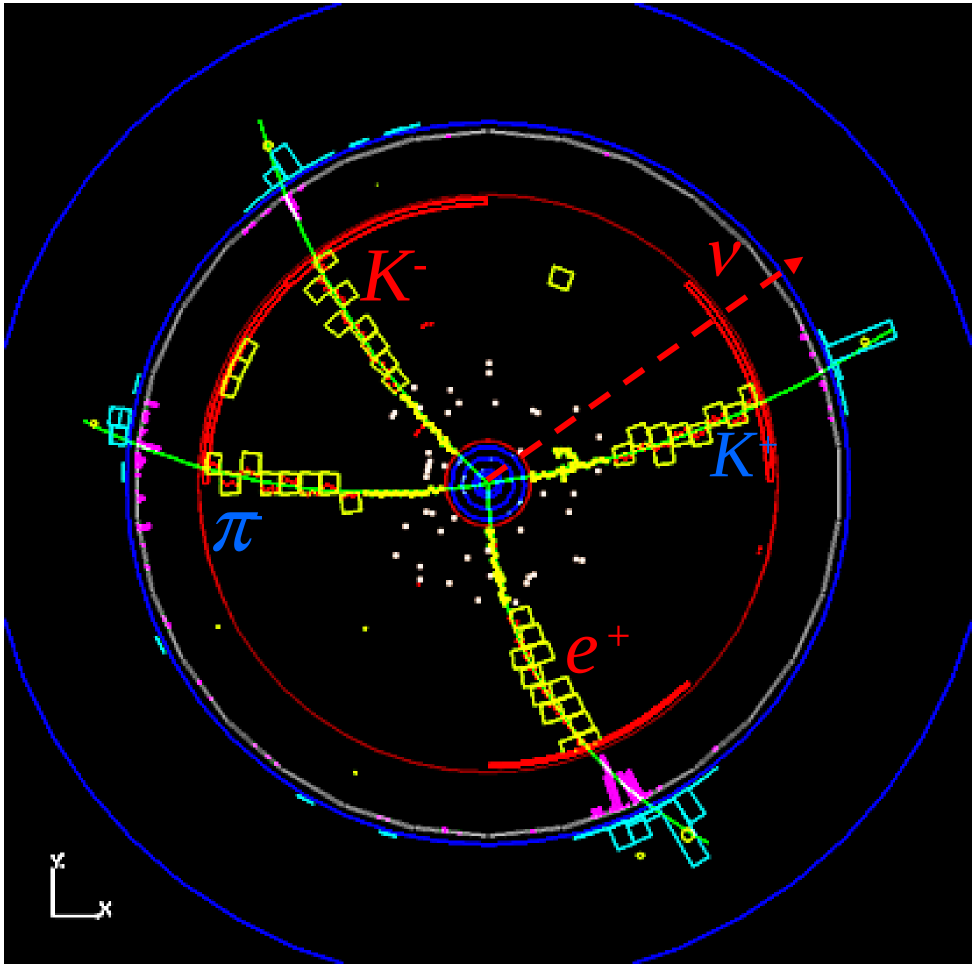
for the
CLEO Collaboration
March 18-25, 2006

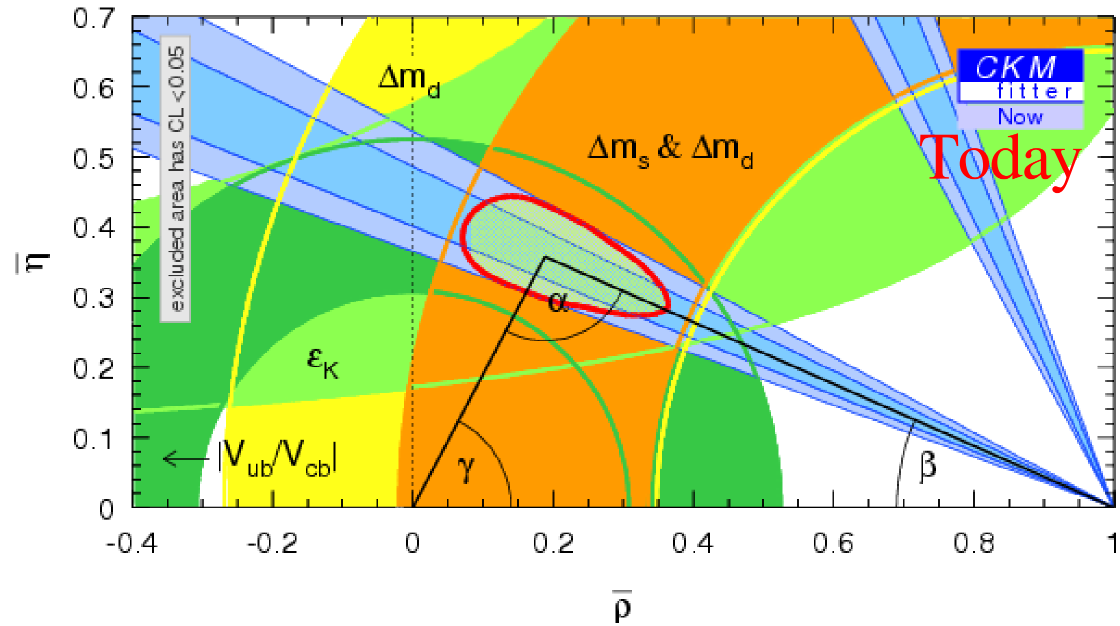
$$e^+ e^- \rightarrow c\,\bar{c} \rightarrow D^0 \overline{D}^0$$

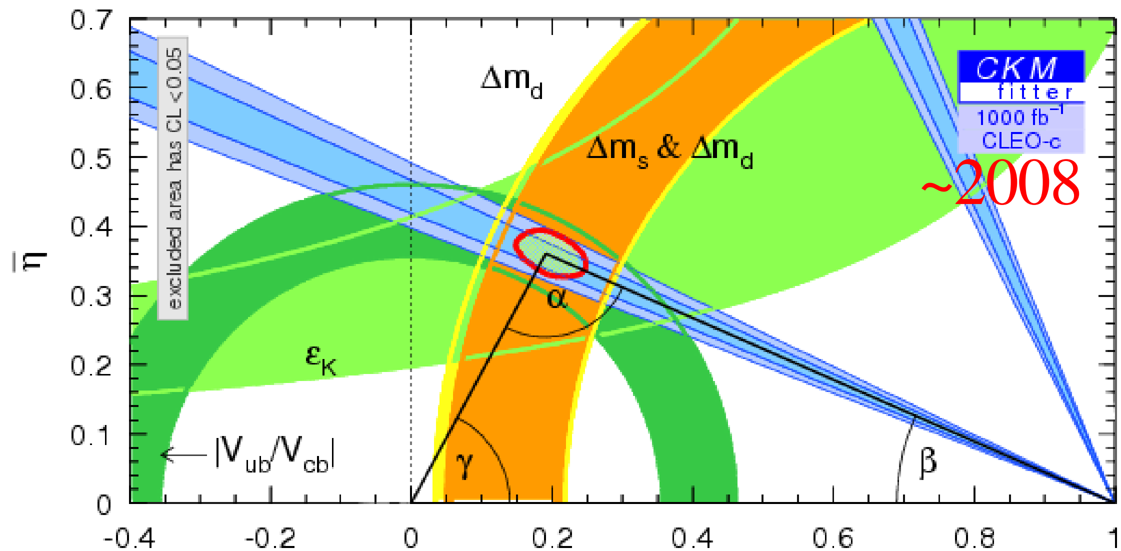
$$\overline{D}^0 \rightarrow K^+ \pi^-, D^0 \rightarrow K^- e^+ \bar{\nu}$$



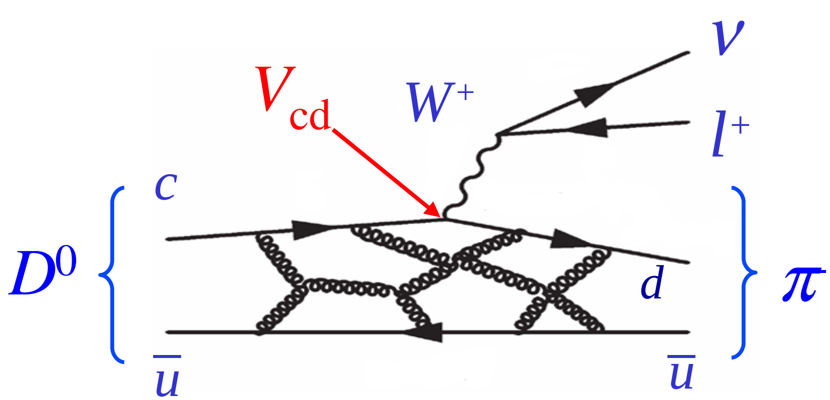
Testing the Quark Mixing (CKM) Matrix

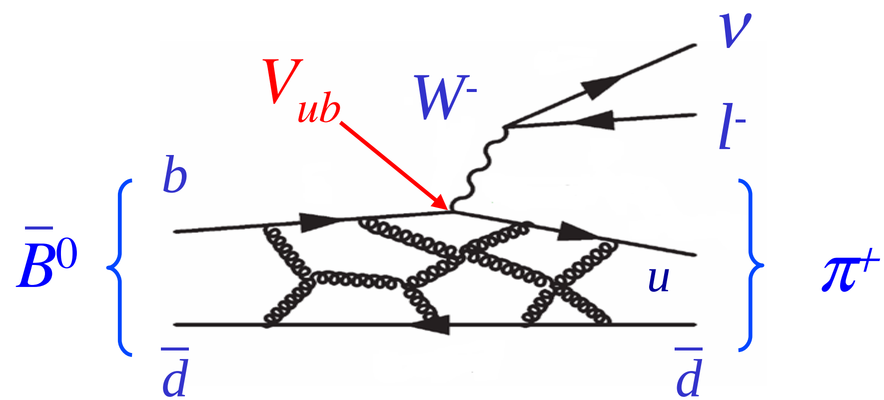
- The CKM matrix provides the only mechanism for *CP* violation in the SM.
- It is an important goal of flavor physics to measure – and overconstrain – the parameters in the CKM matrix.
- Non-perturbative strong effects limit our ability to extract the fundamental parameters from the measurements.
- CLEO-c provides unique measurements that will address this limitation.





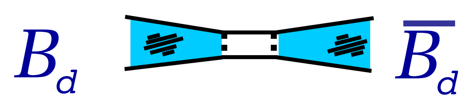
Testing Theories of Strong Interactions



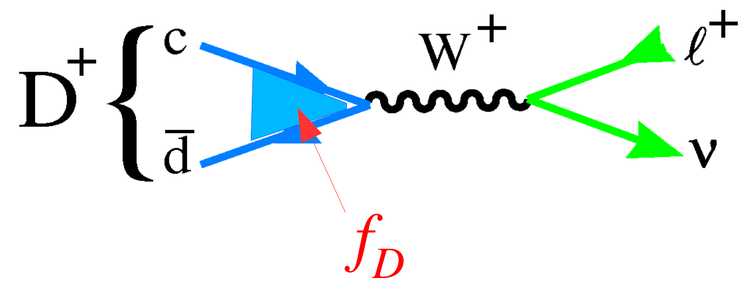


- Measure form factors in $D\rightarrow\pi l\nu$ and validate theoretical calculations
  - Can then use this to extract $|V_{ub}|$ from $B\rightarrow\pi l\nu$

- B mixing is well measured
  $\Delta m_d=(0.502\pm0.007)\times10^{-12}$ s
- But $|V_{td}|$ from Δm_d has large uncertainties from f_B
- CLEO-c can measure f_D



$$\Delta m_d=\frac{G_F^2}{6}M_B M_t^2|V_{td}V_{tb}^*|^2\eta_B S_0(x_t)f_B^2 B_B$$



Outline

- *D* physics at $\psi(3770)$
  - Hadronic branching fractions
  - Semileptonic decays
  - $D^+ \to \mu^+ \nu_\mu$
- D_s scan
- Summary

Hadronic *D*-decays and $\sigma(e^+e^- \to D\overline{D})$

- Based on 56 pb^{-1} of data recorded at $\psi(3770)$
- The $\psi(3770)$ decays to pairs of *D* mesons – and no other particles
- Use a 'double tag' technique, pioneered by MARK III

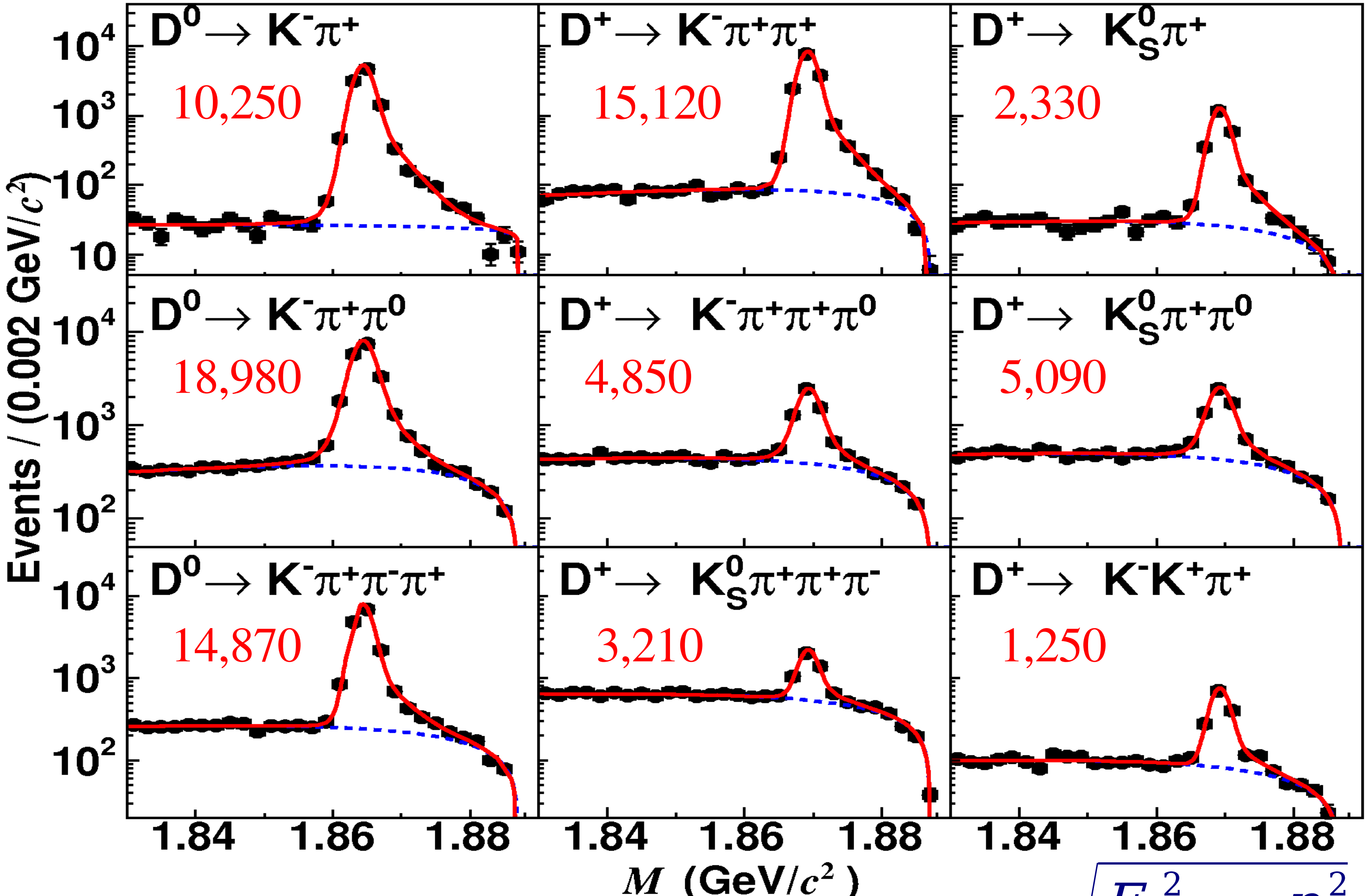
$$N_i = \epsilon_i 2 B_i N_{D\overline{D}}$$

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

$$N_{D\overline{D}} = \frac{N_i N_j \epsilon_{ij}}{4 N_{ij} \epsilon_i \epsilon_j}$$

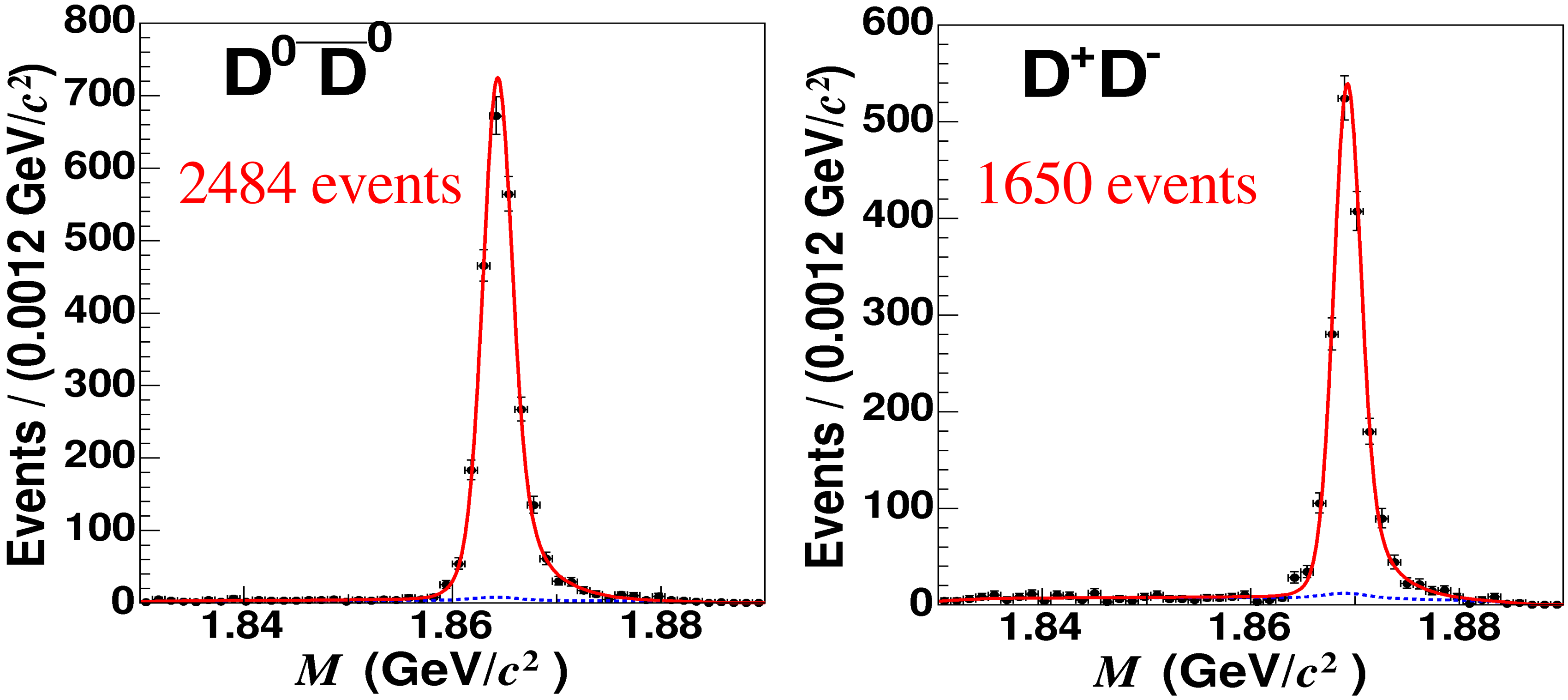
- Use 3 D^0 modes ($K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^-\pi^+$) and 6 D^+ modes ($K^-\pi^+\pi^+$, $K_s\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K_S\pi^+\pi^-\pi^+$, $K_S\pi^+\pi^0$, and $K^-K^+\pi^+$)
- Determine separately the D and $\overline{D}$ yields
  - This gives 18 single tag yields and 45 ($=3^2+6^2$) 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.).

Single Tag Yields (56 pb^{-1})



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

Double Tag Yields (56 pb^{-1})



- The statistical errors on the double tag yields set the errors on the branching fractions (assuming the single tag yields don't dominate the errors).

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 ± 0.6 pb^{-1} we obtain:

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

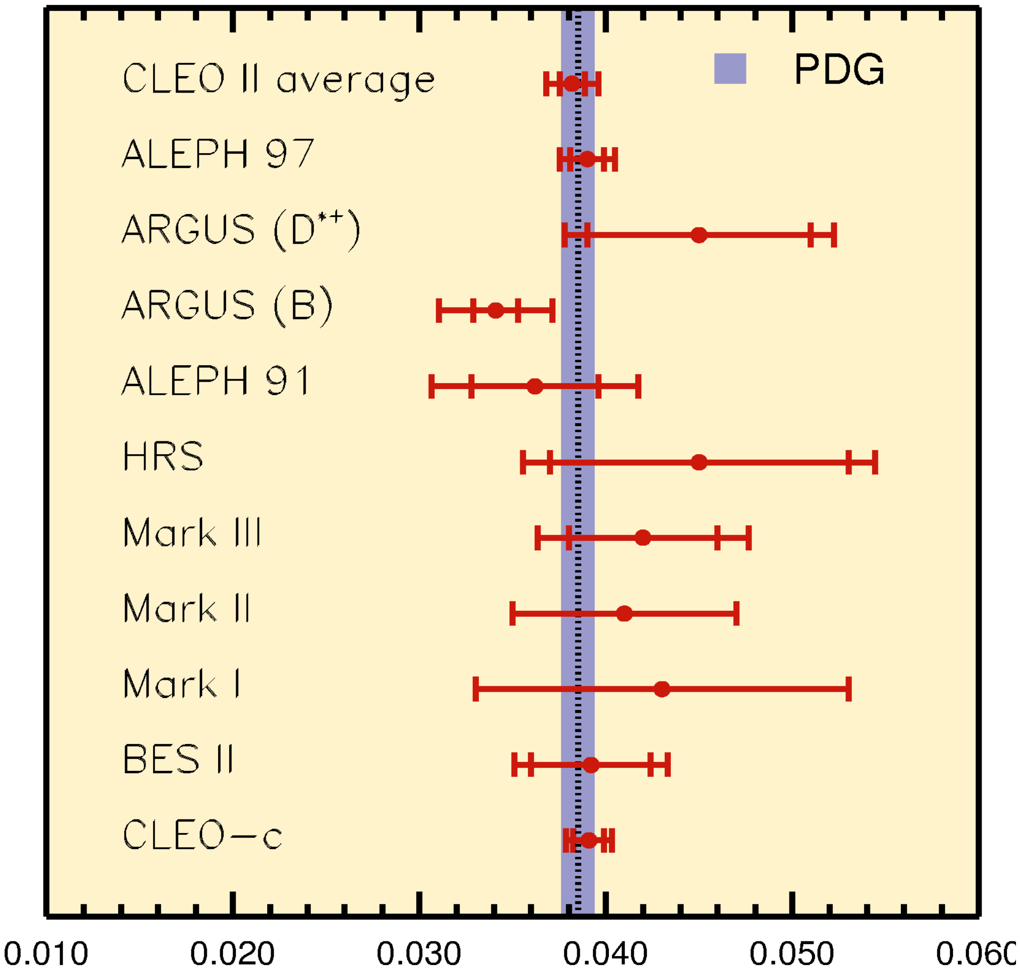
$\sigma(e^+e^- \to D\bar{D}) = (6.39 \pm 0.10 \pm 0.17)$ nb

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

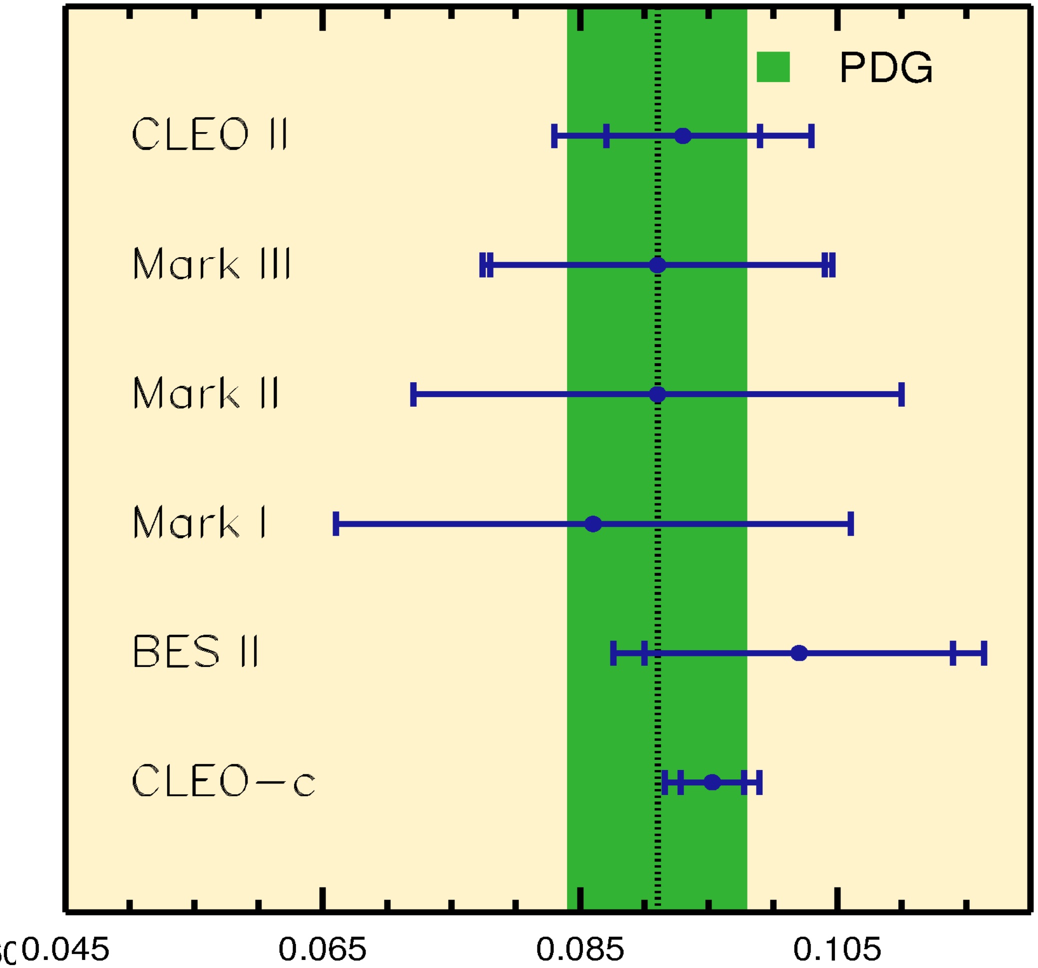
(PRL 96, 092002)

Comparison with Other Exp.

$Br(D^0 \to K^- \pi^+)$

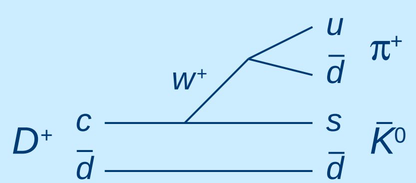


$Br(D^+ \to K^- \pi^+ \pi^+)$

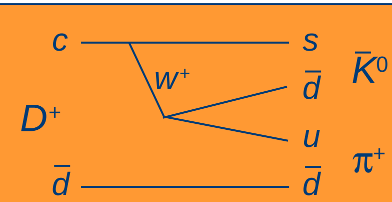


With 56 pb^{-1} CLEO-c measurements are best available, will collect 750 pb^{-1}

$D^+ \to K_{L,S}\pi^+$

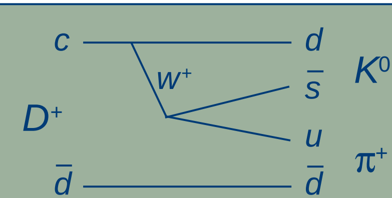


Cabibbo-favored



Color-suppressed

Interfere destructively
(Long D^+ lifetime)



DCS and color-suppressed

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

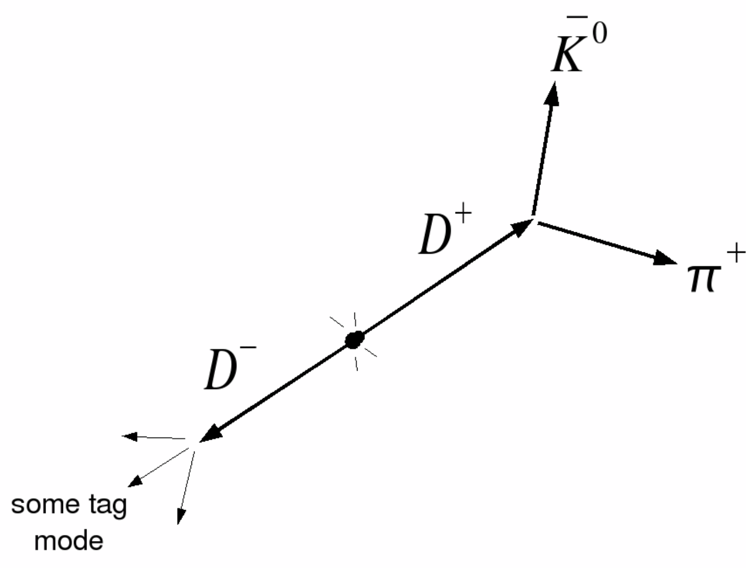
$$K^0 = \frac{1}{\sqrt{2}}\left(K_S^0 + K_L^0\right)$$

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))
Predicts

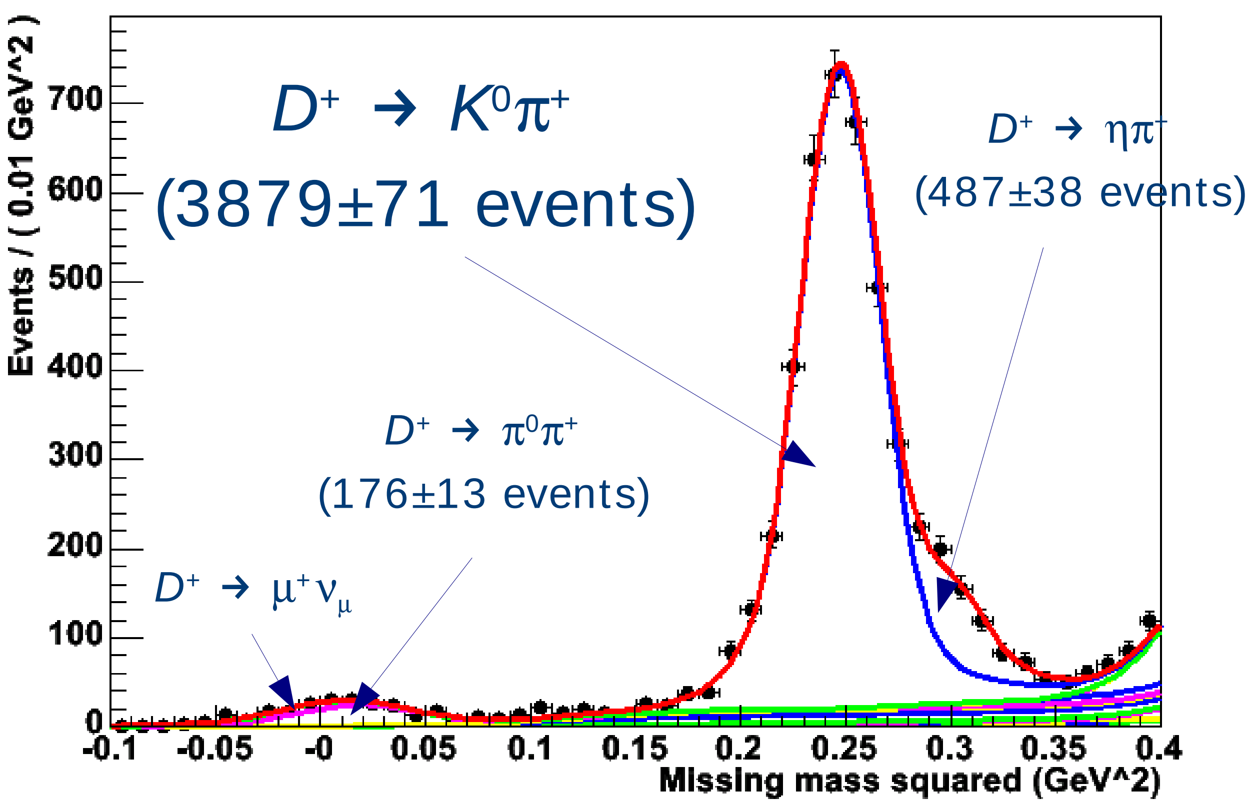
$$\frac{\Gamma(D^+ \to K_L) - \Gamma(D^+ \to K_S)}{\Gamma(D^+ \to K_L) + \Gamma(D^+ \to K_S)} \approx 10\,\%$$

Preliminary Results



Reconstruct tag D and pion, look for signal in the recoil mass

281 pb^{-1}

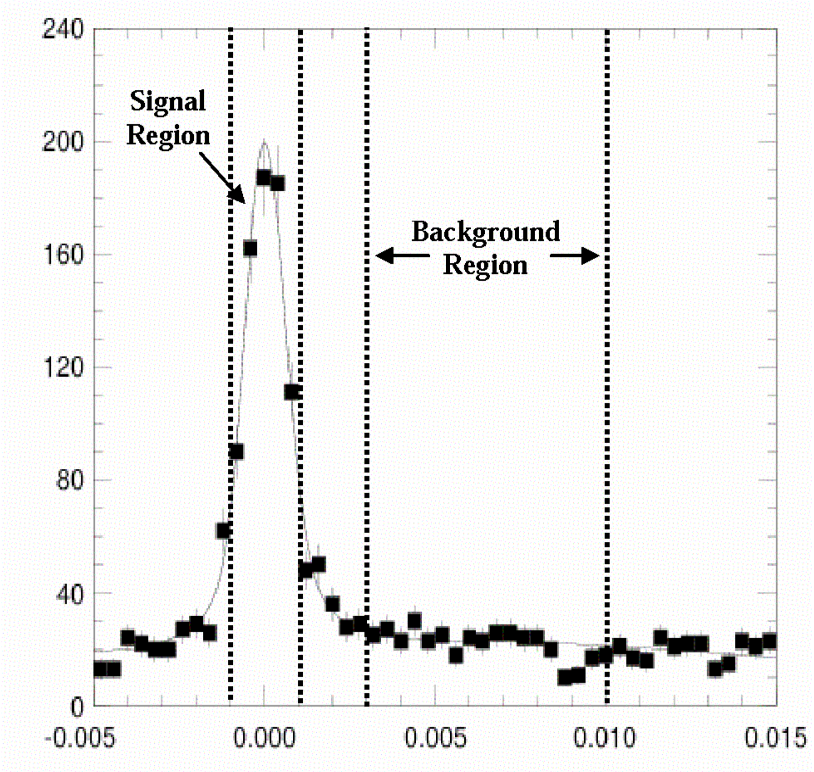


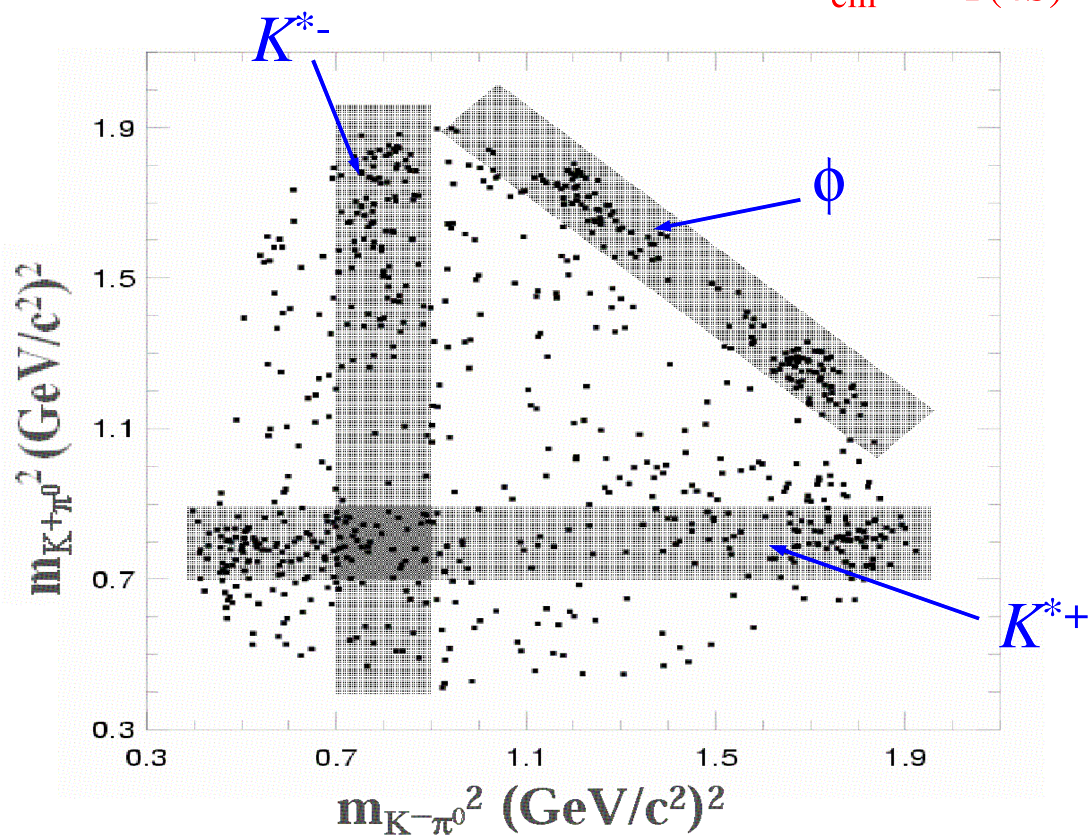
- $B(D^+ \to K^0_S\pi^+) + B(D^+ \to K^0_L\pi^+) = (3.06 \pm 0.06 \pm 0.16)\%$
- Asymmetry = $(K^0_L - K^0_S)/(K^0_L + K^0_S) = -0.01 \pm 0.04 \pm 0.07$
  - Consistent with 10% prediction.
- $B(D^+ \to \eta\pi^+) = (0.39 \pm 0.03 \pm 0.03)\%$ [PDG2004 has $(0.30 \pm 0.06)\%$].

Dalitz Plot Study of $D^0 \to K^+K^-\pi^0$

- Can be used to measure γ in $B^\pm \to DK^\pm$

735 events with 82% purity in 9.0 fb^{-1} from CLEO III data, $E_{cm} \sim m_{\Upsilon(4S)}$

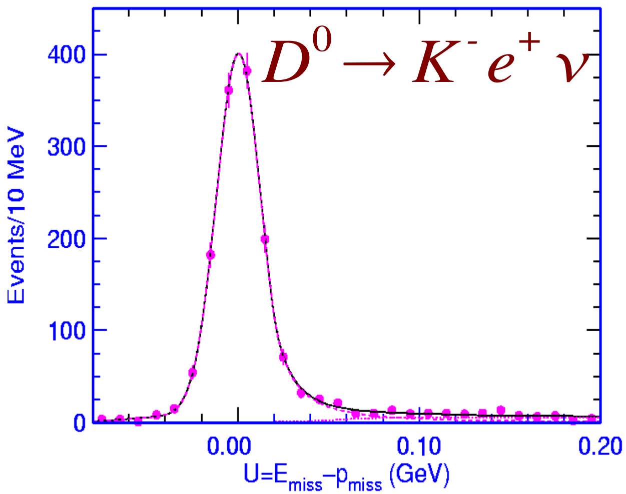


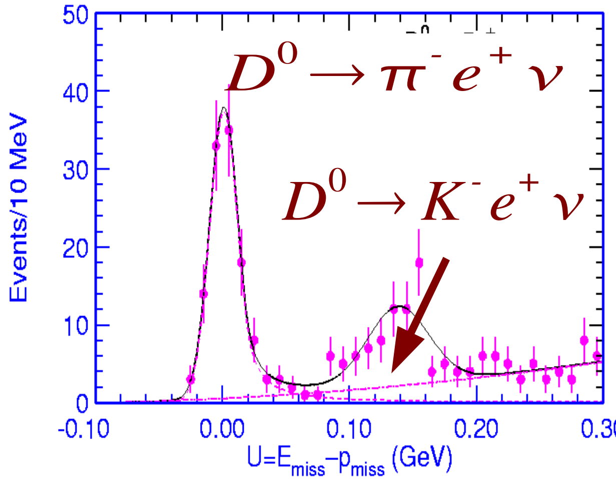


- Measure strong phase of 332°±8°±9° between $D^0 \to K^{*-}K^+$ and $D^0 \to K^{*+}K^-$
- Destructive interference in K^{*-}-K^{*+} overlap region

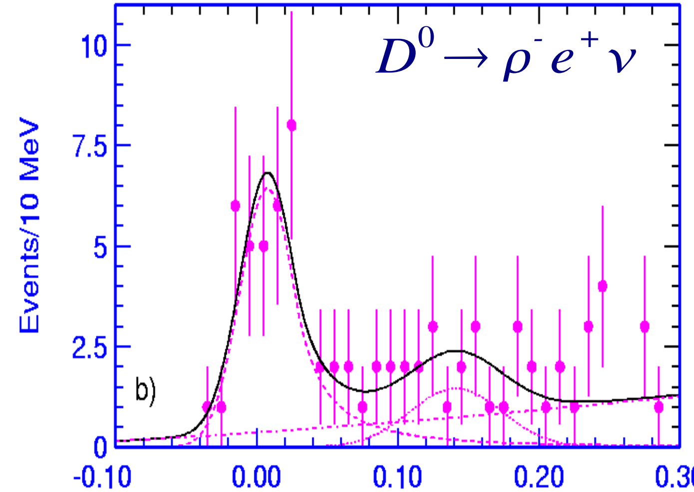
Exclusive Semileptonic Decays 56 pb^{-1}

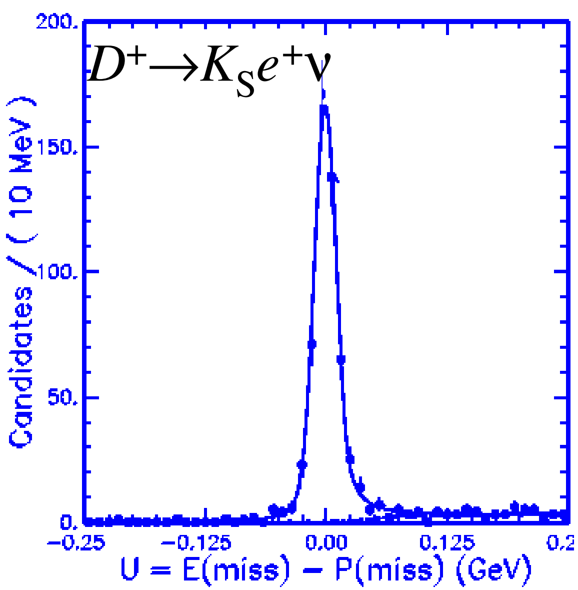
- Recoil against fully reconstructed D

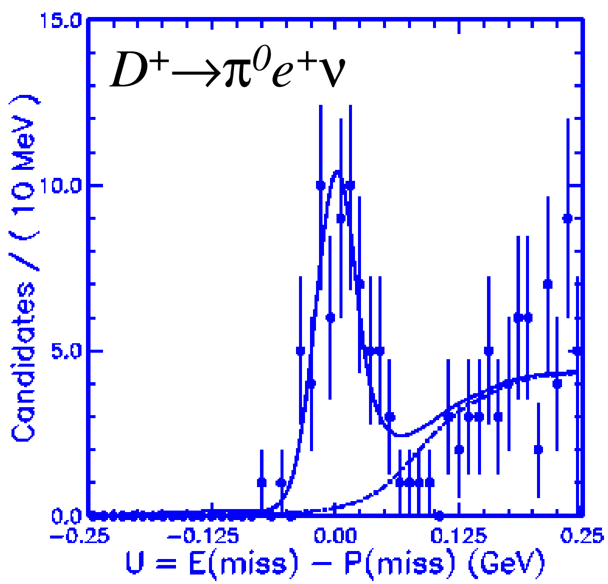




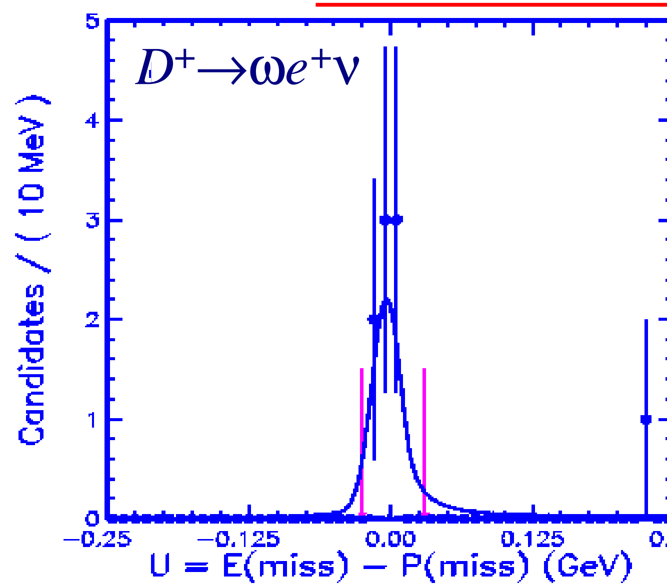
First observation







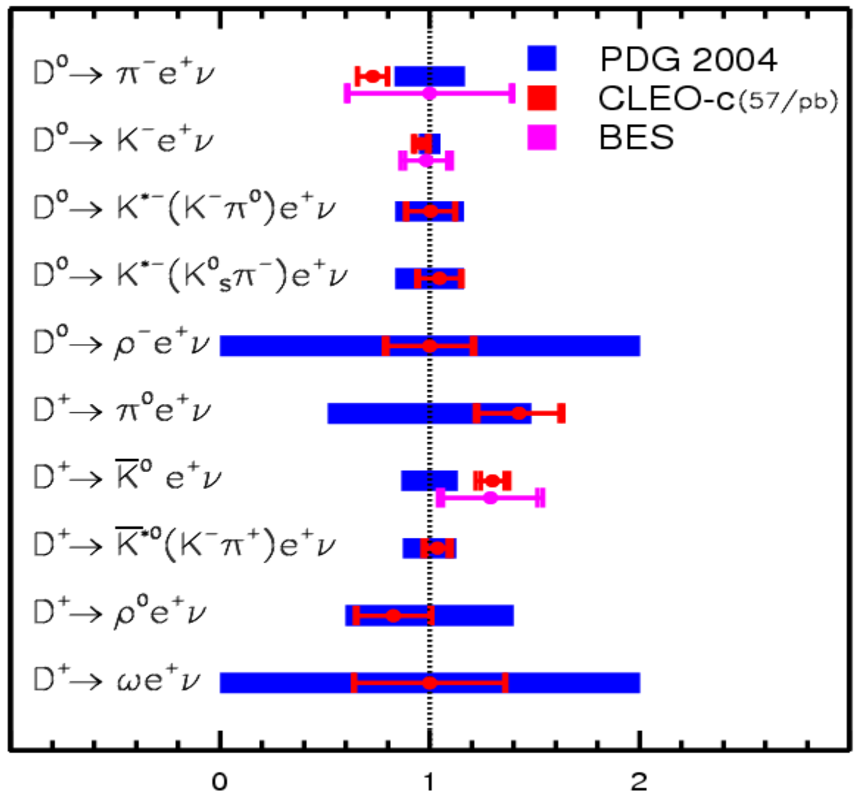
First observation



(PRL 95, 181802, 2005, and PRL 95, 181801, 2005)

Summary of Exclusive Semileptonic Decays in 56 pb^{-1}

Mode	$\mathcal{B}$ (%)	$\mathcal{B}$ (%) (PDG)
$D^0 \to \pi^- e^+ \nu_e$	$0.26 \pm 0.03 \pm 0.01$	0.36 ± 0.06
$D^0 \to K^- e^+ \nu_e$	$3.44 \pm 0.10 \pm 0.10$	3.58 ± 0.18
$D^0 \to K^{*-}(K^- \pi^0) e^+ \nu_e$	$2.11 \pm 0.23 \pm 0.10$	2.15 ± 0.35
$D^0 \to K^{*-}(\bar{K}^0 \pi^-) e^+ \nu_e$	$2.19 \pm 0.20 \pm 0.11$	2.15 ± 0.35
$D^0 \to \rho^- e^+ \nu_e$	$0.19 \pm 0.04 \pm 0.01$	—
$D^+ \to \pi^0 e^+ \nu_e$	$0.44 \pm 0.06 \pm 0.03$	0.31 ± 0.15
$D^+ \to \bar{K}^0 e^+ \nu_e$	$8.71 \pm 0.38 \pm 0.37$	6.7 ± 0.9
$D^+ \to \bar{K}^{*0} e^+ \nu_e$	$5.56 \pm 0.27 \pm 0.23$	5.5 ± 0.7
$D^+ \to \rho^0 e^+ \nu_e$	$0.21 \pm 0.04 \pm 0.01$	0.25 ± 0.10
$D^+ \to \omega e^+ \nu_e$	$0.16^{+0.07}_{-0.06} \pm 0.01$	—

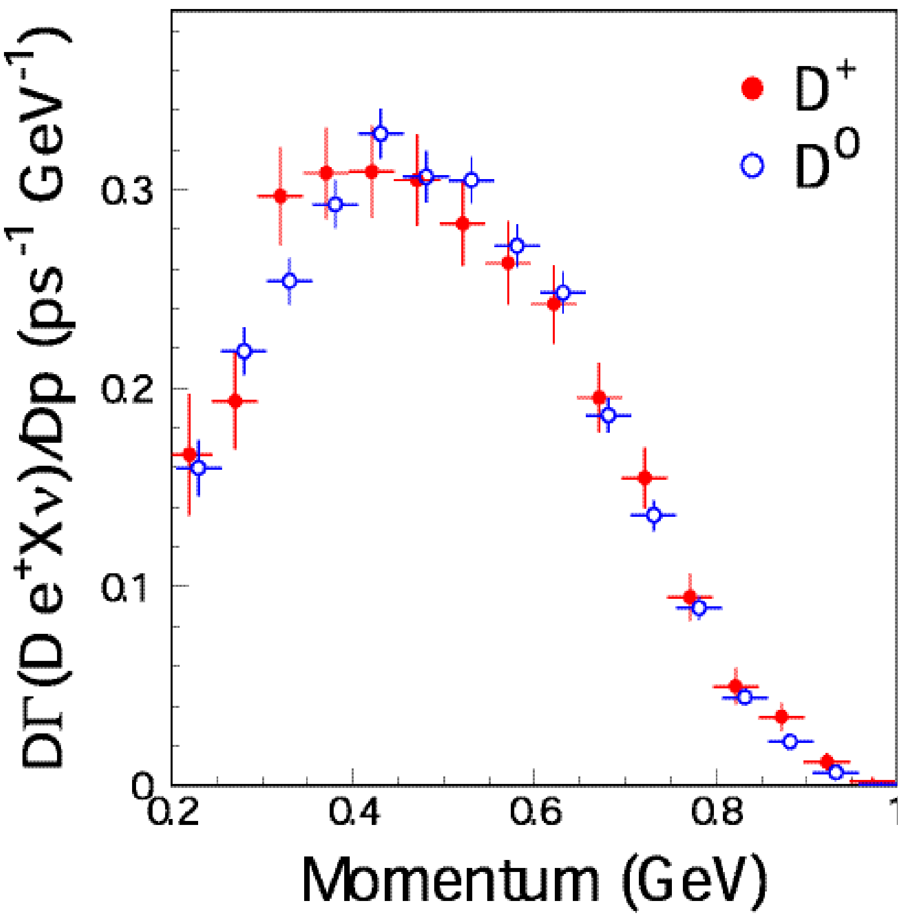


BES results:
PLB 608 24 (2005)
PLB 597 39 (2005)

- Most modes are improvements over the PDG
  - Including two first observations
  - $D^0 \to \rho^- e^+ \nu_e$ and $D^+ \to \omega e^+ \nu_e$
- Most systematics can be reduced with more data
- Updating analysis to 281 pb^{-1} and studying form factors

Inclusive Semileptonic *D*-decays

281 fb^{-1} (Preliminary)



- This analysis uses only the cleanest tags: $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$
- Correct for *e* momentum cut
- Obtain the branching fractions

$$Br(D^+ \to X e \nu_e) = (16.13 \pm 0.20 \pm 0.30)\%$$

(PDG: (17.2±1.9)%)

$$Br(D^0 \to X e \nu_e) = (6.46 \pm 0.17 \pm 0.12)\%$$

(PDG: (6.87±0.28)%)

- Using the measured lifetimes we obtain

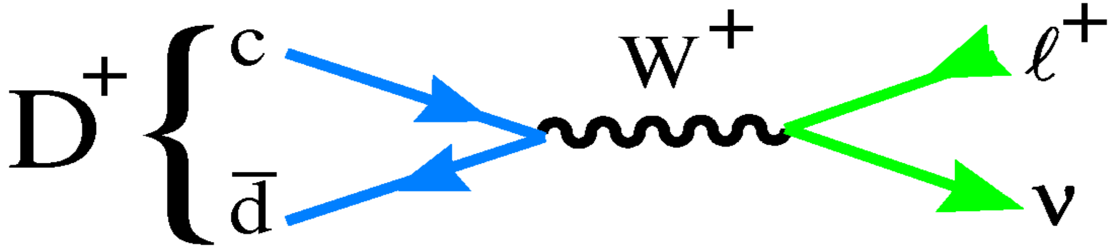
$$\frac{\Gamma(D^+ \to X e \nu_e)}{\Gamma(D^0 \to X e \nu_e)} = (0.984 \pm 0.028 \pm 0.015)$$

- The sum of exclusive final state

$$\sum Br(D^+ \to X_i e \nu_e) = (15.1 \pm 0.5 \pm 0.5)\%$$

$$\sum Br(D^0 \to X_i e \nu_e) = (6.1 \pm 0.2 \pm 0.2)\%$$

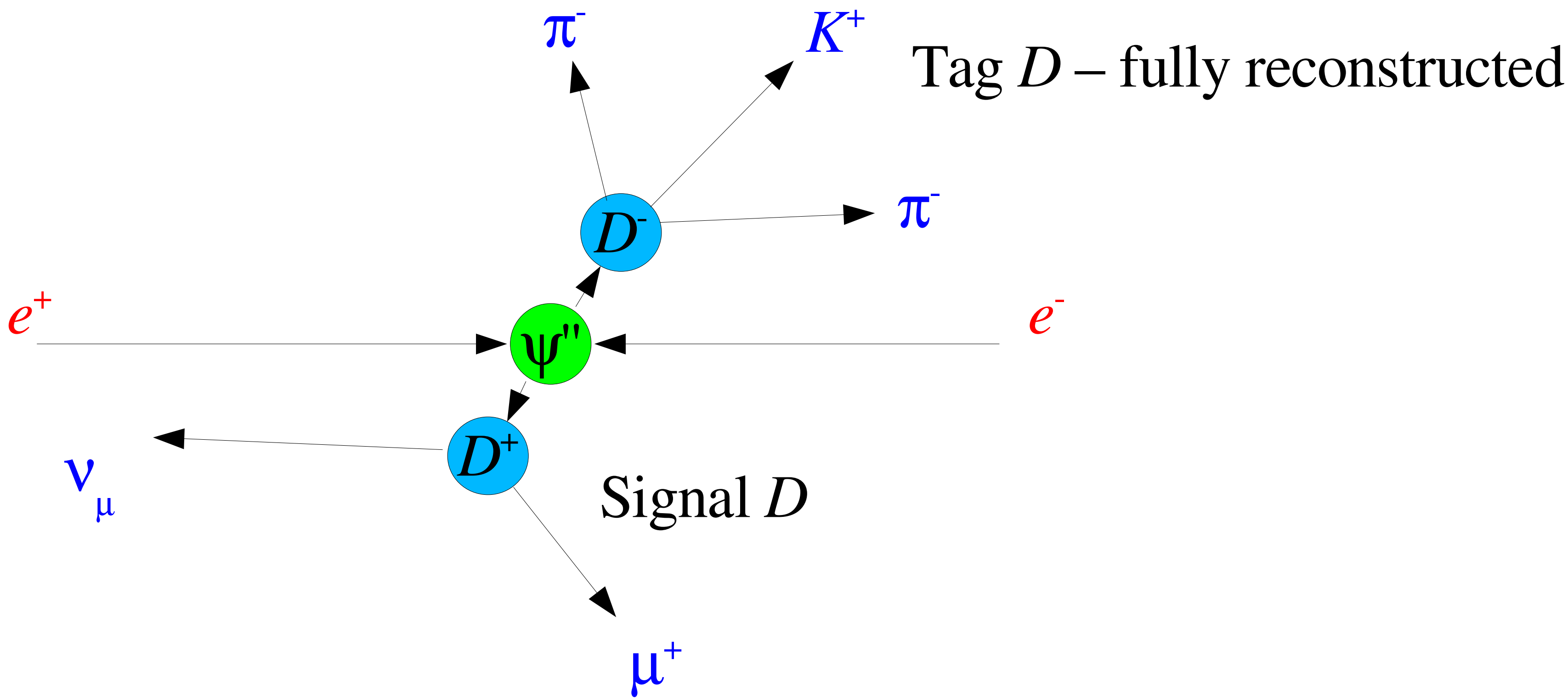
$D^+ \to \mu^+ \nu_\mu$ and f_{D^+}



$$\Gamma(D^+ \to l^+ \nu) = \frac{G_F^2}{8\pi} f_{D^+}^2 m_l^2 M_{D^+} \left(1 - \frac{m_l^2}{M_{D^+}^2}\right)^2 |V_{cd}|^2$$

- A precise measurement of f_{D^+} allows precise comparison with theoretical calculations, such as lattice QCD.
- This will help determining f_B, which currently can not be measured in leptonic B decays.

Analysis Technique



- Detect muon and make sure it recoiled against neutrino.
  - Extract signal in M^2_{miss} which peaks at 0.
- This analysis uses ~160,000 fully reconstructed tags (281 pb^{-1})

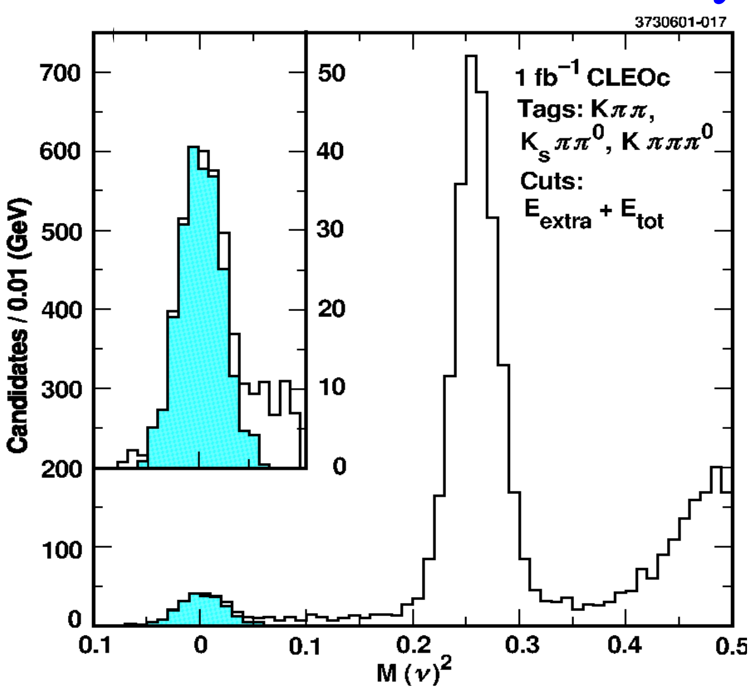
Observed Signal (PRL 95 251801 (2005))

- For events with μ candidate form

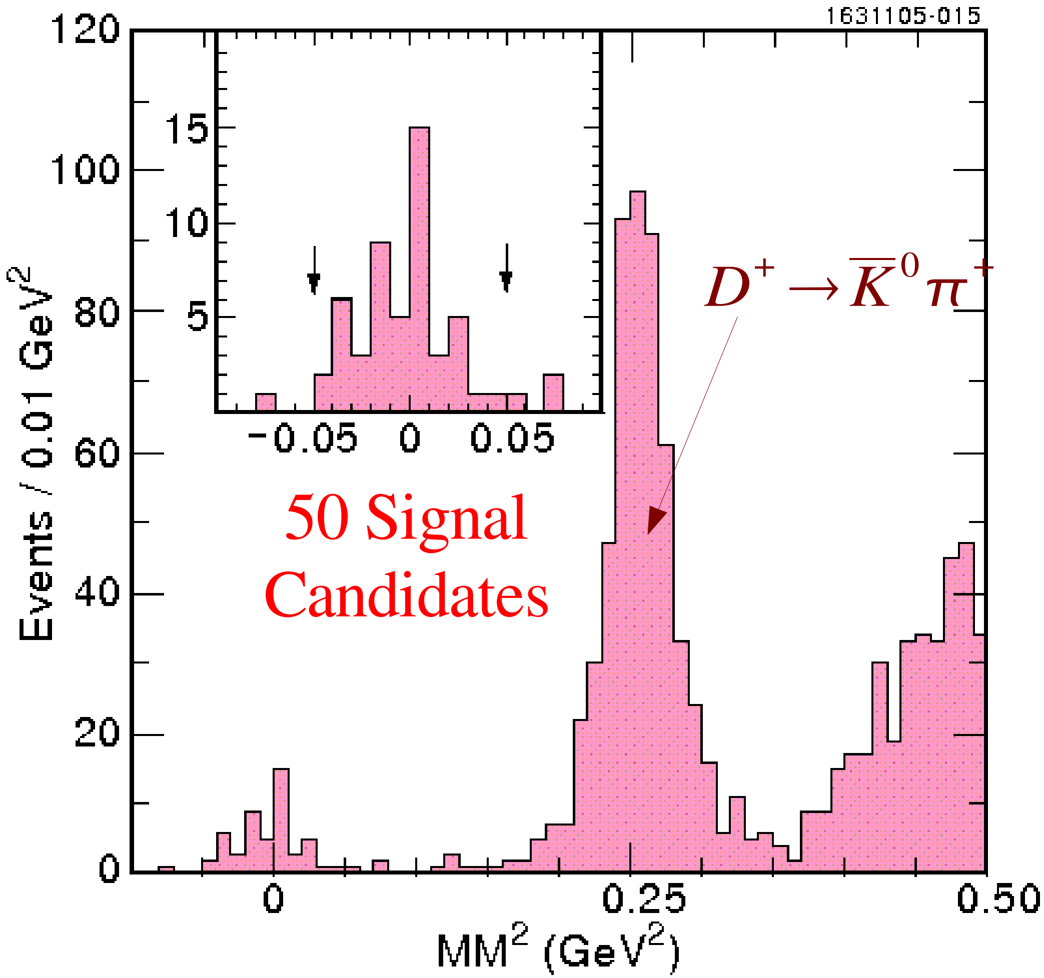
$$MM^2 = (E_{beam} - E_\mu)^2 - (-\vec{p}_{D^-} - \vec{p}_\mu)^2$$

- Signal will peak at $MM^2 = m^2_\nu = 0$

“Yellow book” MC Study

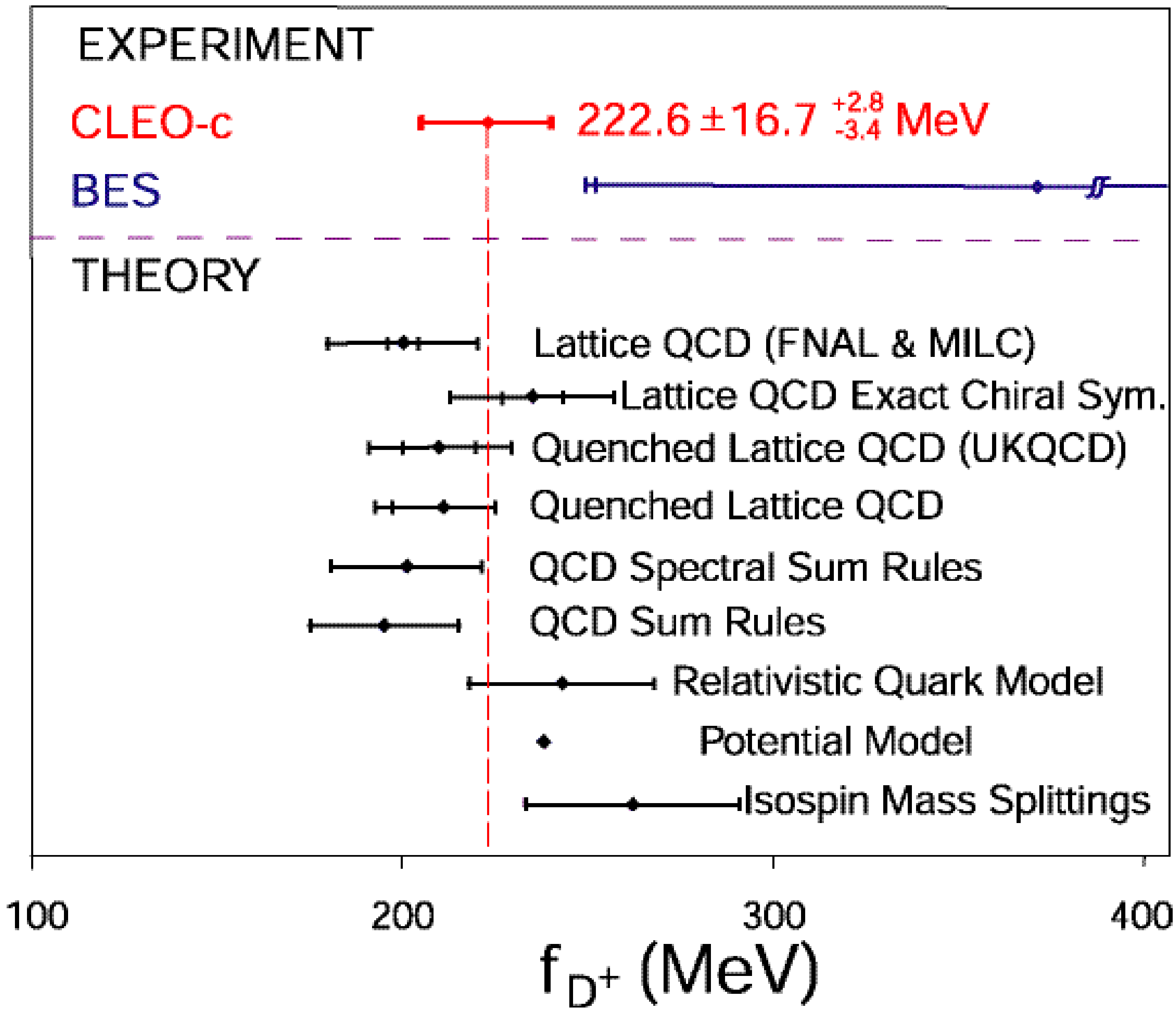


Data 281 pb^{-1}



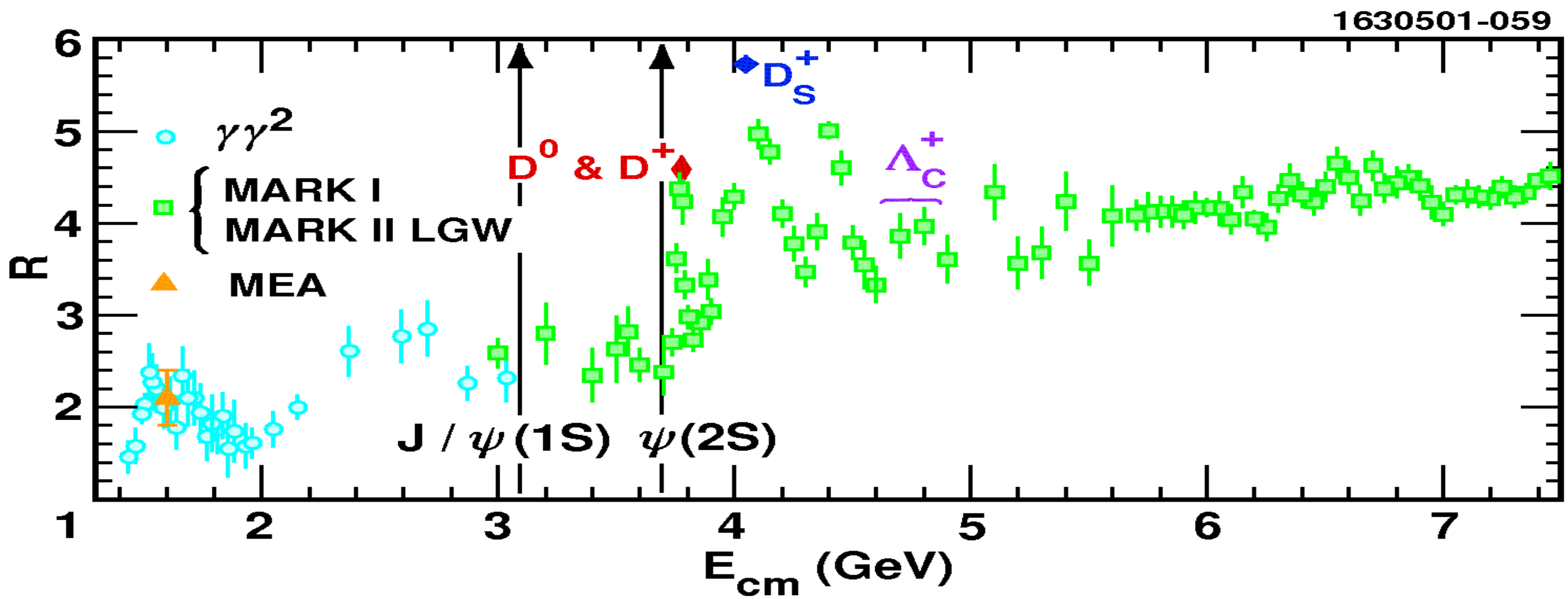
$$Br(D^+ \to \mu^+ \nu_\mu) = (4.40 \pm 0.0.66^{+0.09}_{-0.12}) \times 10^{-4}$$

Comparing with Theory



Scan for D_s Running

- CESR/CLEO-c performed a scan from 3980 to 4260 MeV
- Optimal point for D_s physics is at E_{cm}=4170 MeV.
  - Producing $D_s D^*_s$ pairs



- Plan is to take about 750 pb^{-1} at E_{cm}=4170 MeV
  - Should allow us to measure Br($D_s \to \phi\pi$) to about 4%
  - f_{Ds} to a few percent

Summary - Outlook

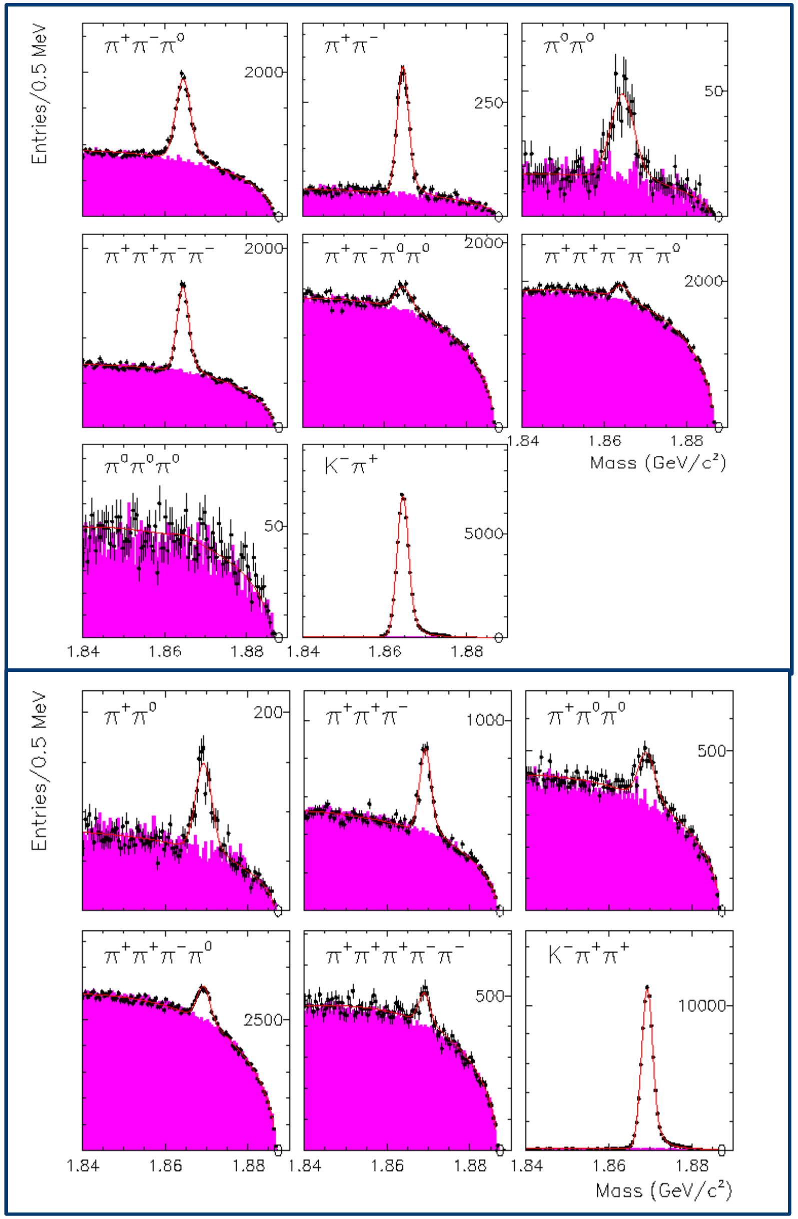
- CLEO-c has recorded 281 pb^{-1} at $\psi(3770)$
  - Hadronic and semileptonic branching fractions from 56 pb^{-1}
  - Should soon have results on 281 pb^{-1}, including form factor measurements in semileptonic decays.
  - Measured $f_D = 222.6 \pm 16.7^{+2.8}_{-3.4}$ in $D^+ \rightarrow \mu^+ \nu_\mu$
  - Plan is to take 750 pb^{-1} of data at the $\psi(3770)$
- Performed scan for D_s running
  - Recorded ~70 pb^{-1} at E_{cm}=4170 MeV
  - Plan is to take 750 pb^{-1} at this energy
  - Should allow measurements of $D_s \rightarrow \phi\pi$ to 4% or better

Backup Slides

$D \rightarrow n(\pi^{\pm})m(\pi^{0})$ (PRL 96, 081802 2006)

- This analysis doesn't use *D*-tags.
- Measure ratio to normalization mode

Mode	*B* (x10^{-3})	PDG (x10^{-3})
$\pi^+\pi^-$	1.40± 0.04± 0.03	1.38± 0.05
$\pi^0\pi^0$	0.78± 0.05± 0.04	0.84± 0.22
$\pi^+\pi^-\pi^0$	13.3± 0.2± 0.5	11± 4
$\pi^0\pi^0\pi^0$	< 0.30	- - -
$\pi^+\pi^+\pi^-\pi^-$	7.42± 0.14± 0.27	7.3± 0.5
$\pi^+\pi^-\pi^0\pi^0$	10.2± 0.6± 0.7	- - -
$\pi^+\pi^+\pi^-\pi^-\pi^0$	4.31± 0.44± 0.18	- - -
$\pi^+\pi^0$	1.23± 0.06± 0.06	1.33± 0.22
$\pi^+\pi^+\pi^-$	3.36± 0.10± 0.16	3.1± 0.4
$\pi^+\pi^0\pi^0$	4.80± 0.27± 0.34	- - -
$\pi^+\pi^+\pi^-\pi^0$	11.7± 0.4± 0.7	- - -
$\pi^+\pi^+\pi^+\pi^-\pi^-$	1.67± 0.18± 0.17	1.82± 0.25
$\eta\pi^+$	3.56± 0.24± 0.21	3.0± 0.6
$\eta\pi^0$	0.61± 0.14± 0.05	- - -
$\omega\pi^+\pi^-$	1.66± 0.47± 0.10	- - -



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

Source	56 pb^{-1}	281 pb^{-1}	750 pb^{-1}
Trk. eff.	0.7%	0.35%	0.25%
Kaon PID eff.	1.3%	0.3%	0.3%
Pion PID eff.	0.3%	0.2%	0.2%
ΔE selection	1.0%	0.3%	0.3%
Fit shape	0.8%	0.5%	0.5%
FSR	0.5%	0.5%	0.5%
Res. Sub. Structure	0.6%	0.4%	0.4%
Double DCSD interf.	0.8%	0.8%	0.5%
$D^0 \to K^-\pi^+$ Stat	2.1%	0.9%	0.6%
$D^0 \to K^-\pi^+$ Syst	3.1%	1.3%	1.1%
$D^0 \to K^-\pi^+$ Total	3.7%	1.6%	1.2%
$D^+ \to K^-\pi^+\pi^+$ Stat	3.9%	1.2%	0.7%
$D^+ \to K^-\pi^+\pi^+$ Syst	2.6%	1.4%	1.2%
$D^+ \to K^-\pi^+\pi^+$ Total	4.7%	1.8%	1.4%

- Systematics limited at 281 pb^{-1}
  - Some systematics should improve with additional statistics

$D^+ \to \mu^+ \nu_\mu$ Results

- 50 signal candidate events with the following backgrounds

Background	$\mathcal{B}$ (%)	# of events
$D^+ \to \pi^+\pi^0$	0.13 ± 0.02	$1.40 \pm 0.18 \pm 0.22$
$D^+ \to K^0\pi^+$	2.77 ± 0.18	$0.33 \pm 0.19 \pm 0.02$
$D^+ \to \tau^+\nu$	$2.6 \times \mathcal{B}(D^+ \to \mu^+\nu)$	$1.08 \pm 0.15 \pm 0.16$
$D^0\bar{D}^0,\ D^+D^-$	—	$< 0.4, < 0.4,\ 90\%$ C.L.
continuum	—	$< 1.2\ \ 90\%$ C.L.
Total		$2.81 \pm 0.30 \pm^{+0.84}_{-0.27}$

- With 158,354 D^+ tags and an efficiency of 67.7% for signal events to satisfy the selection criteria given a D^+ tag we obtain:

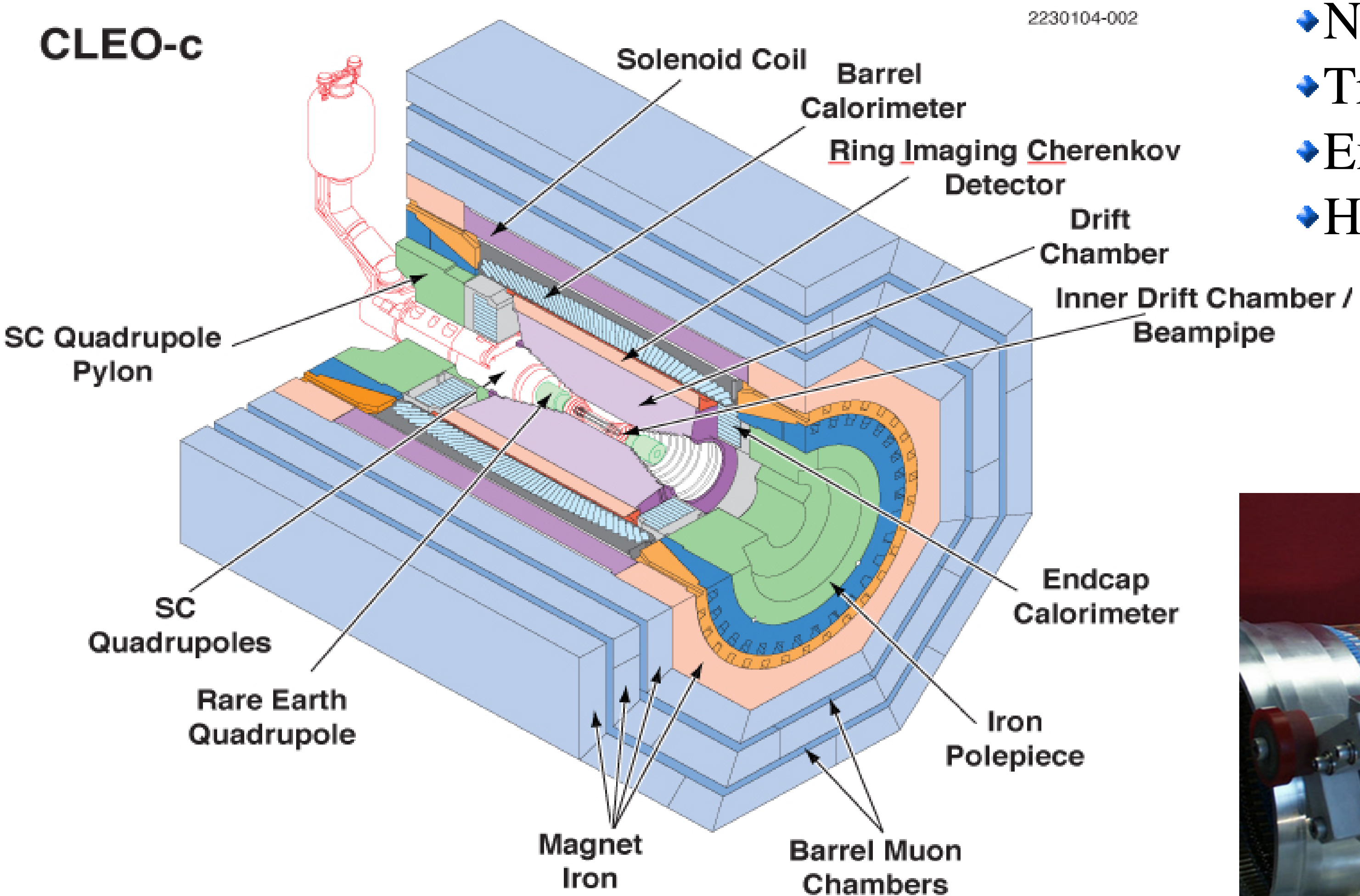
$$Br(D^+ \to \mu^+ \nu) = (4.40 \pm 0.66^{+0.09}_{-0.12}) \times 10^{-4} \qquad f_{D^+} = (222.6 \pm 16.7^{+2.8}_{-3.4})\,\text{MeV}$$

(Accepted by PRL)

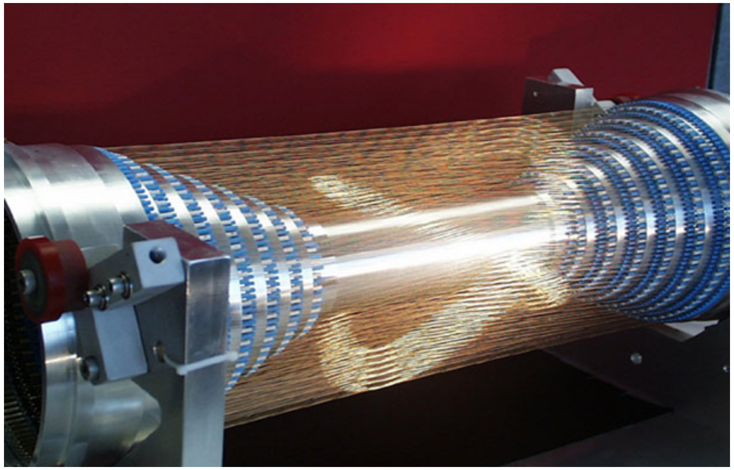
- We also obtain $Br(D^+ \to e^+ \nu) < 2.4 \times 10^{-5}$ at 90 C.L.

CLEO-c Experiment

Most results use 56 pb^{-1} or 281 pb^{-1} of data collected at $\Psi(3770)$ resonance



- New inner drift chamber
- Tracking in 1.0 T field
- Excellent E-M calorimeter
- Hadron PID from RICH



Comparison with PDG Averages