Recent CLEO-c Results on *D* and D_s Mesons

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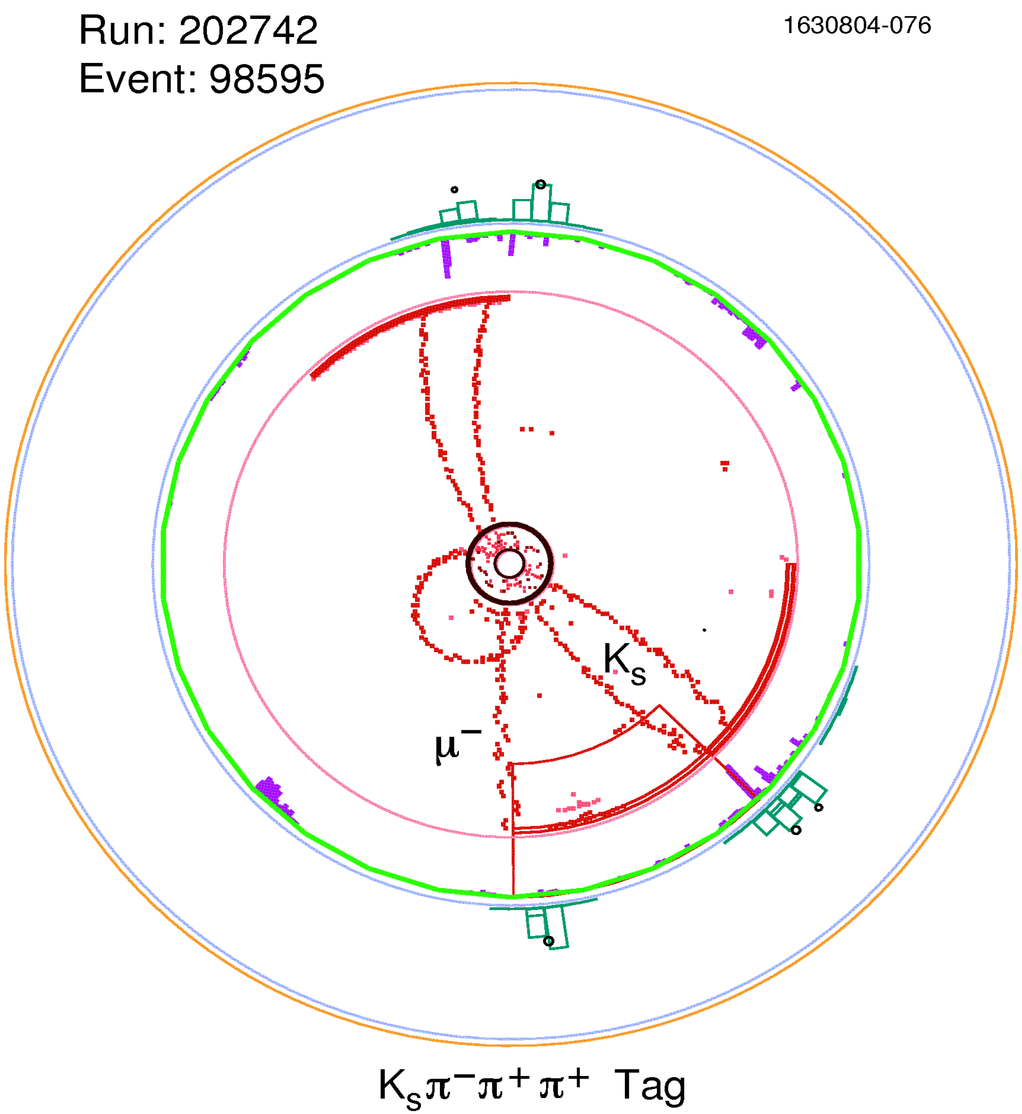
LBNL, Oct. 3, 2006

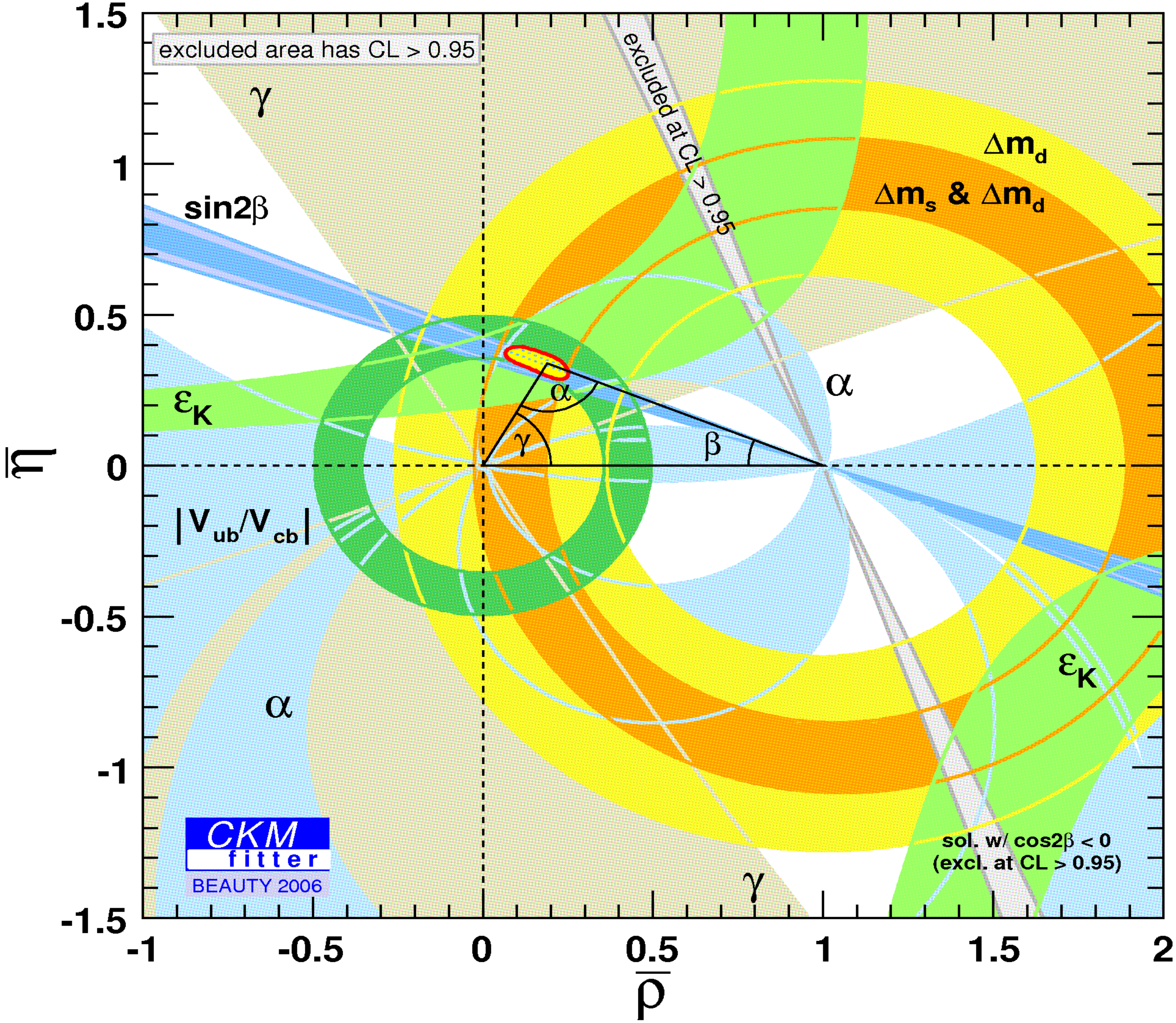


Outline:

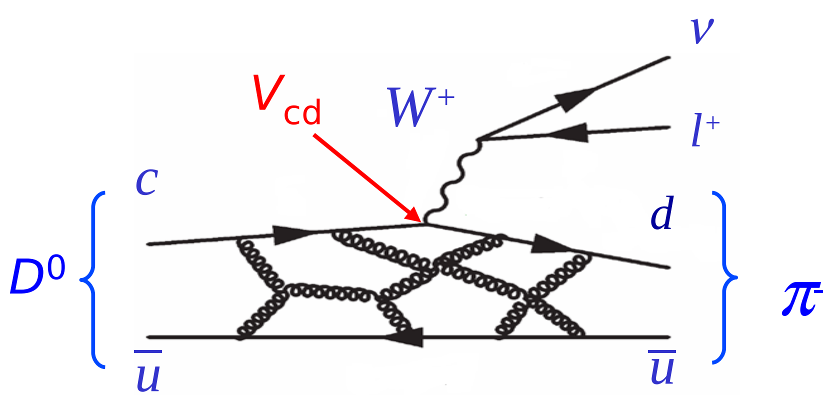
- The CLEO-c program
- Physics at the ψ(3770)
- D_s scan
- Hadronic *D* and D_s decays
- Leptonic *D* and D_s decays
- Semileptonic *D* decays

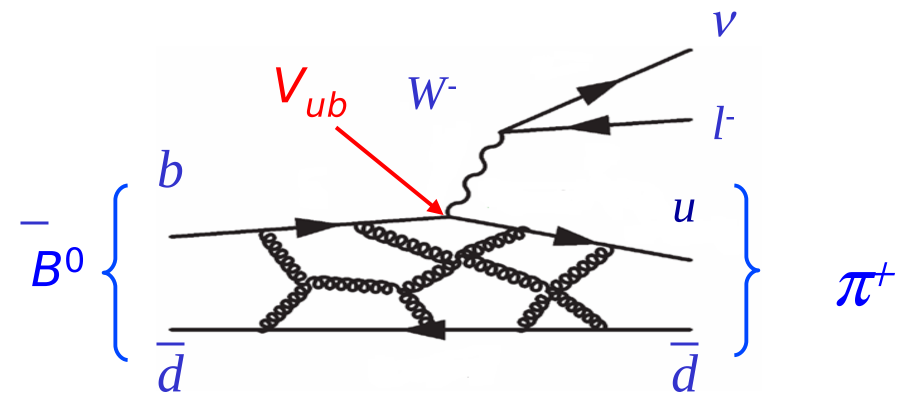
Physics Motivation

- The CLEO-c program impacts many of the CKM parameters
- In particular, leptonic D and D_s decays allow measurements of the decay constants
- This will help the determination of V_{td}
- Semileptonic D decays will check form factor calculations and improve V_{ub}
- Hadronic D decays are important for normalization of B decays



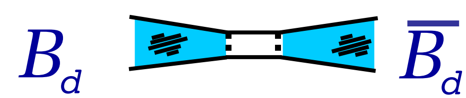
Testing Theories of Strong Interactions



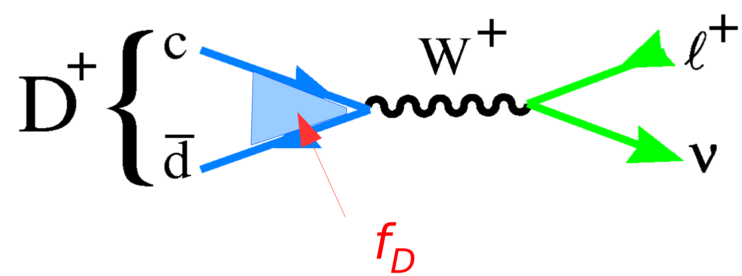


- Measure form factors in $D \to \pi l \nu$ and validate theoretical calculations
  - Can then use this to extract $|V_{ub}|$ from $B \to \pi l \nu$

- B mixing is well measured $\Delta m_d = (0.502 \pm 0.007) \times 10^{-12}$ s
- But $|V_{td}|$ from Δm_d has large uncertainties from f_B
- CLEO-c can measure f_D

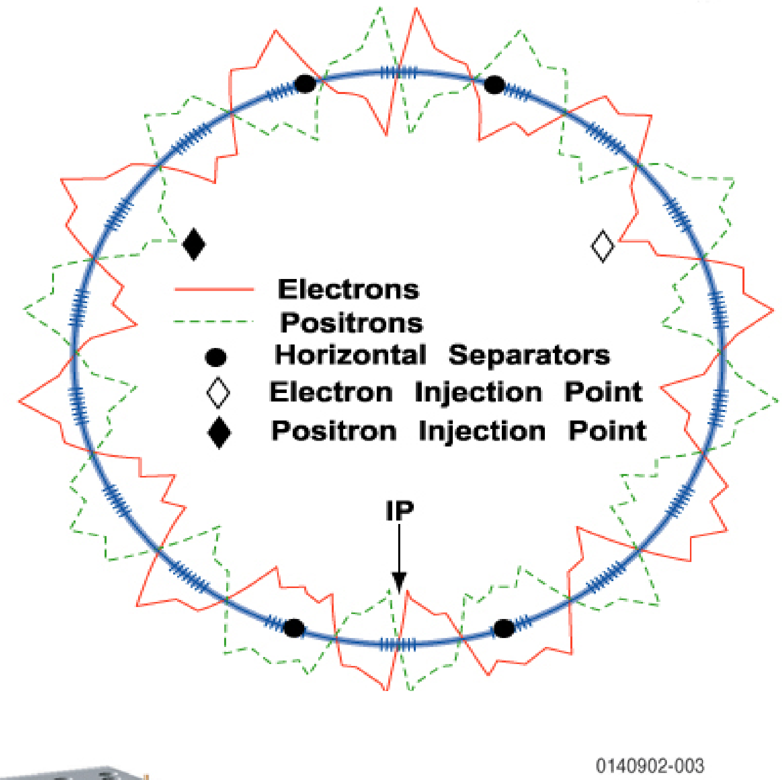


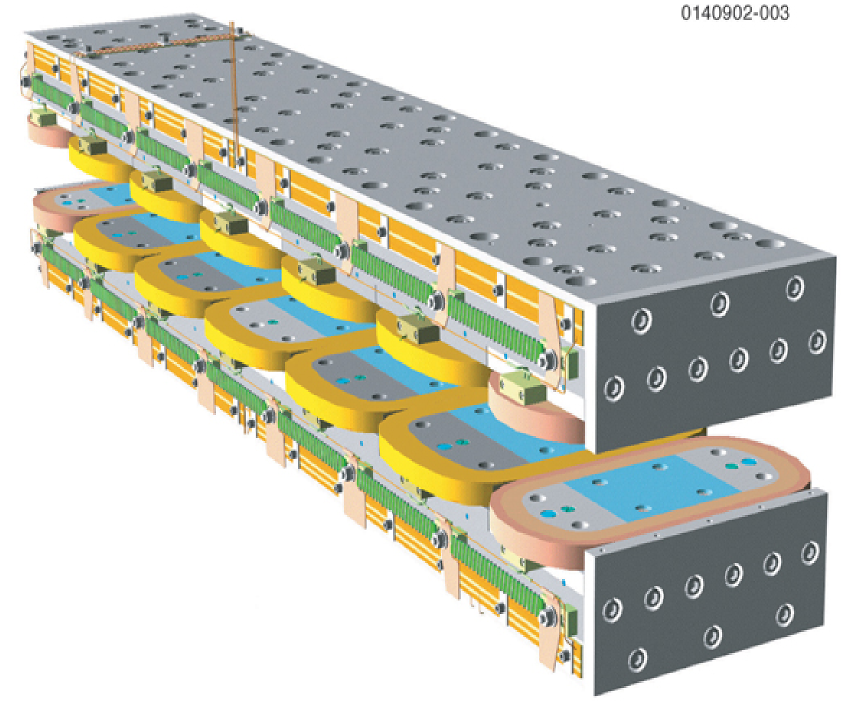
$$\Delta m_d = \frac{G_F^2}{6} M_B M_t^2 |V_{td} V_{tb}^*|^2 \eta_B S_0(x_t) f_B^2 B_B$$



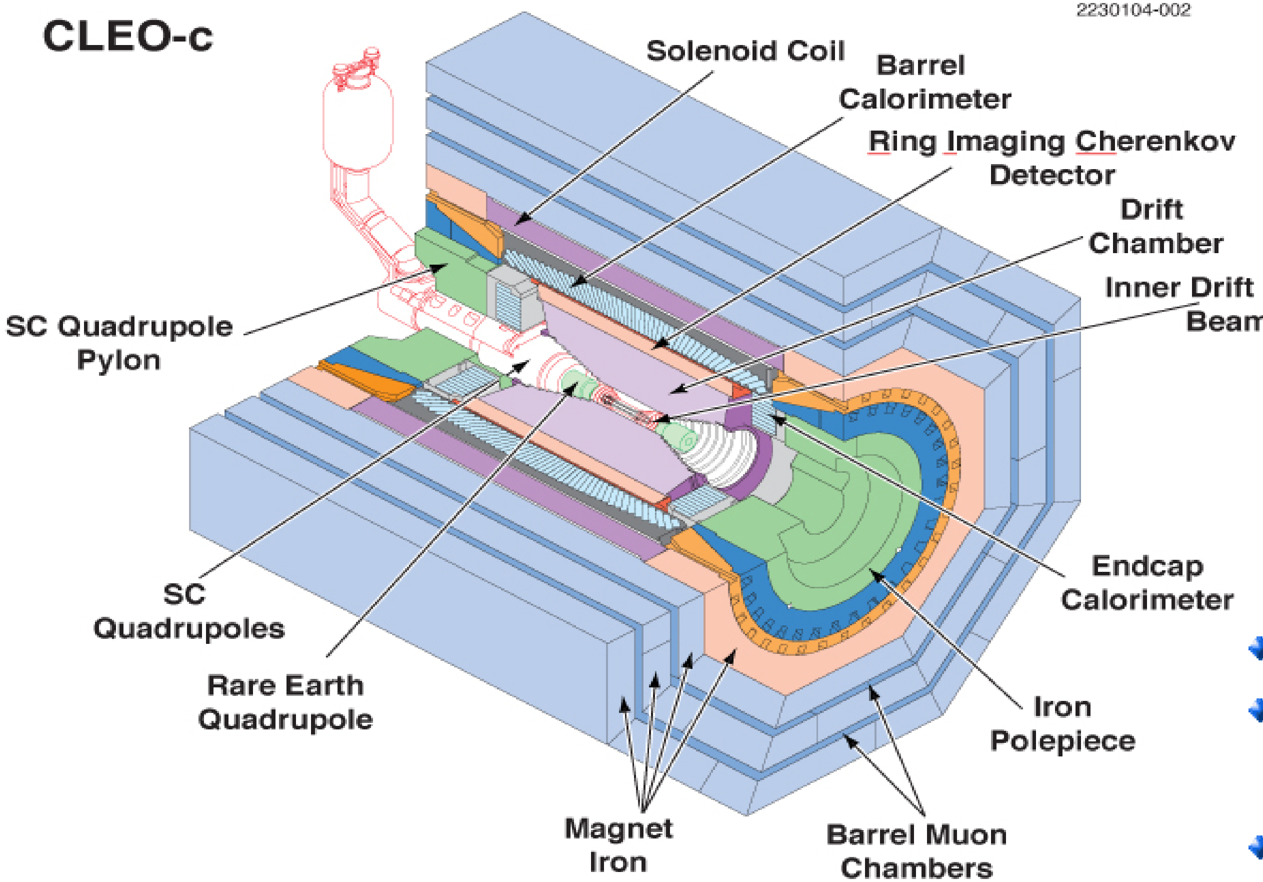
CESR-c

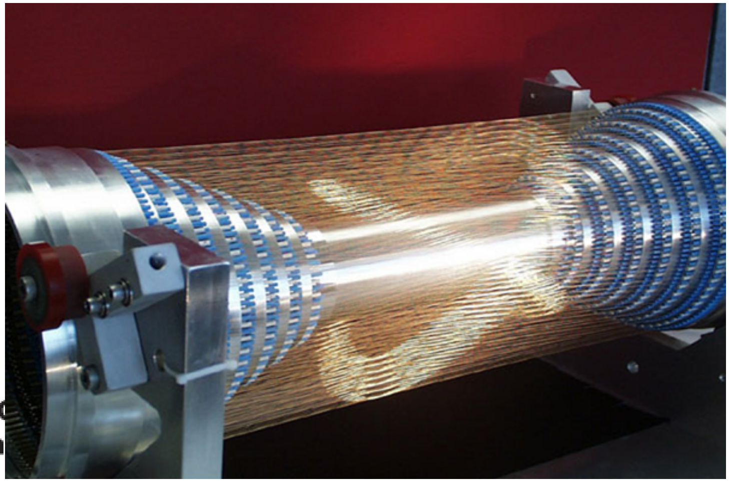
- CESR was upgraded with wiggler magnets to increase damping at lower energies
- These super conducting magnets have worked very well
- However, the currents that can be stored are lower than planed
  - Luminosity about ¼ of design
- Compensating solenoids were installed last winter
  - The compensations with the skew quads used at 5GeV does not work well at lower energy





CLEO-c Experiment





- New inner drift chamber
- Tracking in 1.0 T field
  - $\sigma_p/p \approx 0.6\%$ at 1 GeV
- Excellent E-M calorimeter
  - $\sigma_E/E \approx 2\%$ at 1 GeV
- Hadron PID from RICH
  - Very good below 1 GeV

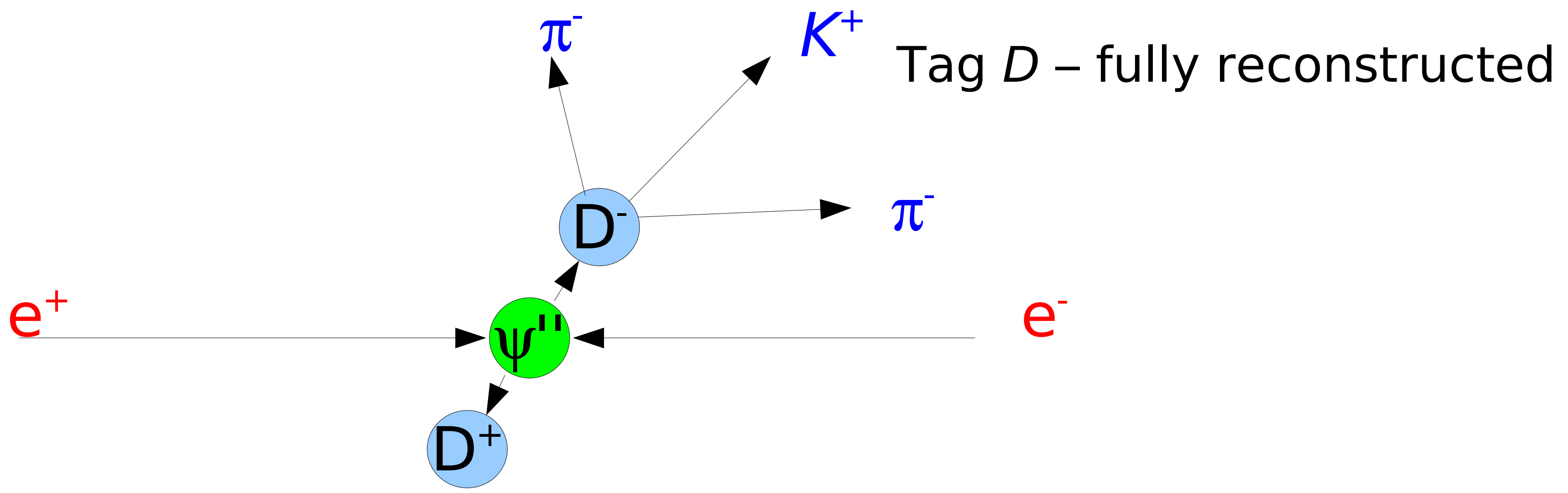
CLEO-c Data Samples and Plans

- With a better understanding of the performance of CESR-c and looking at the physics case we are now looking at a somewhat modified run plan
  - ~750 pb^{-1} at $\psi(3770)$
  - ~750 pb^{-1} at $D_s D_s$ threshold
  - ~5% of running time at $\psi(2S)$, 30M events

Recorded:
281 pb^{-1}
330 pb^{-1}
27M events

- Solid motivation for J/ψ running was hard to find. The $f_J(2220)$ no longer there. Studying this was an important goal for the J/ψ program
- We have done a scan in the D_s threshold region to understand where to run and measure the cross-section
- Will continue running until March 31, 2008

Physics at the $\psi(3770)$



- At threshold produce only D^+D^- and $D^0\bar{D}^0$
  - No additional pions.
- By reconstructing one *D* meson we know that we had another *D* produced with opposite momentum in the $\psi(3770)$ frame.
- This tag technique is used in many CLEO-c analysis and was pioneered by MARK III.

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

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

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

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

$$re^{i\delta}=\frac{\langle\overline{D}^0|K^-\pi^+\rangle}{\langle D^0|K^-\pi^+\rangle}$$

$$z=2\cos\delta$$

- 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)

$$N(D^0\to K_S^0\pi^0)=2\mathrm{N}_{D^0\overline{D}^0}B(D^0\to K_S^0\pi^0)(1+y)$$

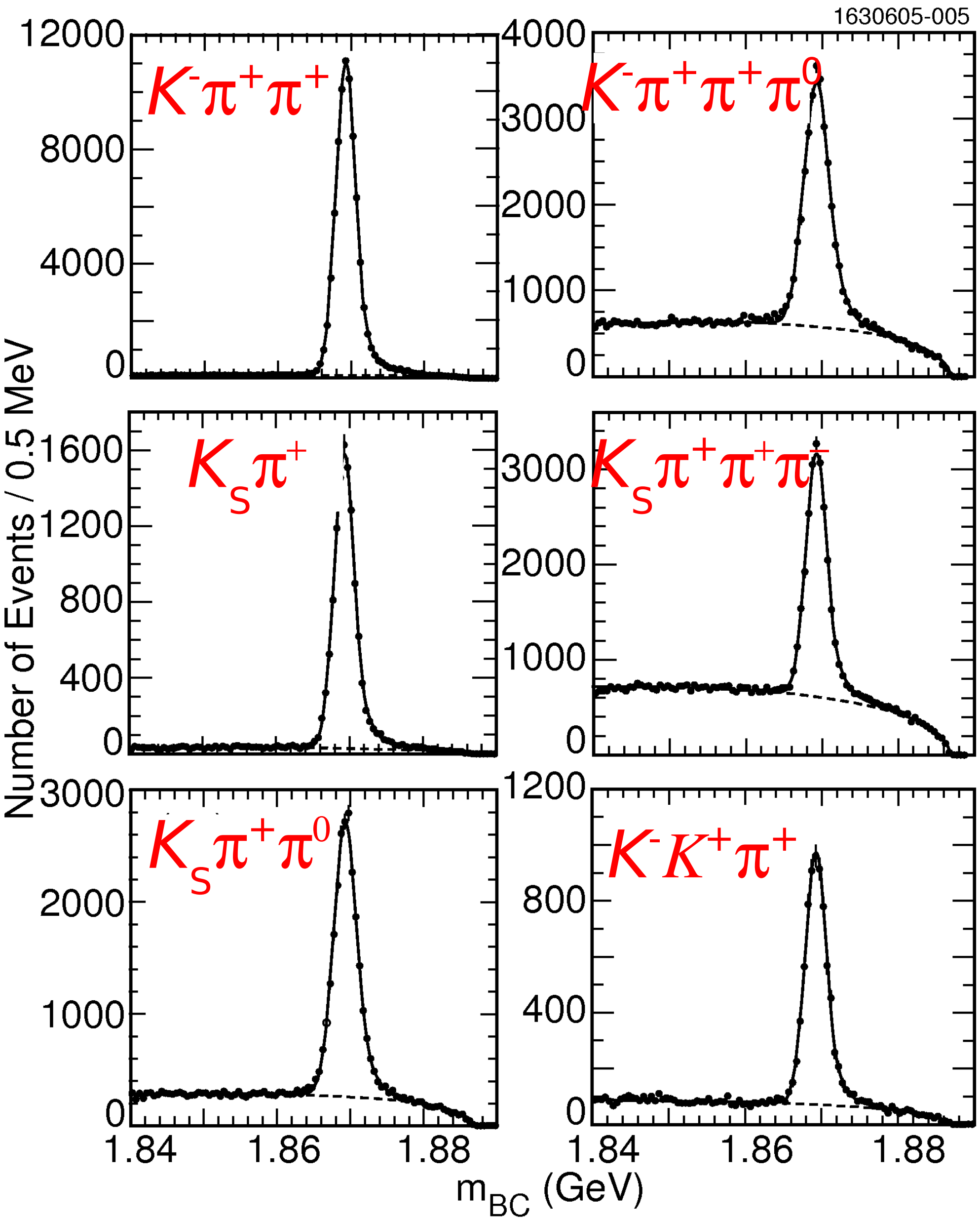
- Where the other *D* is a flavor tag $D\to f$

$$N(D^0\to K_S^0\pi^0)=N_{D^0\overline{D}^0}B(D^0\to K_S^0\pi^0)(1-2\mathrm{r}_f\cos\delta_f)$$

Allow us to measure phase δ_f, in 280 pb^{-1}

$$\sigma_{\cos\delta_{K\pi}}=\pm 0.64$$

CLEO-c *D*-tag Reconstruction



- From $D \to \mu\nu$ analysis
- 281 pb^{-1}
- Six tag modes used
- ~160,000 reconstructed $D^\pm$
- ~300,000 reconstructed D^0
- Cut on E_D-E_{beam}

Mode	Signal	Background
$K^+\pi^-\pi^-$	77387 ± 281	1868
$K^+\pi^-\pi^-\pi^0$	24850 ± 214	12825
$K_S\pi^-$	11162 ± 136	514
$K_S\pi^-\pi^-\pi^+$	18176 ± 255	8976
$K_S\pi^-\pi^0$	20244 ± 170	5223
$K^+K^-\pi^-$	6535 ± 95	1271
Sum	158354 ± 496	30677

$$M_{BC} = \sqrt{E_{\rm beam}^2 - |p(D)|^2}$$

Initial State Radiation

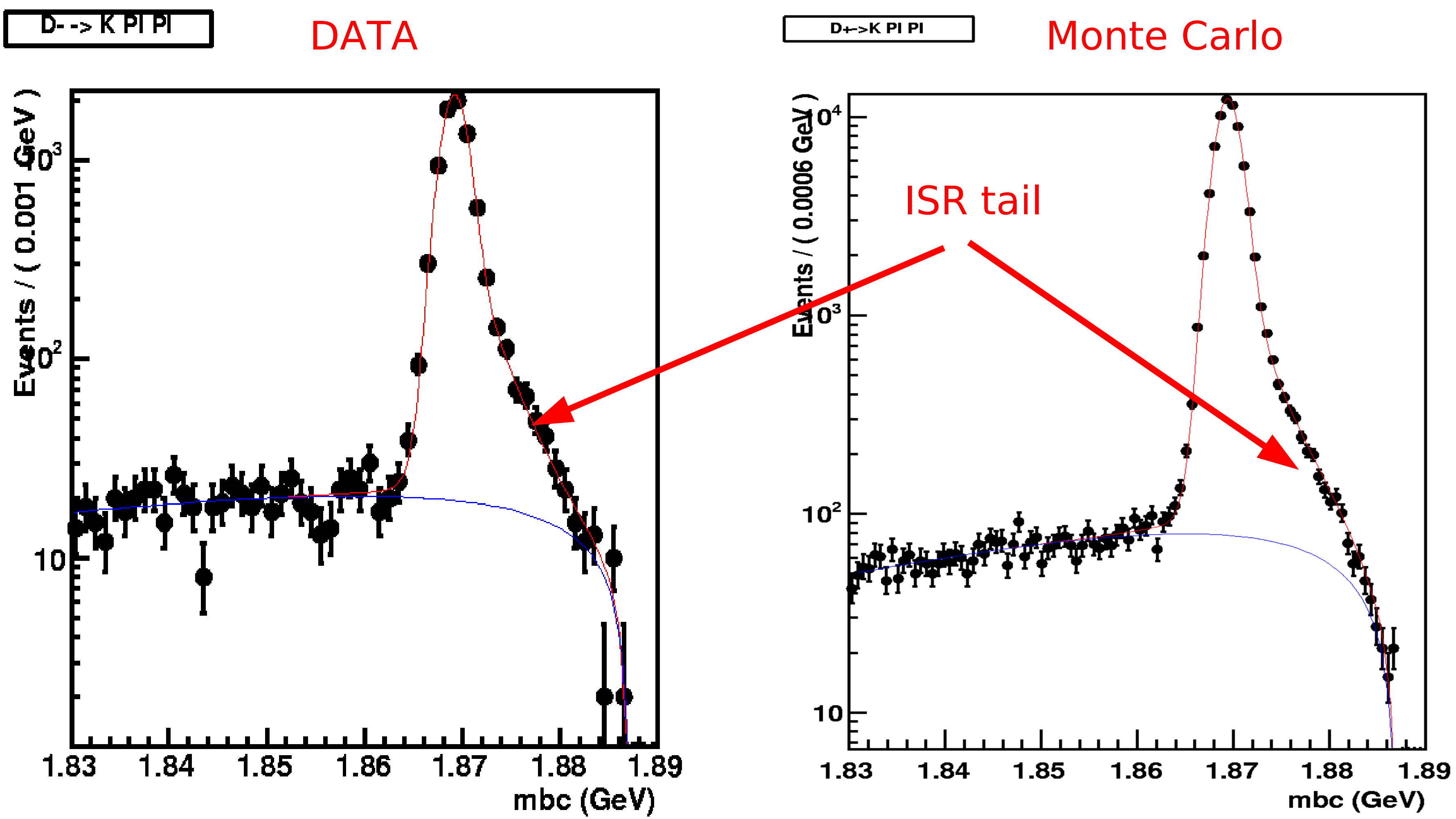
- We run at E_{cm}=3.77 GeV to produce the $\psi(3770)$
  - The spread in E_{cm} is about 2 MeV
  - The width of the $\psi(3770)$ is about 25 MeV
- However, the beam particles can radiate a photon and produce the $\psi(3770)$ at a lower energy.
  - In fact in every interaction many photons are emitted, but at such a low energy that we can not detect them. The distribution of energy radiated by (soft) photons is given by:

$$f(E_\gamma) \propto E_\gamma^{\beta-1} \qquad \beta = \frac{2\alpha}{\pi}\left[2\ln\frac{E_{cm}}{m_e} - 1\right] \approx 0.07$$

- Many analyses use a first principle lineshape for the m_{BC} fit

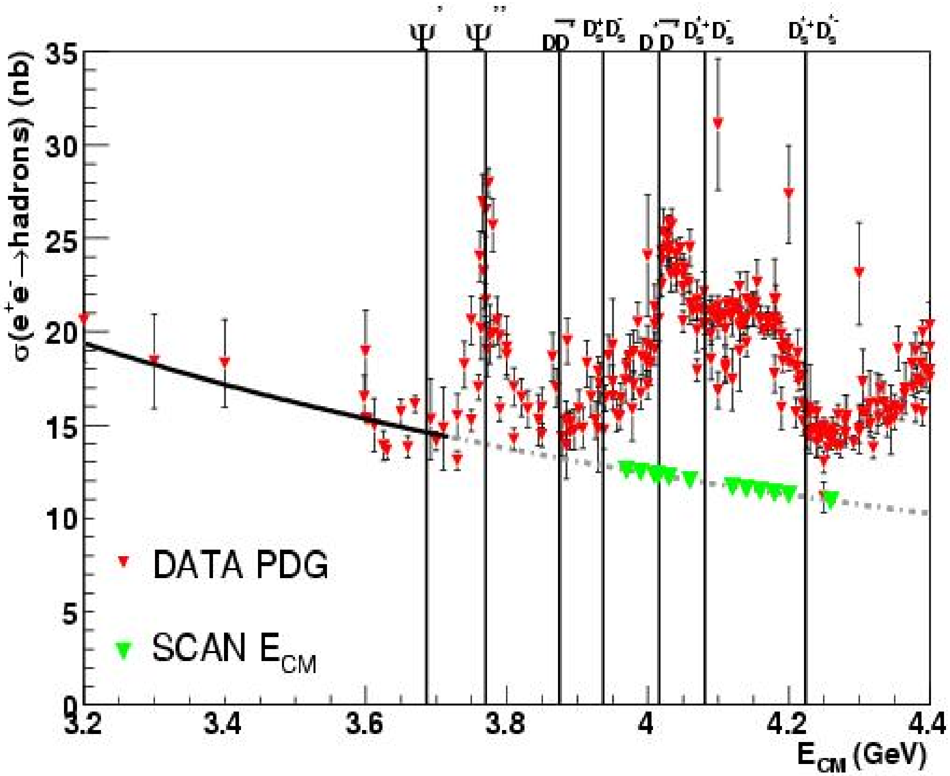
ISR in Data *vs.* MC

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



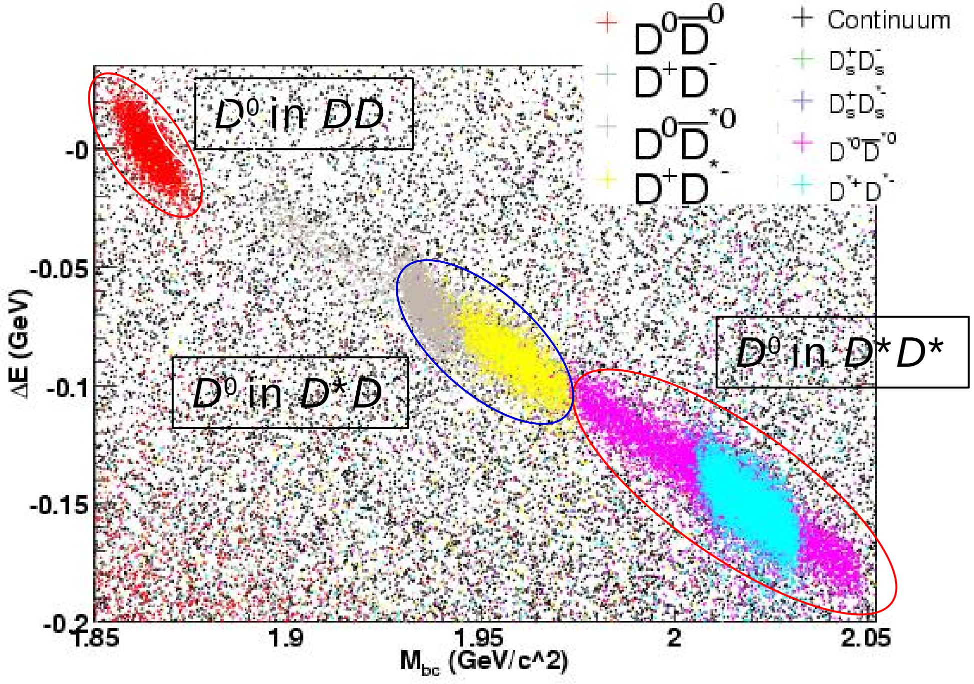
$$M_{BC} = \sqrt{E_{beam}^2 - |p(D)|^2}$$

D_S Scan



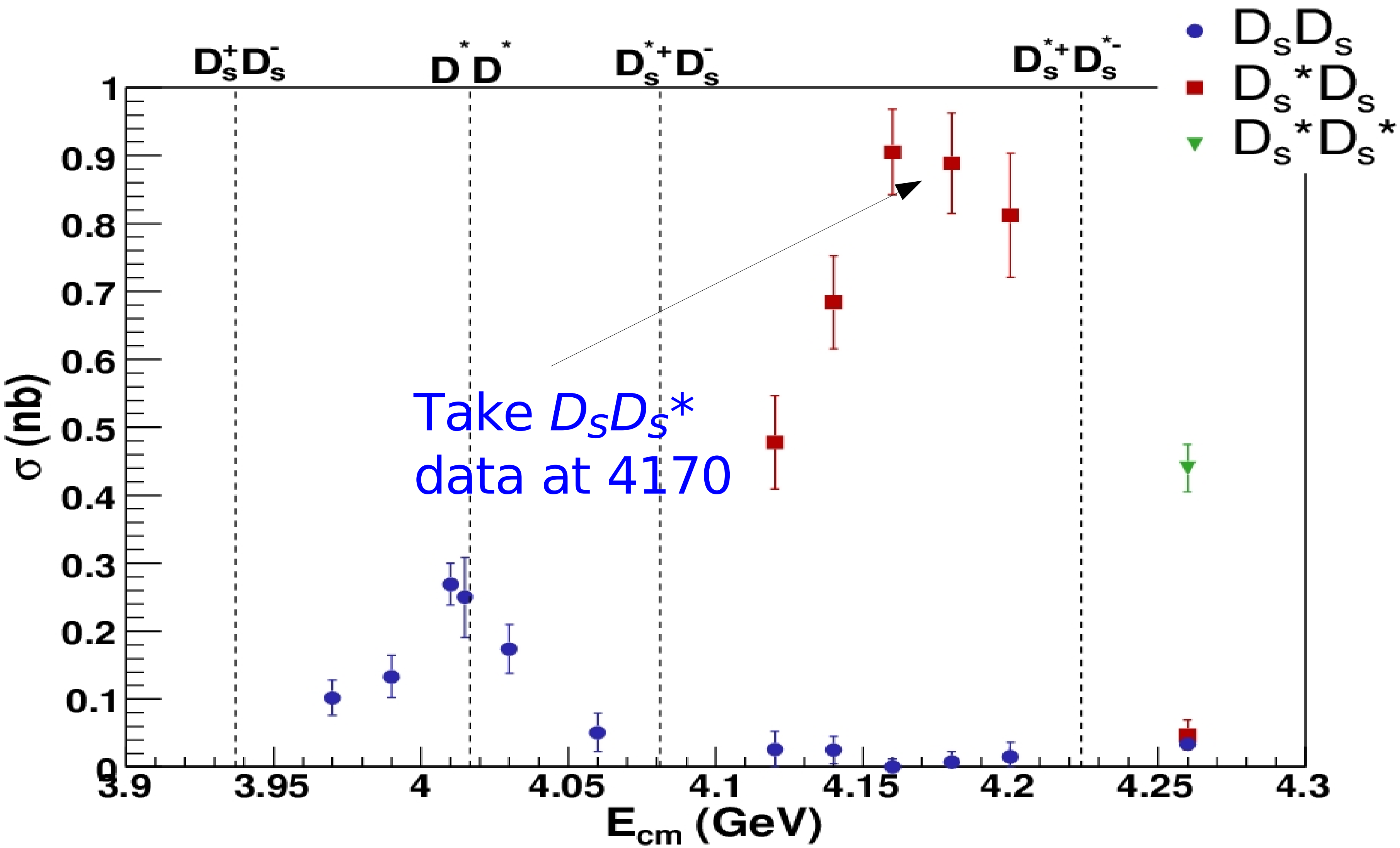
- Took 12 scan points in the energy from 3.97 to 4.26 GeV

- Identify the final states D^0D^0, D^+D^-, D^0D^{*0}, D^+D^{*-}, $D^{*0}D^{*0}$ $D^{*+}D^{*-}$, D_SD_S, $D_SD_S^*$, and $D_S^*D_S^*$ based on the reconstructed momentum of D^0, D^+ and D_S mesons

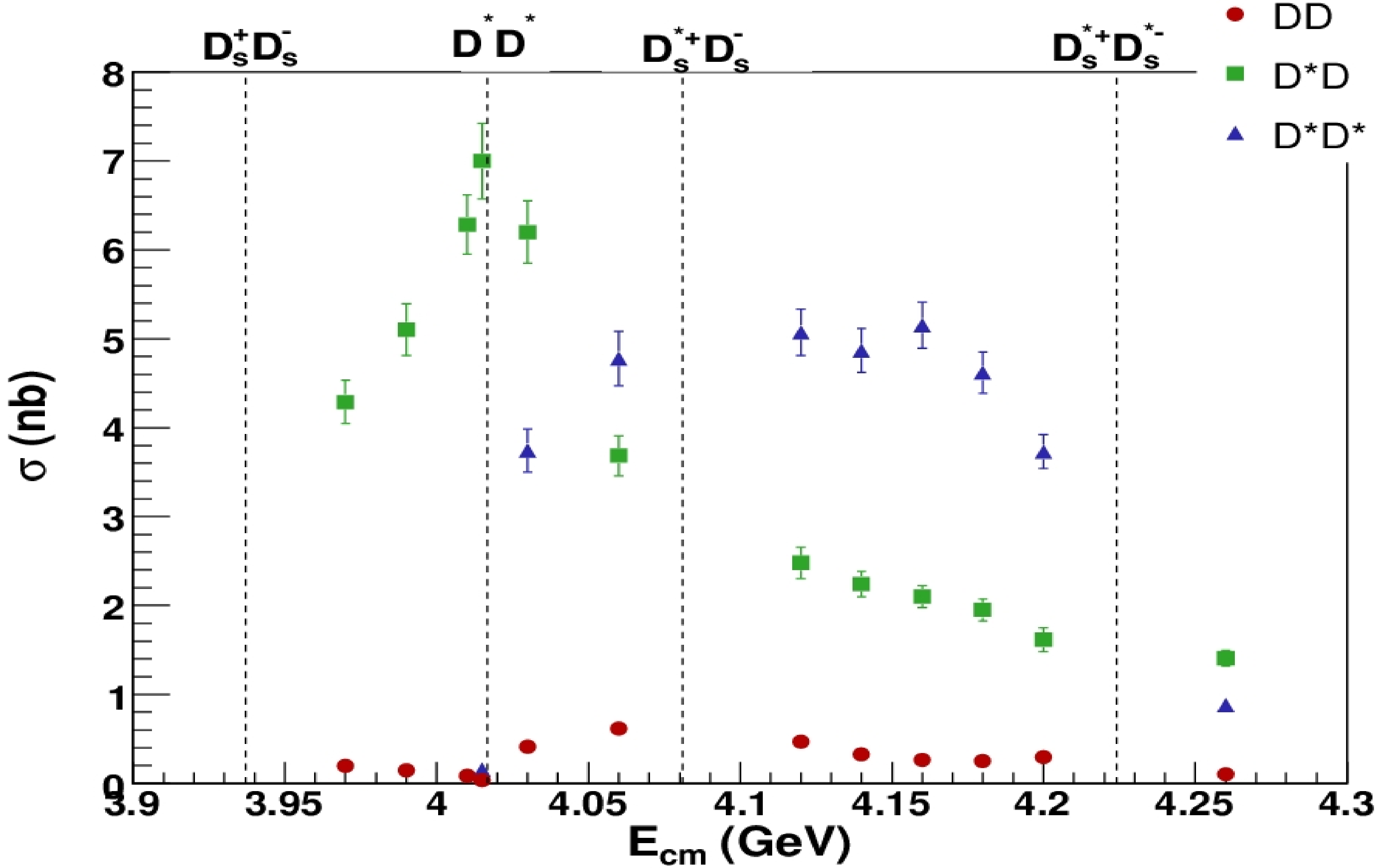


$$M_{BC} = \sqrt{E_{\text{beam}}^2 - |p(D)|^2}$$

Scan Results: D_sD_s, $D_sD_s^*$, and $D_s^*D_s^*$



Scan Results: *DD*, *D*D*, and *D*D**



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

- The ψ(3770) decays to pairs of *D* mesons – and no other particles
- Use a 'double tag' technique, pioneered by MARK III

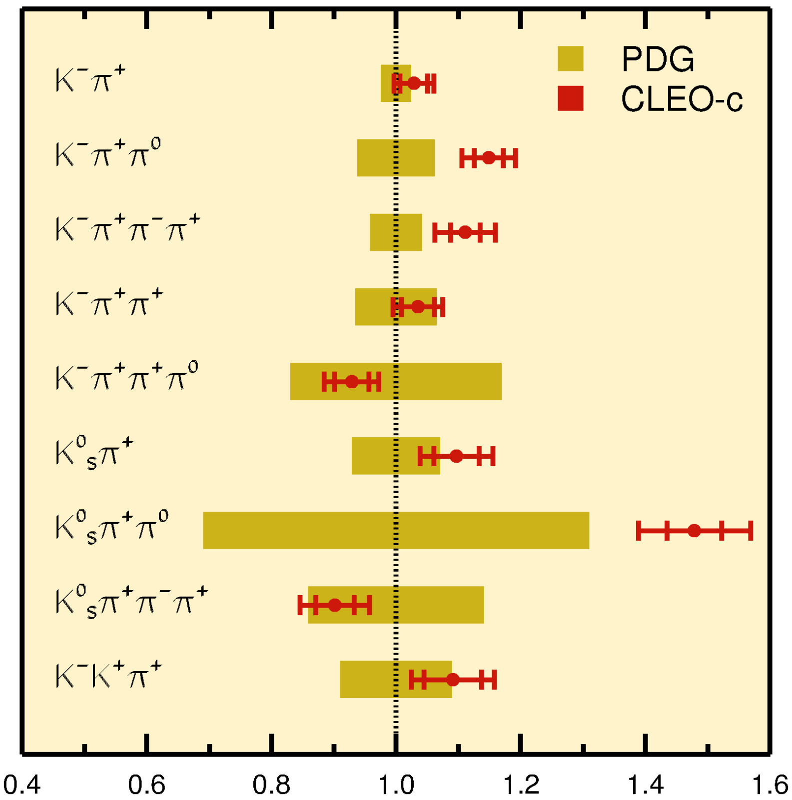
$$N_i = \epsilon_i B_i N_{D\overline{D}}$$
$$\overline{N}_j = \overline{\epsilon}_j B_j N_{D\overline{D}}$$
$$N_{ij} = \epsilon_{ij} B_i B_j N_{D\overline{D}}$$

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

- 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.).

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

(PRL 96, 092002)

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

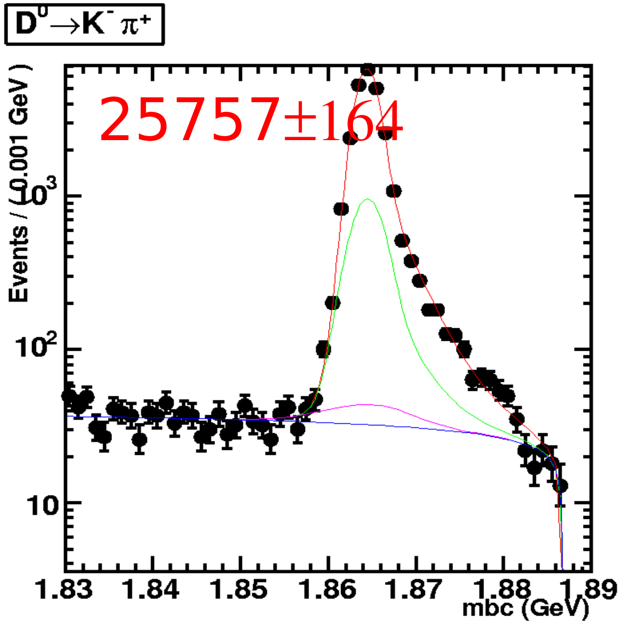
Single Tag Yields (281 pb^{-1})

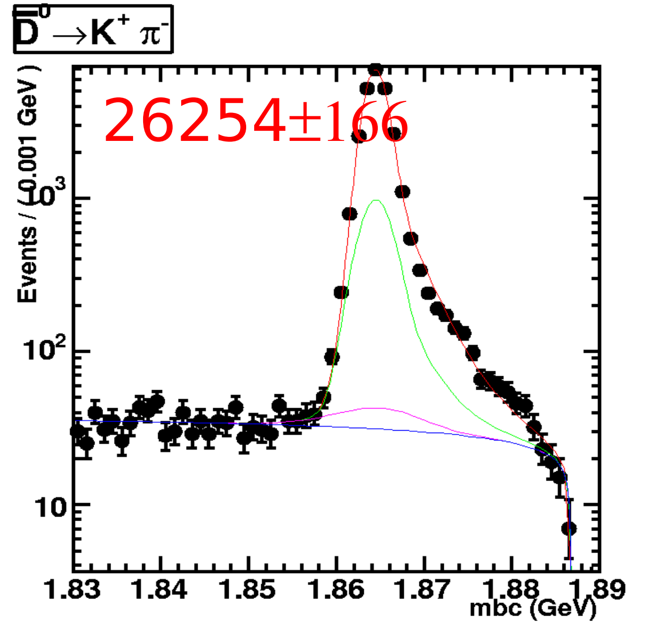
Extract yields from

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

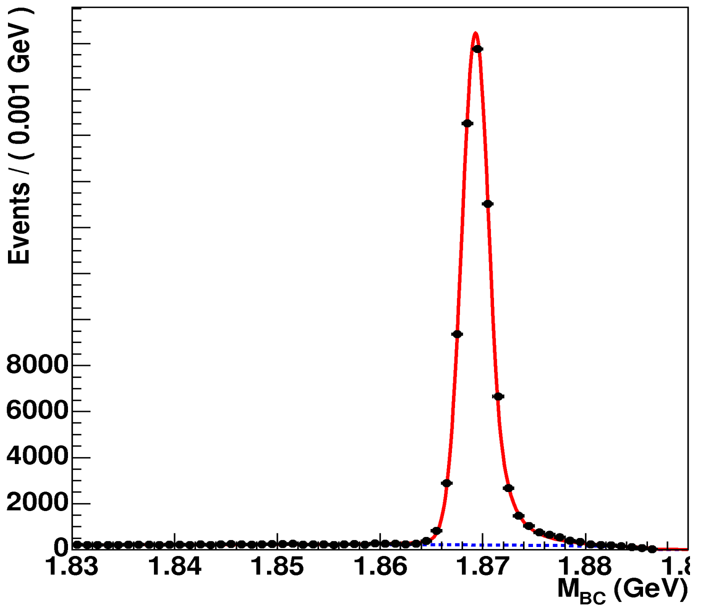
Lineshape includes

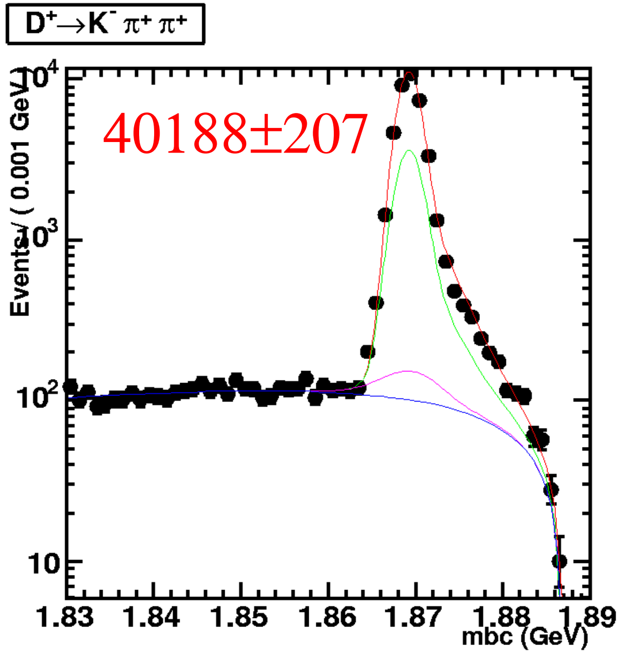
- Detector resolution
- ISR in $e^+e^- \to \psi(3770)$
- $\psi(3770)$ lineshape
- Beam energy spread

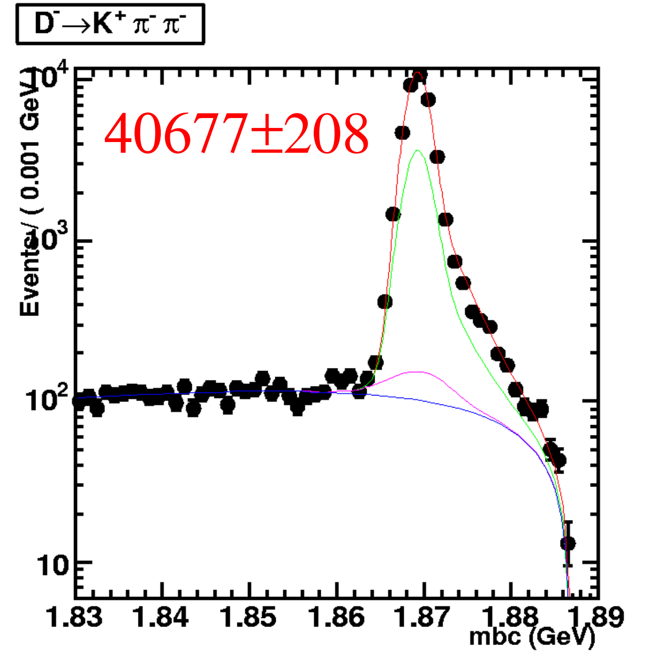




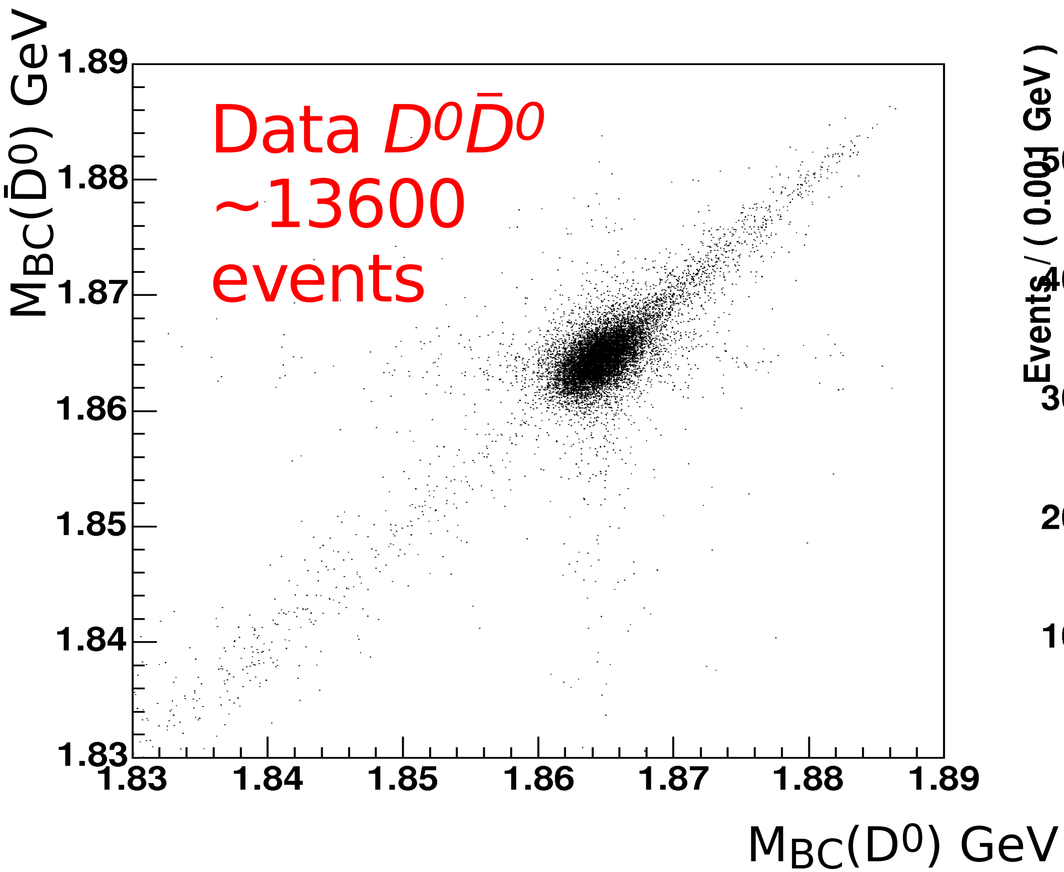
Linear scale

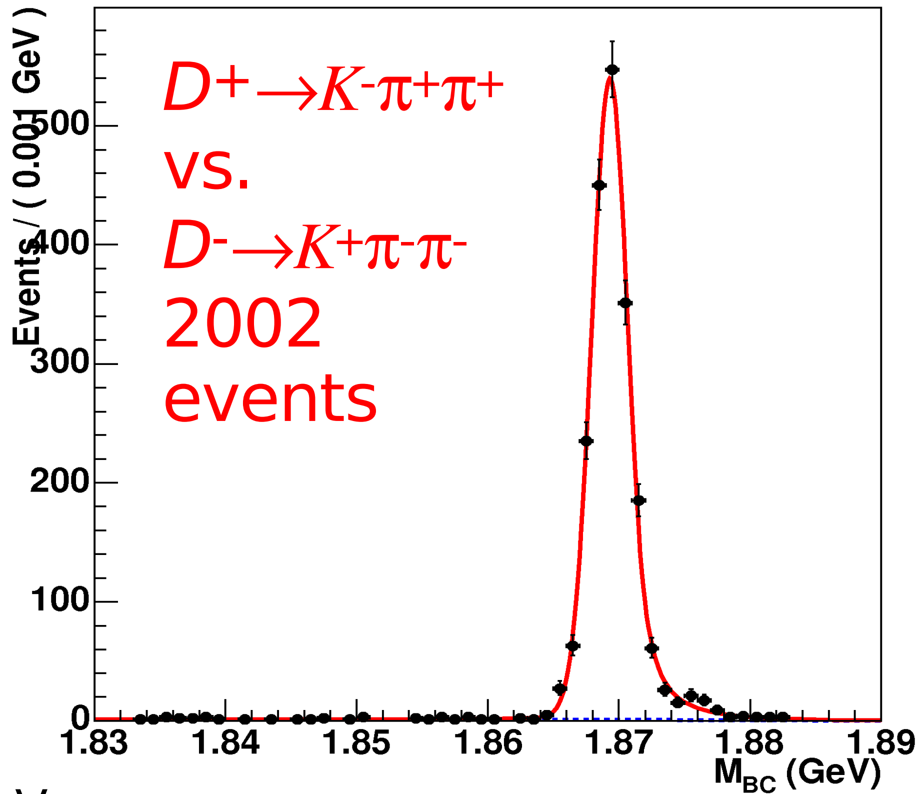






Double Tag Yields (281 pb^{-1})





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

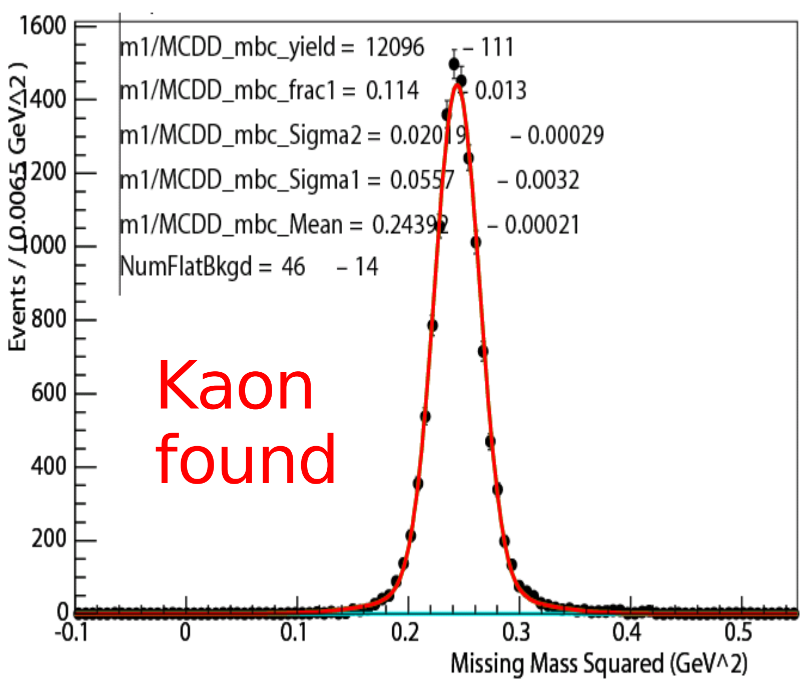
Systematics

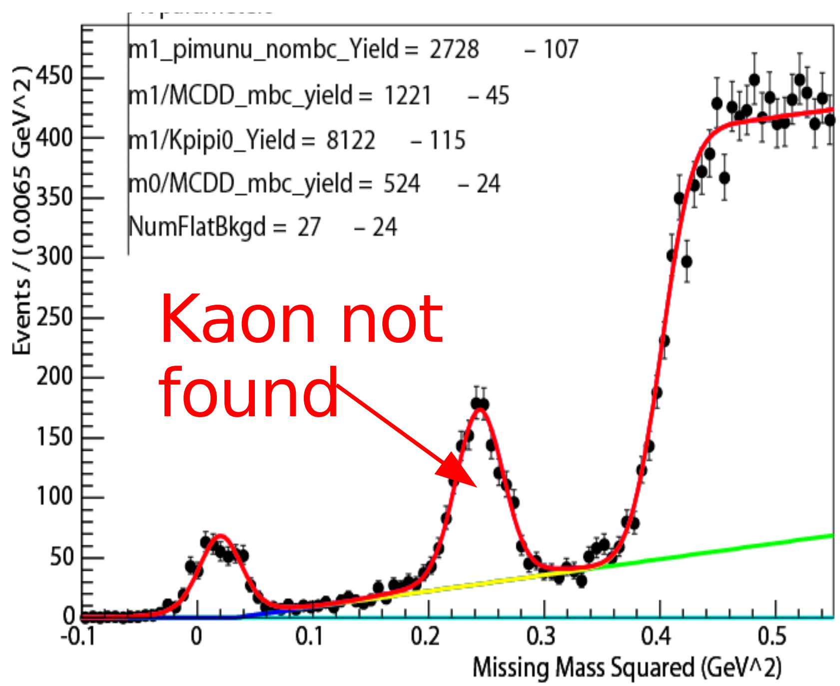
- Some systematics improve with more data.

Systematic	Old Value (56 pb^{-1})	New Value (281 pb^{-1})
Data processing	0.3%	0.0%
Background shape	0.5%	0.5%
Double DCSD interference	0.8%	0.8%
Tracking efficiency	0.7%	0.3%
K_S^0 efficiency	3.0%	1.1%
π^0 efficiency	2.0%	2.0%
Pion particle ID	0.3%	0.25%
Kaon particle ID	1.3%	0.3%
Trigger simulation	0.0-0.2%	0.0-0.2%
Final state radiation	0.5%	0.5%
ΔE cuts	1.0-2.5%	0.5-1.0%
Signal shape	0.6%	0.4-0.6%
Resonant substructure	0.4-1.5%	0.3-1.3%
Multiple candidates	0.0-1.3%	0.0-1.3%

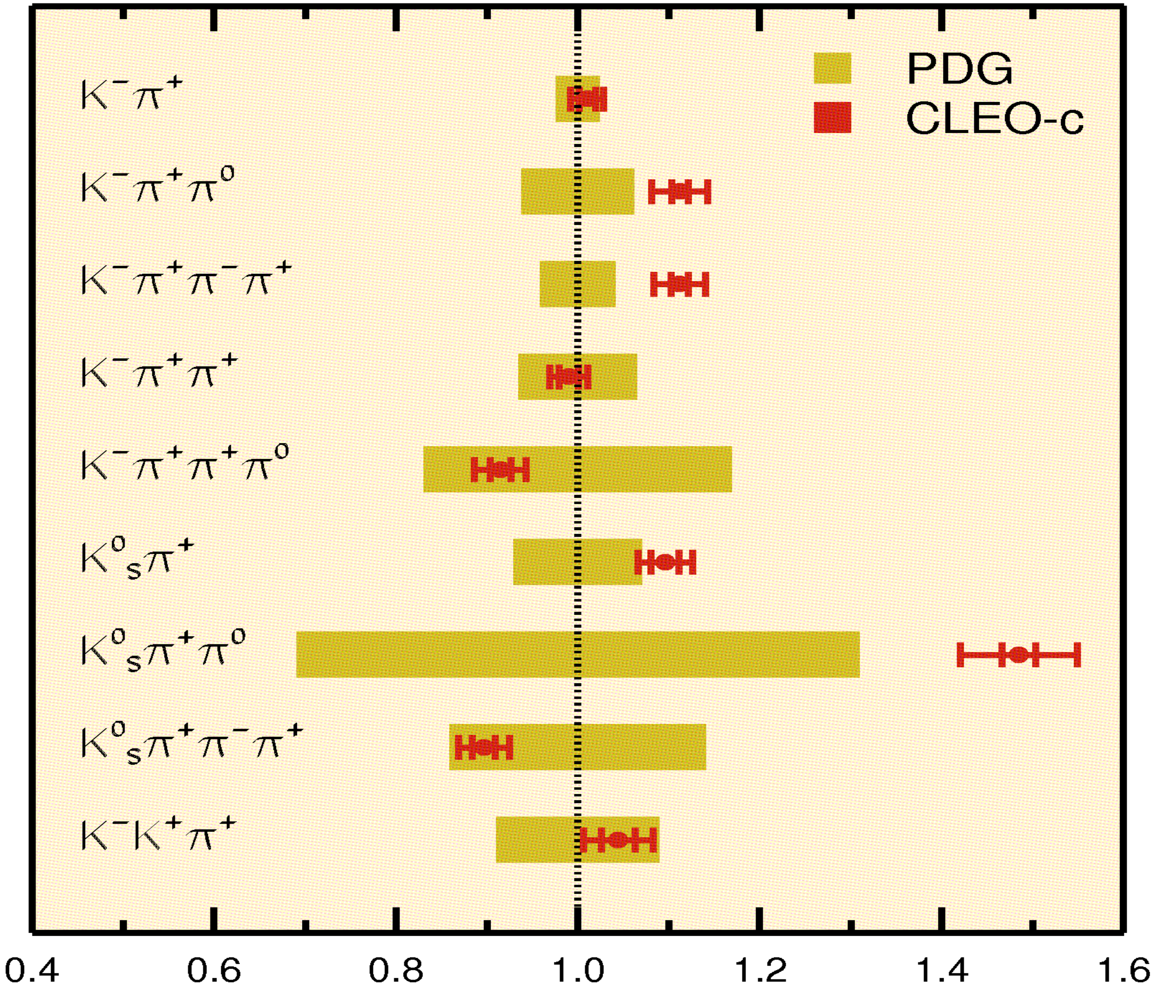
Tracking Efficiencies

- Events that can be fully reconstructed can be used for very clean studies of tracking efficiencies
- We have used $D\bar{D}$ events and $\psi(2S)\rightarrow J/\psi\,\pi^+\pi^-$ events
- Look at recoil mass against D^0-tag and pion – see how often kaon is found
  - In data we find $\varepsilon=(90.8\pm0.4)\%$





Preliminary Results for 281 pb^{-1}



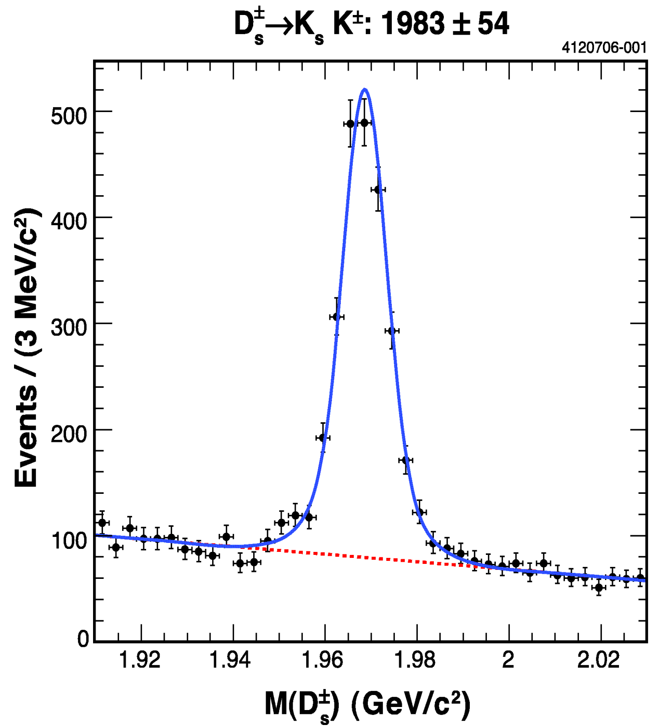
- Statistical error ~1%
- Systematics dominated
  - Will improve some errors
- Final results on 281 pb^{-1} later this year.

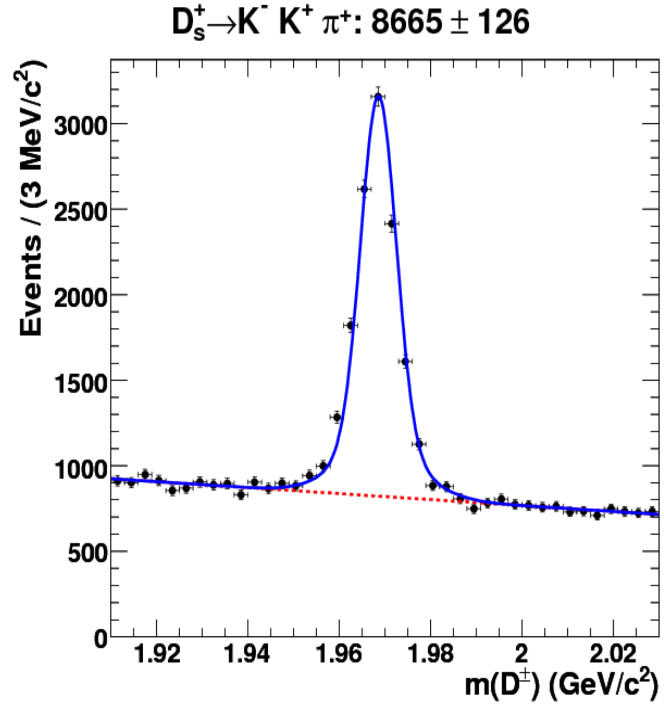
D_s Absolute Hadronic Branching Fractions

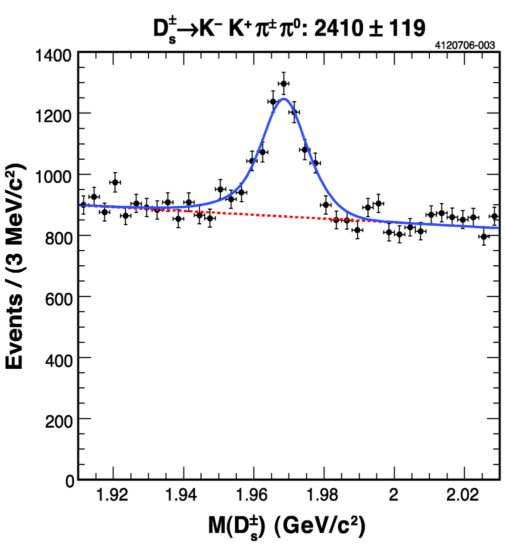
- Use same technique as for the D^0 and D^+ branching fractions
  - Pairs of D_s and D_s^*
- Use invariant mass after cut on m_{BC} for signal extraction
  - Signal will not peak in m_{BC} unless the D_s is direct
- We use 195 pb^{-1} of data recorded at (or near) E_{cm}=4170 MeV
- We study the final states:
  - $K_S K^+$
  - $K^+ K^- \pi^+$
  - $K^+ K^- \pi^+ \pi^0$
  - $\pi^+ \pi^- \pi^+$
  - $\eta \pi^+$
  - $\eta' \pi^+$

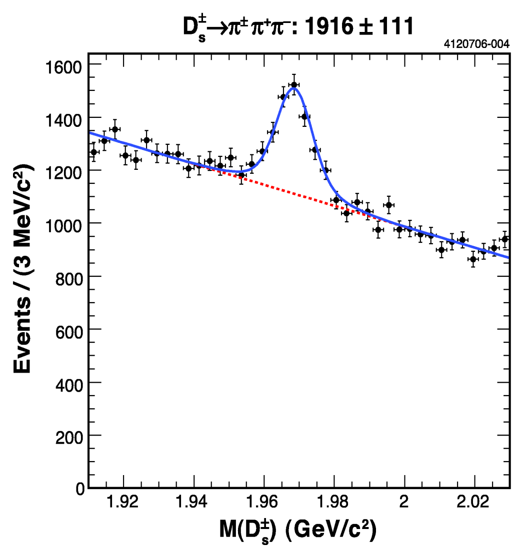
Single Tag Yields

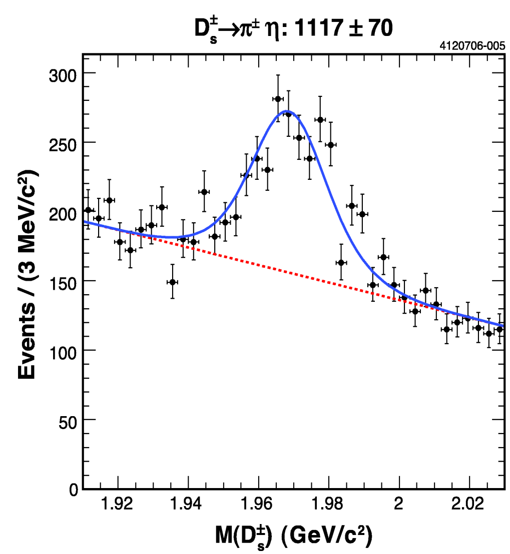
Mode	D_s+	D_s-
K_sK^+	1055±39	928±37
$K^+K^-\pi^+$	4316±89	4350±89
$K^+K^-\pi^+\pi$	1160±85	1251±84
$\pi^+\pi^-\pi^+$	970±80	947±78
$\eta\pi^+$	547±50	570±50
$\eta'\pi^+$	362±23	372±24

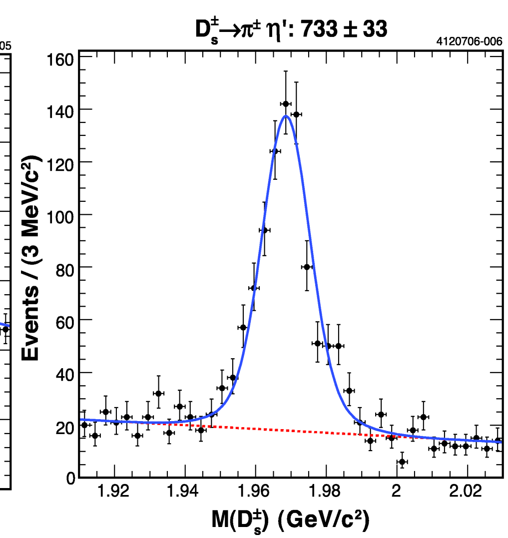




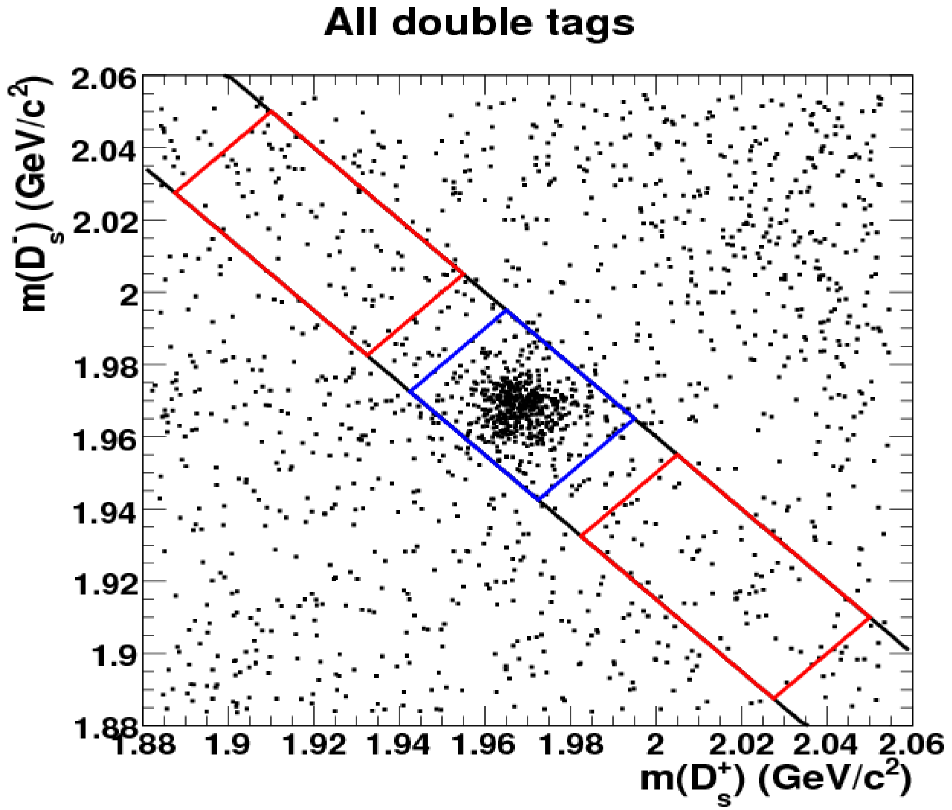


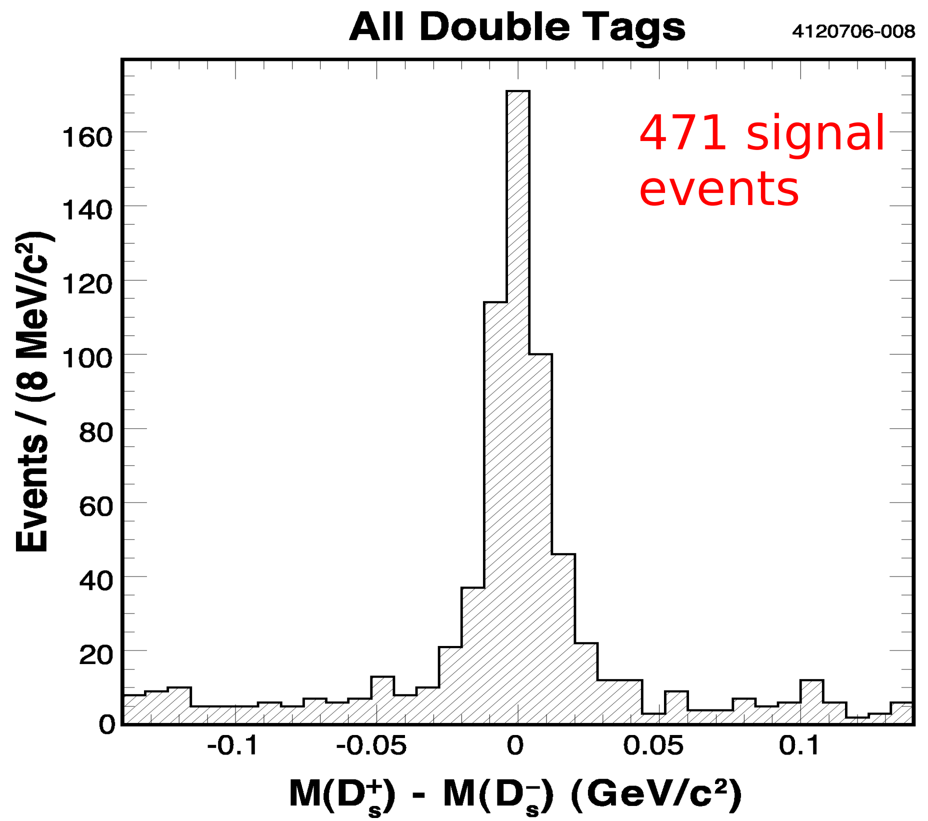






Double Tag Yields

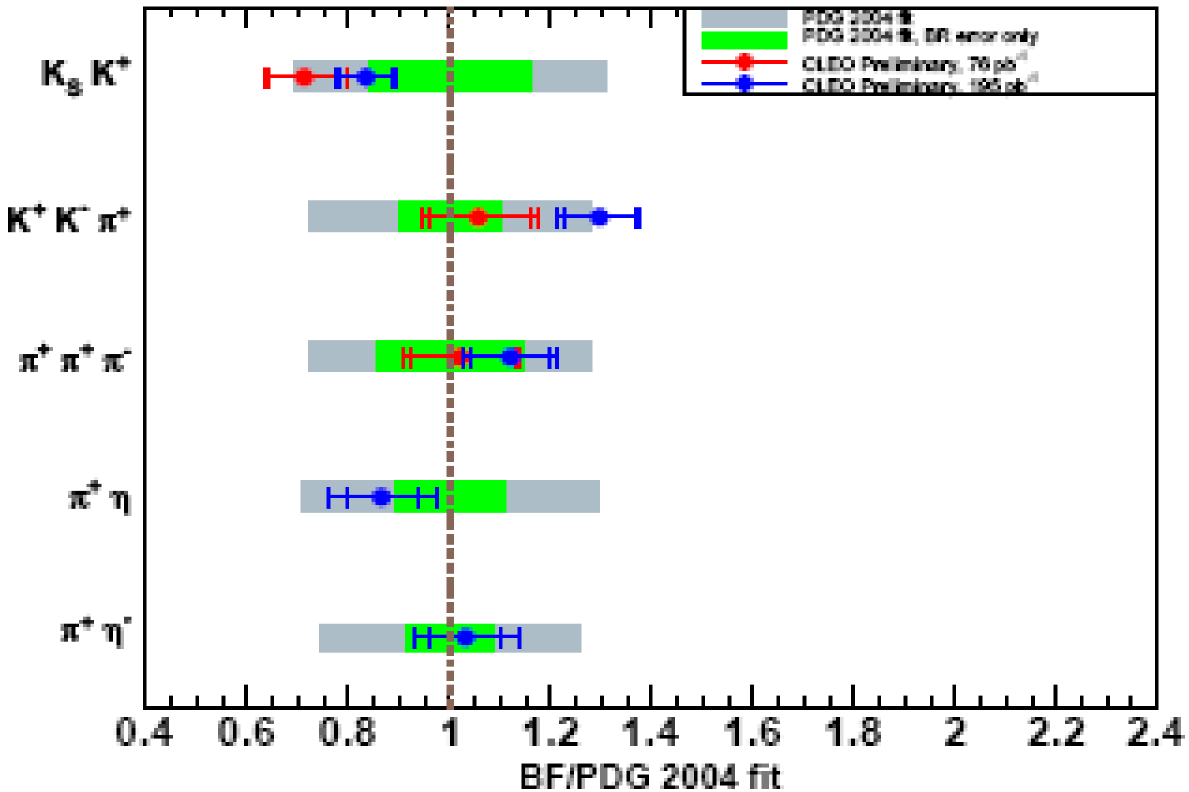




Yields from cut-and-count in blue signal region

	$K_S K^-$	$K^+K^-\pi^-$	$K^+K^-\pi^-\pi^0$	$\pi^-\pi^-\pi^+$	$\pi^-\eta$	$\pi^-\eta'$
$K_S K^+$	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



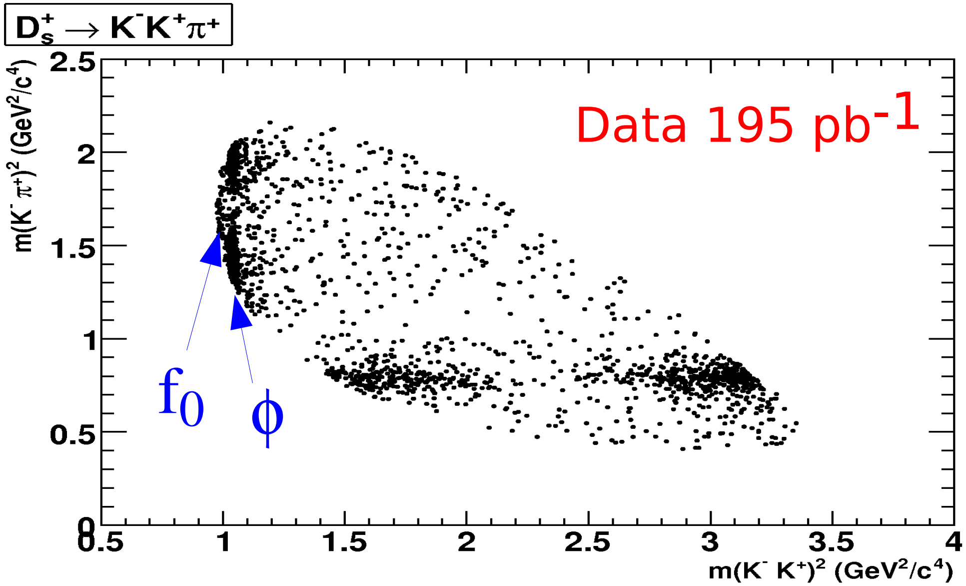
Mode	195 pb^{-1} (%)	PDG 2004 fit (%)
$\mathcal{B}(K_S K^+)$	$1.50 \pm 0.09 \pm 0.05$	1.8 ± 0.55
$\mathcal{B}(K^- K^+ \pi^+)$	$5.57 \pm 0.30 \pm 0.19$	4.3 ± 1.2
$\mathcal{B}(K^- K^+ \pi^+ \pi^0)$	$5.62 \pm 0.33 \pm 0.51$	—
$\mathcal{B}(\pi^+ \pi^+ \pi^-)$	$1.12 \pm 0.08 \pm 0.05$	1.00 ± 0.28
$\mathcal{B}(\pi^+ \eta)$	$1.47 \pm 0.12 \pm 0.14$	1.7 ± 0.5
$\mathcal{B}(\pi^+ \eta')$	$4.02 \pm 0.27 \pm 0.30$	3.9 ± 1.0

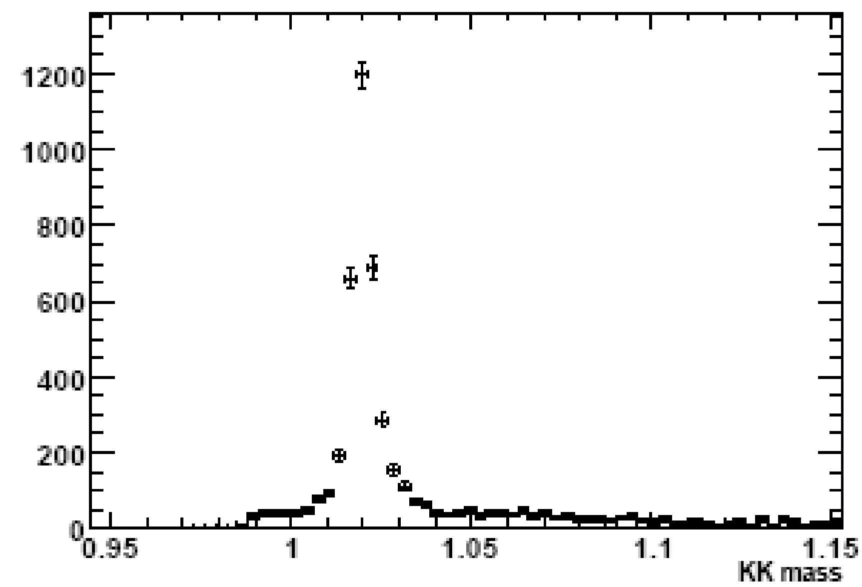
What about $D_s \to \phi\pi$?

- $D_s \to \phi\pi$ interferes with $D_s \to f_0\pi$
  - $B(D_s \to \phi\pi)$ is not well defined and we are not quoting it now
- We can calculate a "partial br. fr." in a m_{KK} window around the ϕ mass

$D_s \to K^+K^-\pi^+$ partial BF:
CLEO-c ($\pm$10 MeV around ϕ)
1.98 $\pm$ 0.12 $\pm$ 0.09
(~ *x*2 + O(10%)) (Preliminary !!)

For reference: $D_s \to \phi\pi^+$
PDG06: 4.4 $\pm$ 0.6
BaBar: 4.8 $\pm$ 0.5 $\pm$ 0.4
(1.008 < M(K+ K-) < 1.035 GeV)



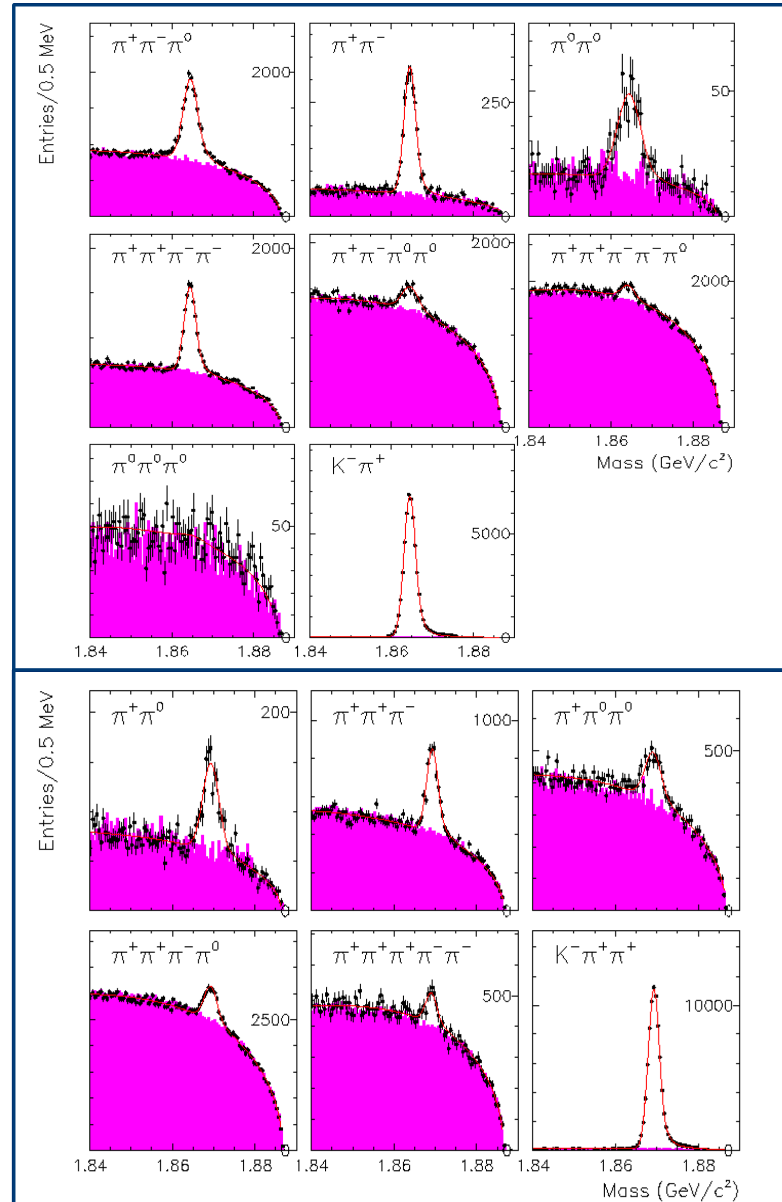


$D \to n(\pi^\pm)m(\pi^0)$ (PRL 96, 081802 2006)

- This analysis doesn't use *D*-tags.
- Measure relative to normalization mode ($D^0 \to K^- \pi^+$ or $D^+ \to K^- \pi^+ \pi^+$)

Mode	*B* ($\times 10^{-3}$)	PDG ($\times 10^{-3}$)
$\pi^+\pi^-$	$1.40 \pm 0.04 \pm 0.03$	1.38 ± 0.05
$\pi^0\pi^0$	$0.78 \pm 0.05 \pm 0.04$	0.84 ± 0.22
$\pi^+\pi^-\pi^0$	$13.3 \pm 0.2 \pm 0.5$	11 ± 4
$\pi^0\pi^0\pi^0$	< 0.30	---
$\pi^+\pi^+\pi^-\pi^-$	$7.42 \pm 0.14 \pm 0.27$	7.3 ± 0.5
$\pi^+\pi^-\pi^0\pi^0$	$10.2 \pm 0.6 \pm 0.7$	---
$\pi^+\pi^+\pi^-\pi^-\pi^0$	$4.31 \pm 0.44 \pm 0.18$	---
$\pi^+\pi^0$	$1.23 \pm 0.06 \pm 0.06$	1.33 ± 0.22
$\pi^+\pi^+\pi^-$	$3.36 \pm 0.10 \pm 0.16$	3.1 ± 0.4
$\pi^+\pi^0\pi^0$	$4.80 \pm 0.27 \pm 0.34$	---
$\pi^+\pi^+\pi^-\pi^0$	$11.7 \pm 0.4 \pm 0.7$	---
$\pi^+\pi^+\pi^+\pi^-\pi^-$	$1.67 \pm 0.18 \pm 0.17$	1.82 ± 0.25
$\eta\pi^+$	$3.56 \pm 0.24 \pm 0.21$	3.0 ± 0.6
$\eta\pi^0$	$0.61 \pm 0.14 \pm 0.05$	---
$\omega\pi^+\pi^-$	$1.66 \pm 0.47 \pm 0.10$	---

281 pb^{-1}



Inclusive η, η', and ϕ Production in D and D_s Decays

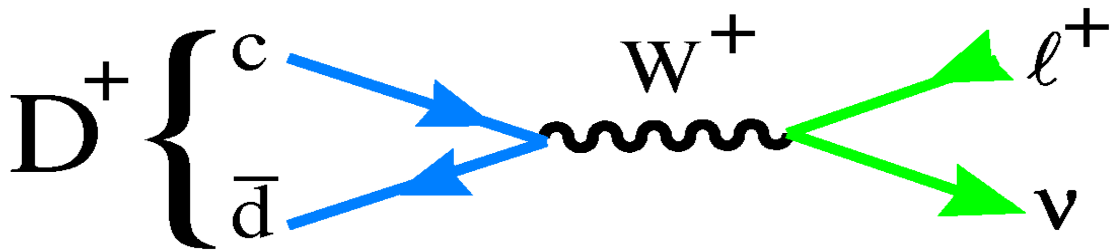
- Tag one D or D_s and look at the recoil
  - 281 pb^{-1} for D^0 and D^+
  - 71 pb^{-1} for D_s
- We see that the production of η, η', and ϕ is larger in D_s decays than in D decays.
- Important branching fractions for studying B_s decays.

B	η (%)	PDG
D^0	9.4 ± 0.4 ± 0.6	<13%
D^+	5.7 ± 0.5 ± 0.5	<13%
D_s^+	23.7 ± 3.1 ± 1.9	-

B	η' (%)	PDG
D^0	2.6 ± 0.2 ± 0.2	-
D^+	1.0 ± 0.2 ± 0.1	-
D_s^+	8.7 ± 1.9 ± 0.6	-

B	ϕ (%)	PDG
D^0	1.0 ± 0.1 ± 0.1	1.7 ± 0.8
D^+	1.1 ± 0.1 ± 0.2	<1.8
D_s^+	16.1 ± 1.2 ±0.6	18^{+15}_{-10}

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

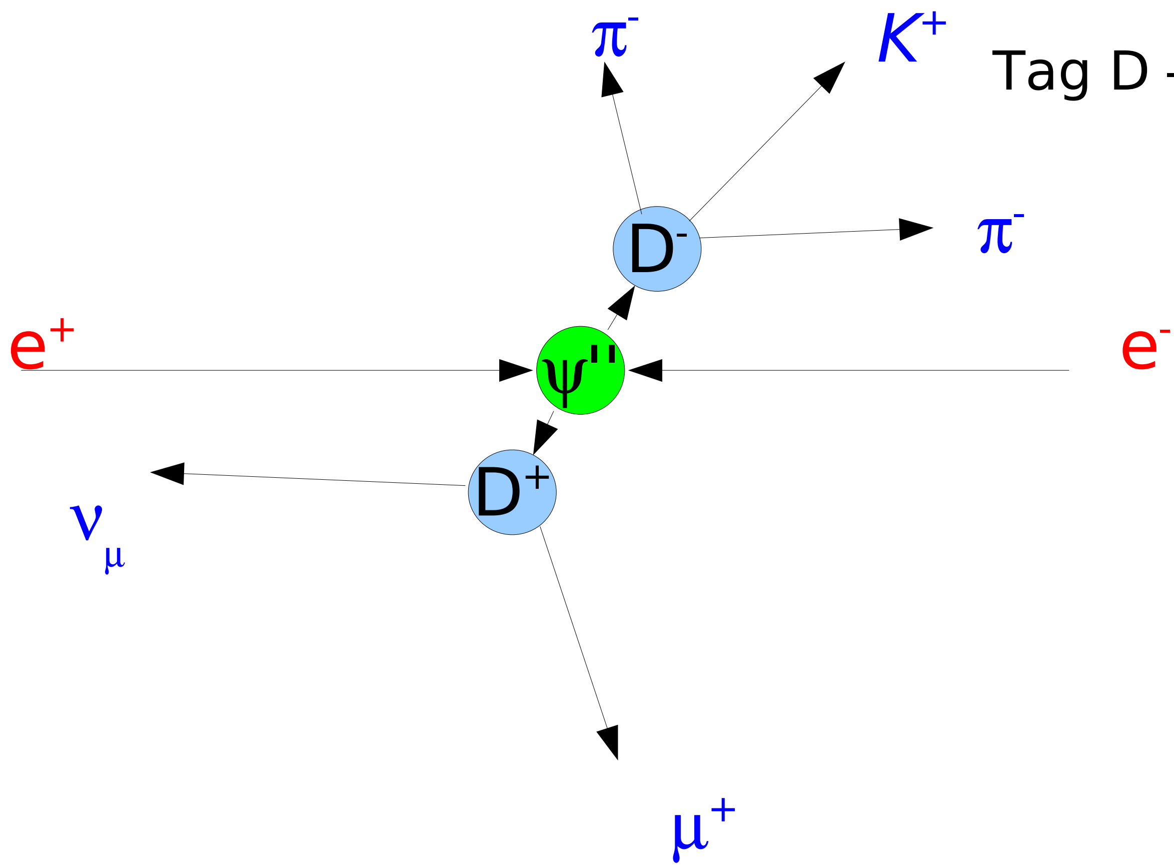


$$\Gamma(D^+ \to l^+ \nu) = \frac{G_F^2}{8\pi} f_{D^+}^2 m_l^2 M_{D^+} \left(1 - \frac{m_l^2}{M_{D^+}^2}\right)^2 |V_{cd}|^2$$

- Rate of e:μ:τ is ~10^{-4}:1:2.65
- A precise measurement of f_D allows precise comparison with theoretical calculations, such as lattice QCD.
- This will help determining f_B .

Analysis Technique

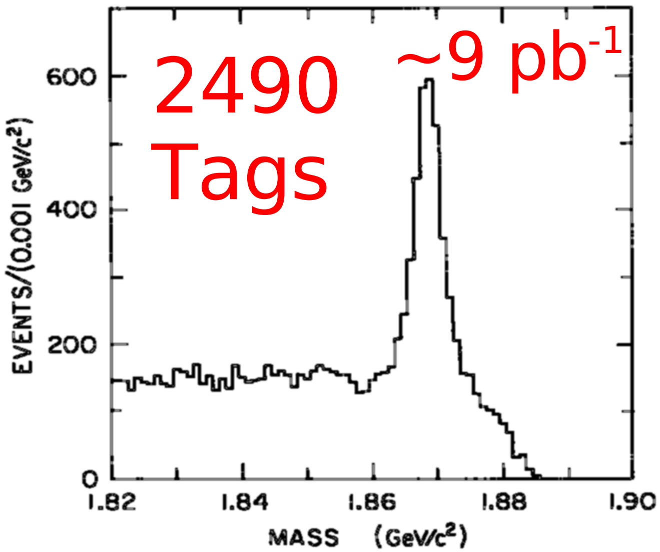
Tag D – fully reconstructed

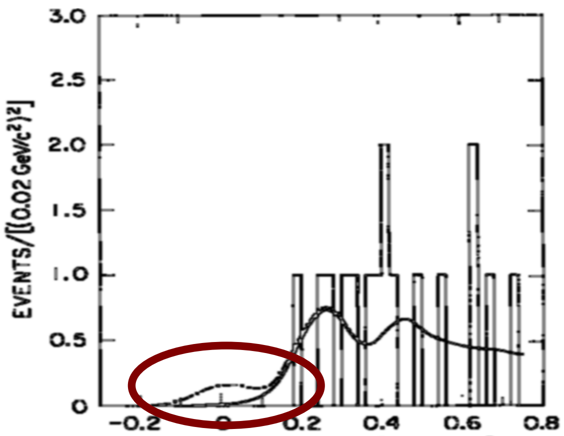


- At threshold produce only D^+D^-, no additional pions.
- Detect muon and make sure it recoiled against neutrino.
  - Extract signal in M^2_{miss} which peaks at 0.

MARK III and BES Results

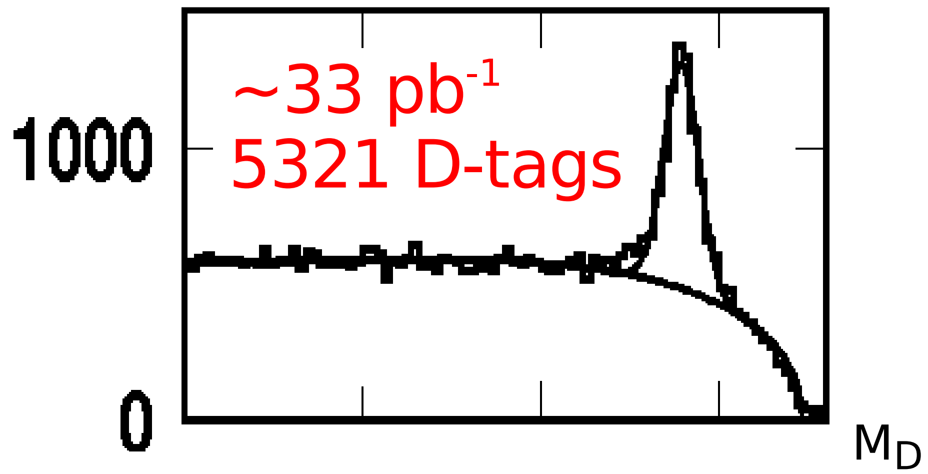
MARK III PRD 60, 1375

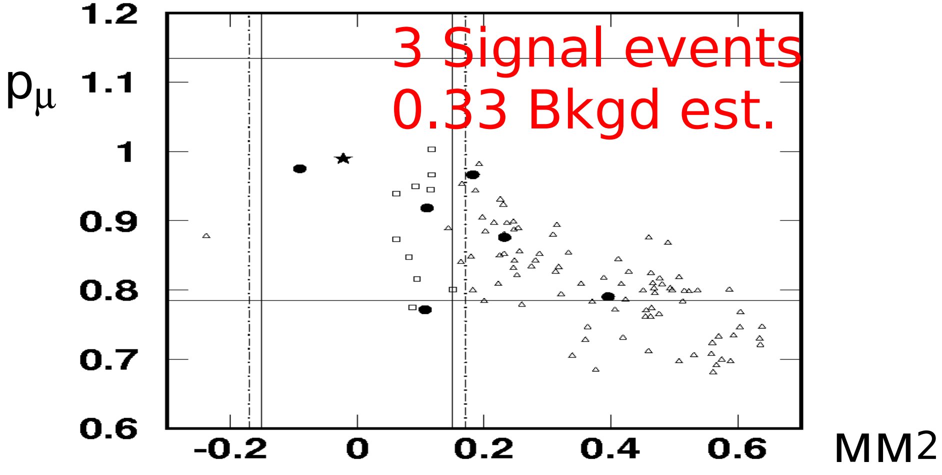




$$\mathcal{B}(D^+ \to \mu^+\nu_\mu) < 7.2 \times 10^{-4}$$
$$f_{D^+} < 290 \text{ MeV}$$

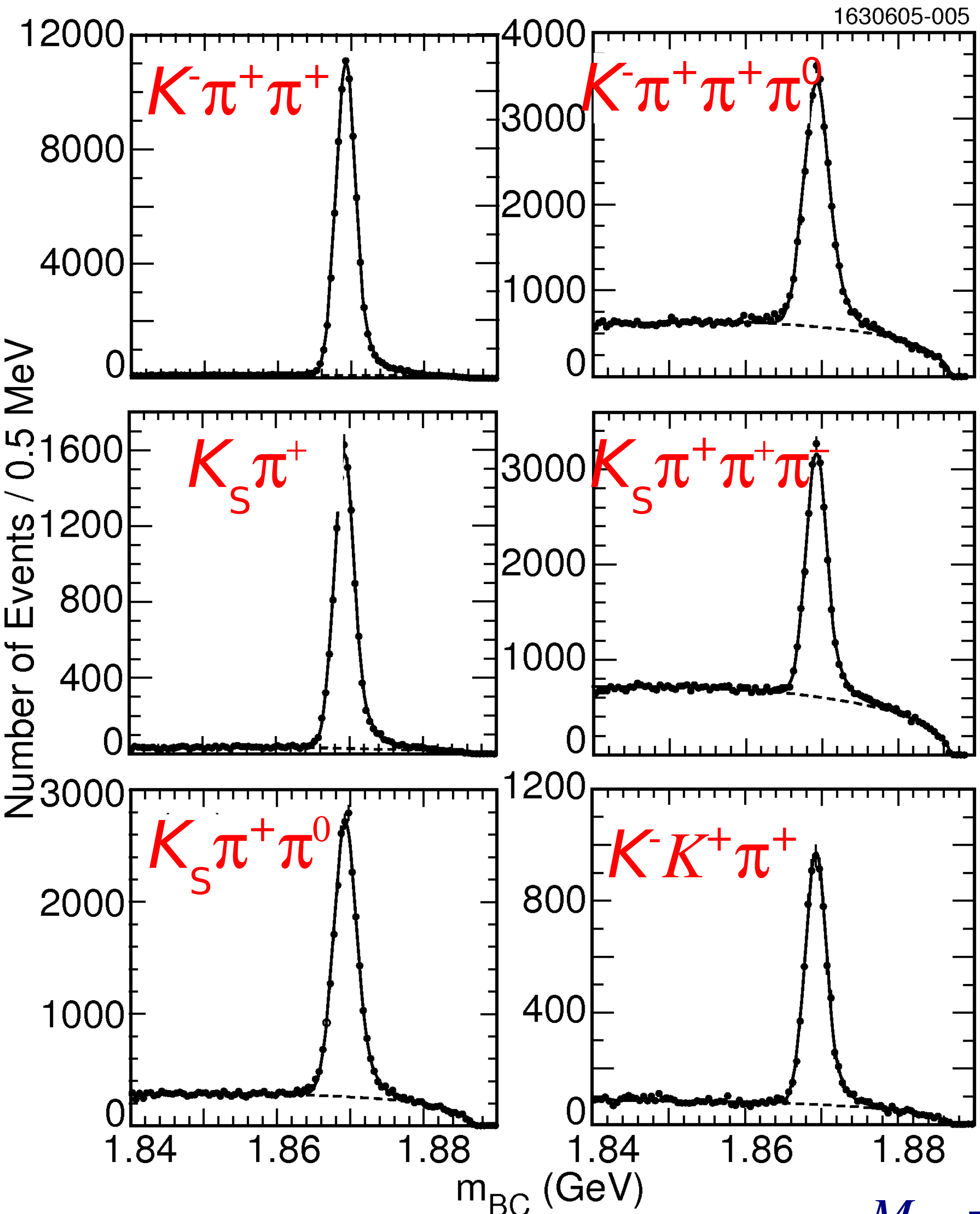
BES II PLB 610 (2005), 183





$$\mathcal{B}(D^+ \to \mu^+\nu_\mu) = (12.2^{+11.1}_{-5.3} \pm 0.10) \times 10^{-4}$$
$$f_{D^+} = (371^{+129}_{-119} \pm 25) \text{ MeV}$$

CLEO-c *D*-tag Reconstruction



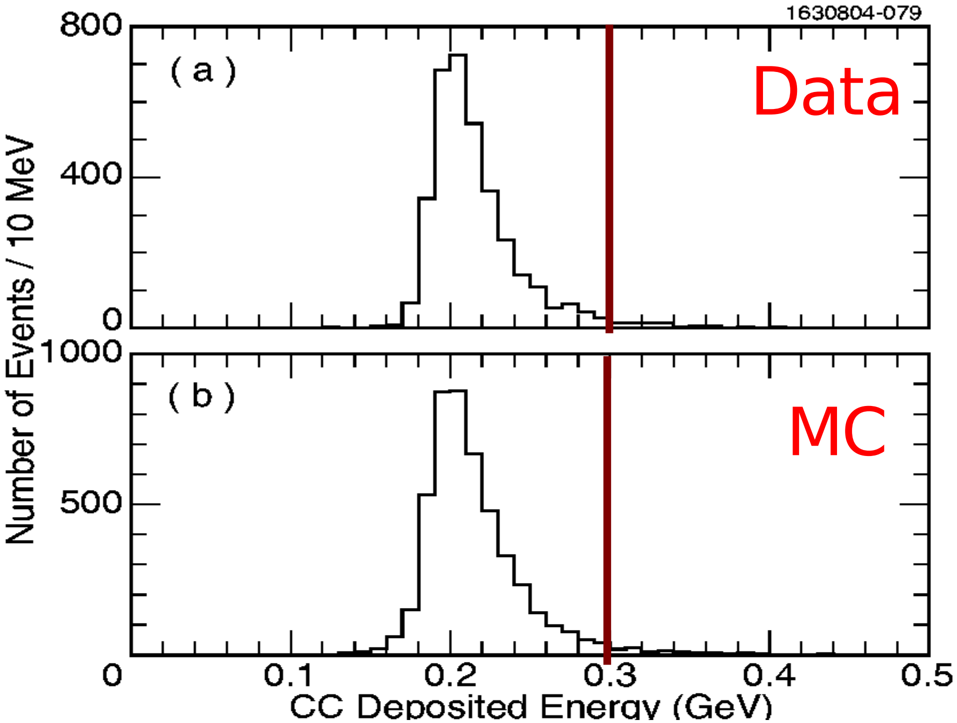
- 281 pb^{-1}
- Six tag modes used
- ~160,000 reconstructed $D^{\pm}$

Mode	Signal	Background
$K^+\pi^-\pi^-$	77387 ± 281	1868
$K^+\pi^-\pi^-\pi^0$	24850 ± 214	12825
$K_S\pi^-$	11162 ± 136	514
$K_S\pi^-\pi^-\pi^+$	18176 ± 255	8976
$K_S\pi^-\pi^0$	20244 ± 170	5223
$K^+K^-\pi^-$	6535 ± 95	1271
Sum	158354 ± 496	30677

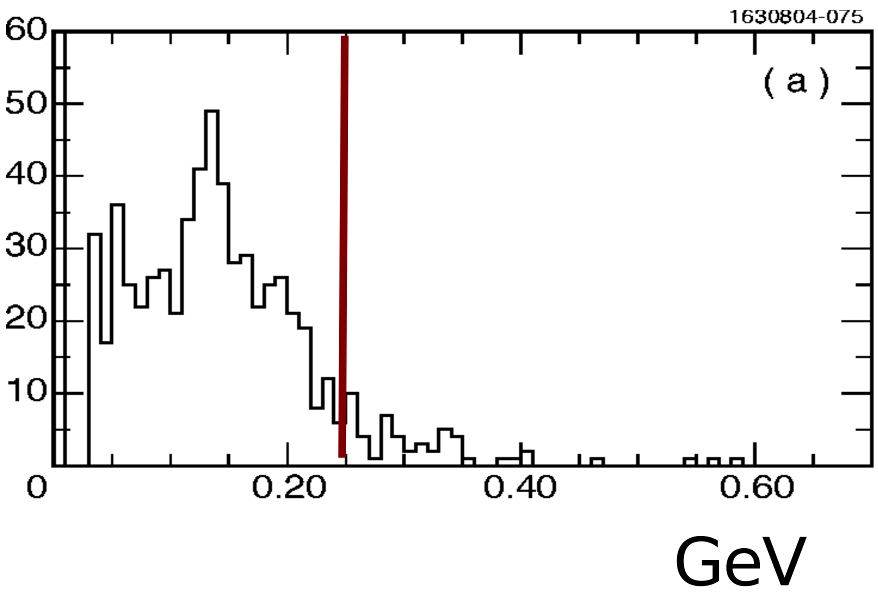
$$M_{BC} = \sqrt{E_{\text{beam}}^2 - |p(D)|^2}$$

Signal Side Selection

- Require one track consistent with coming from the IP for the muon.
  - Muon candidate deposit less than 300 MeV in EM calorimeter
- No additional track from IP
- Veto background from $D^+ \to \pi^+ \pi^0$
  - Require no unmatched showers over 250 MeV



Highest energy unmatched cluster



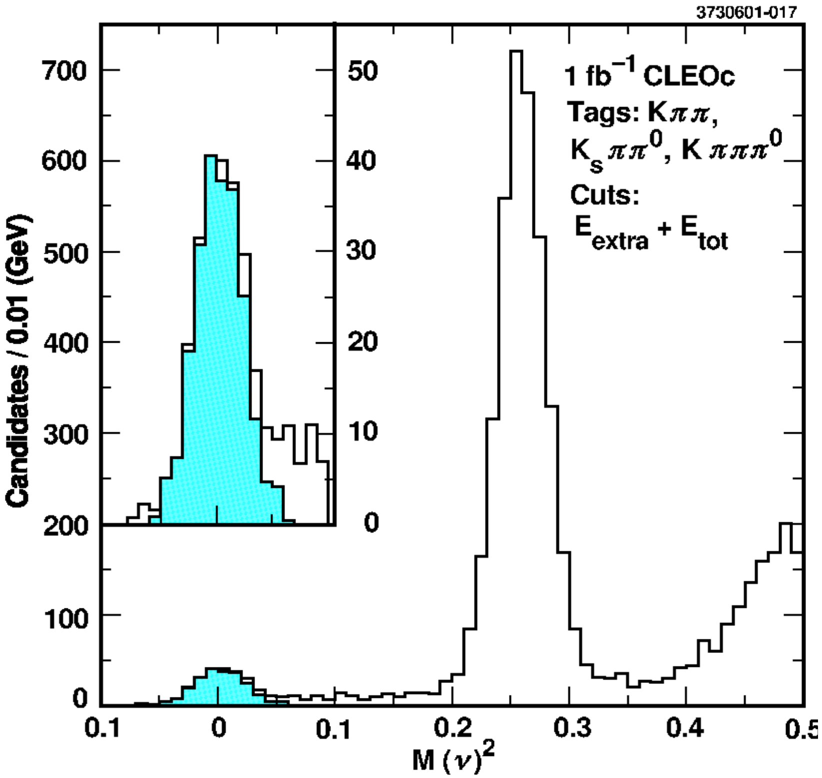
Signal Extraction

- For events with μ candidate form

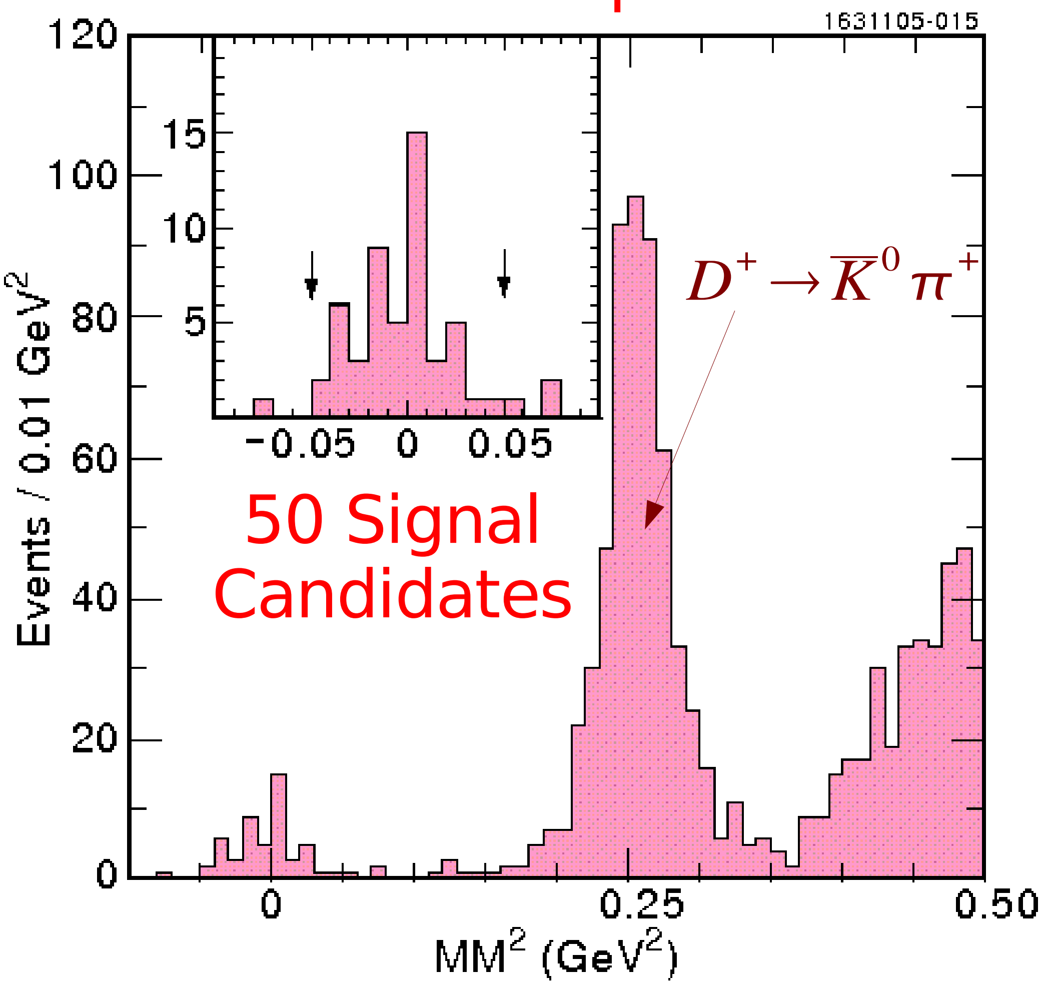
$$MM^2 = (E_{beam} - E_{\mu})^2 - (-\vec{p}_{D^-} - \vec{p}_{\mu})^2$$

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

"Yellow book" MC Study



Data 281 pb^{-1}



$D^+ \rightarrow \mu^+ \nu_\mu$ 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:

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

PRL 95, 251801 (2005)

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

Search for $D \to \tau \nu_\tau$

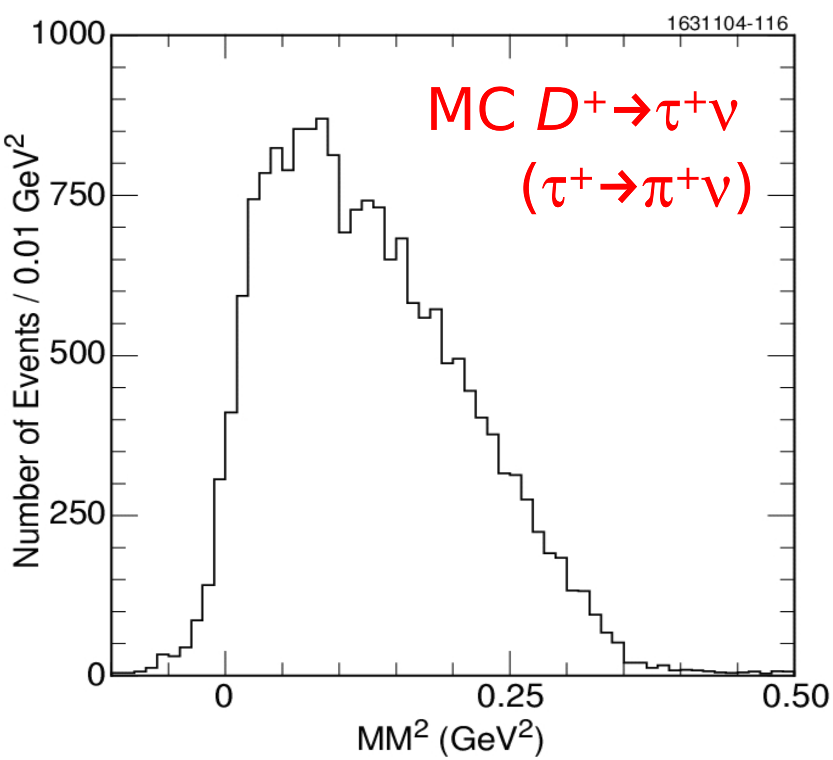
281pb^{-1} hep-ex/0604043

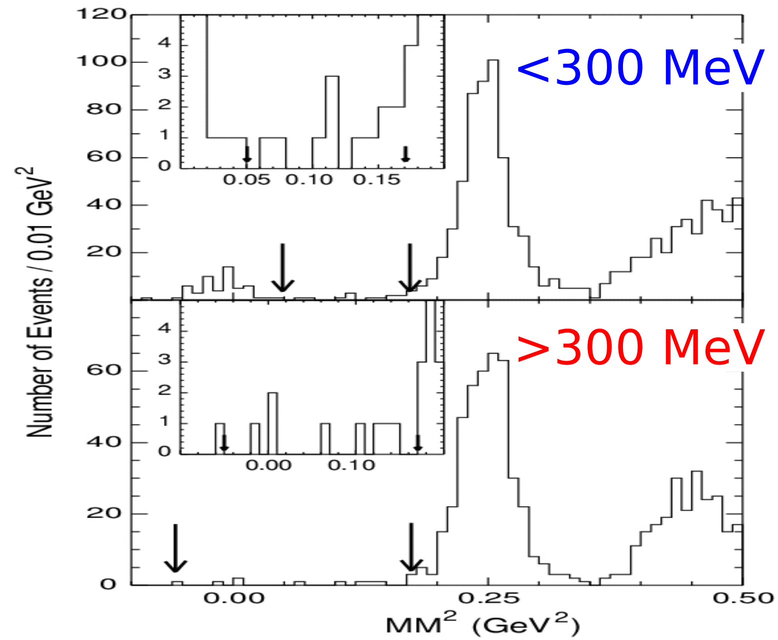
(accepted by PRD)

Look for $D^+ \to \tau^+ \nu$ ($\tau^+ \to \pi^+ \nu$) in events with tags selected as for $D^+ \to \mu^+ \nu$.

Sample subdivided based on energy deposit of candidate track: (a) <300 MeV and (b) >300 MeV.

MM^2 small due to m_τ close to m_D





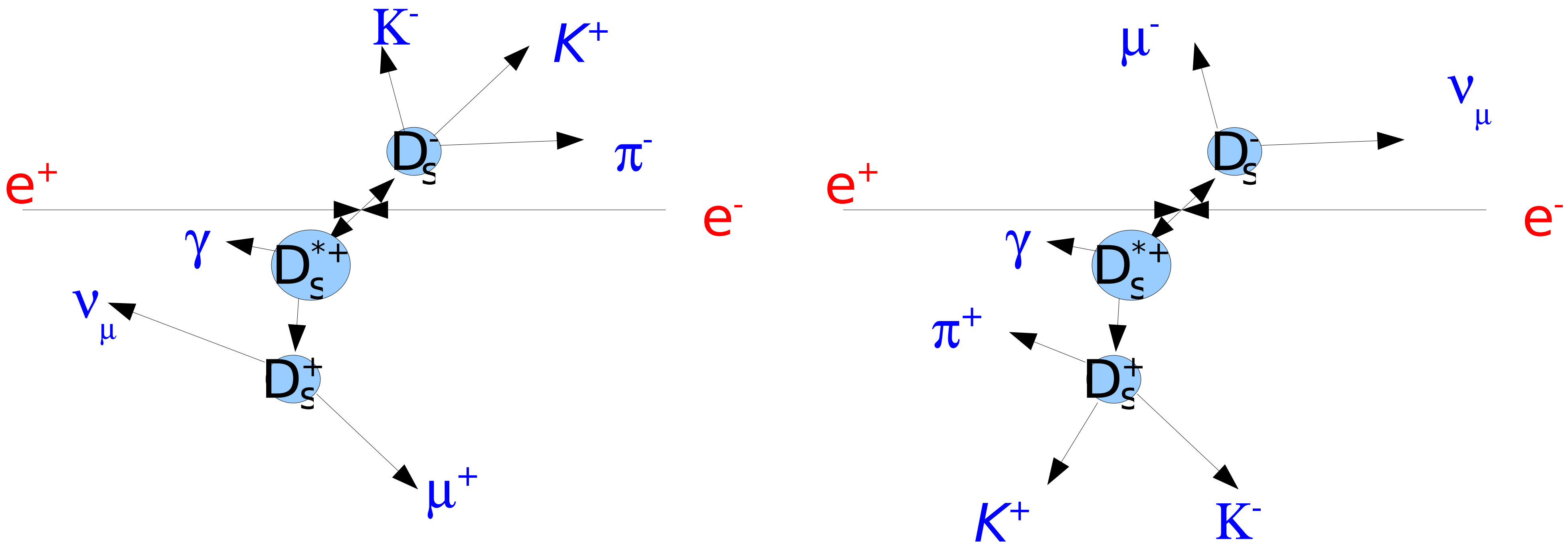
	(a)	(b)
Signal Region	12	8
Estimated BG	6.1±0.6±0.3	5.0±0.6±0.2
Net	5.9±3.5±0.3	3.0±2.9±0.2

$$BF(D^+ \to \tau^+ \nu) < 2.1 \times 10^{-3} \text{ (90\% CL)}$$

$$SM: BF(D^+ \to \tau^+ \nu) = (1.1 \pm 0.2) \times 10^{-3}$$

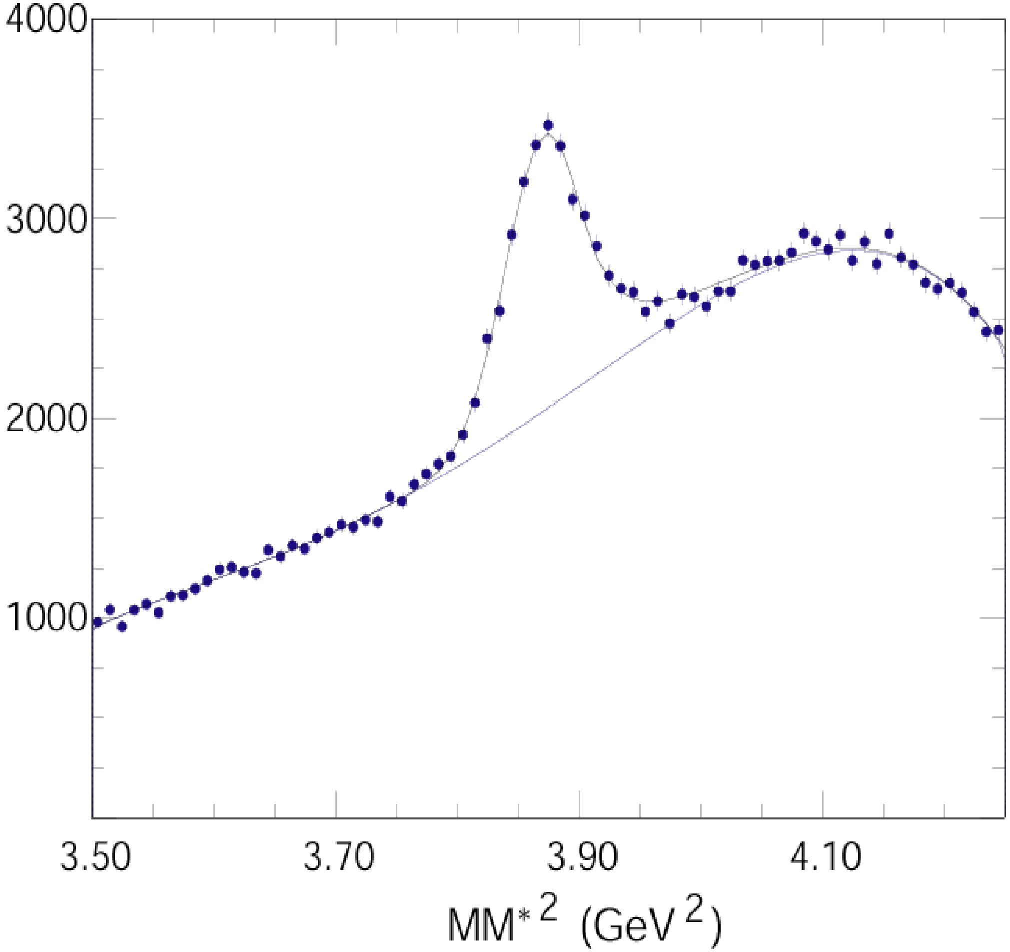
$D_s \to \mu\nu_\mu$

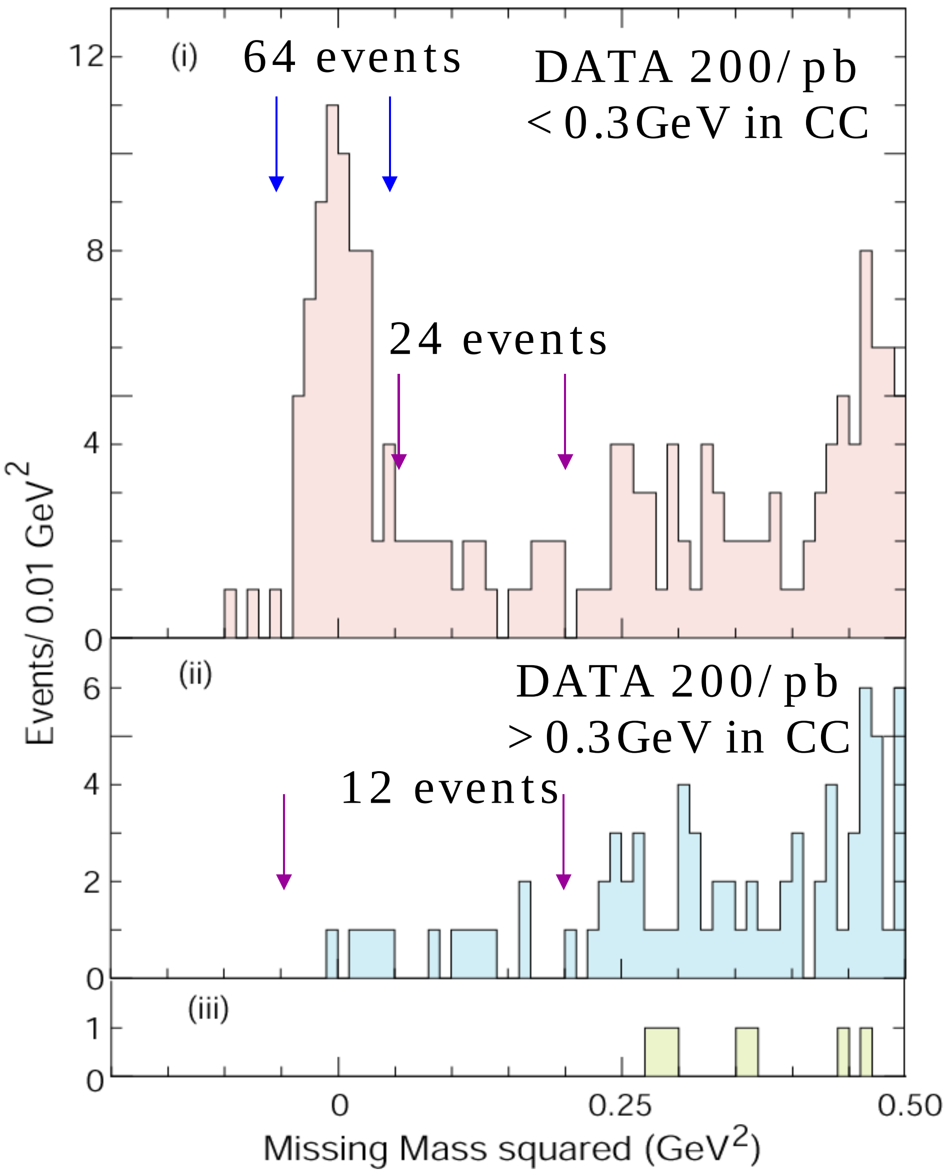
- CLEO-c has used ~200 pb^{-1} to study $D_s \to \mu\nu_\mu$
- Signal D_s can come directly or from D_s^*



- Form χ^2 with both hypothesis for where the photon comes from. Keep best.
- Look for signal in missing mass.

Tag Yields and Signal





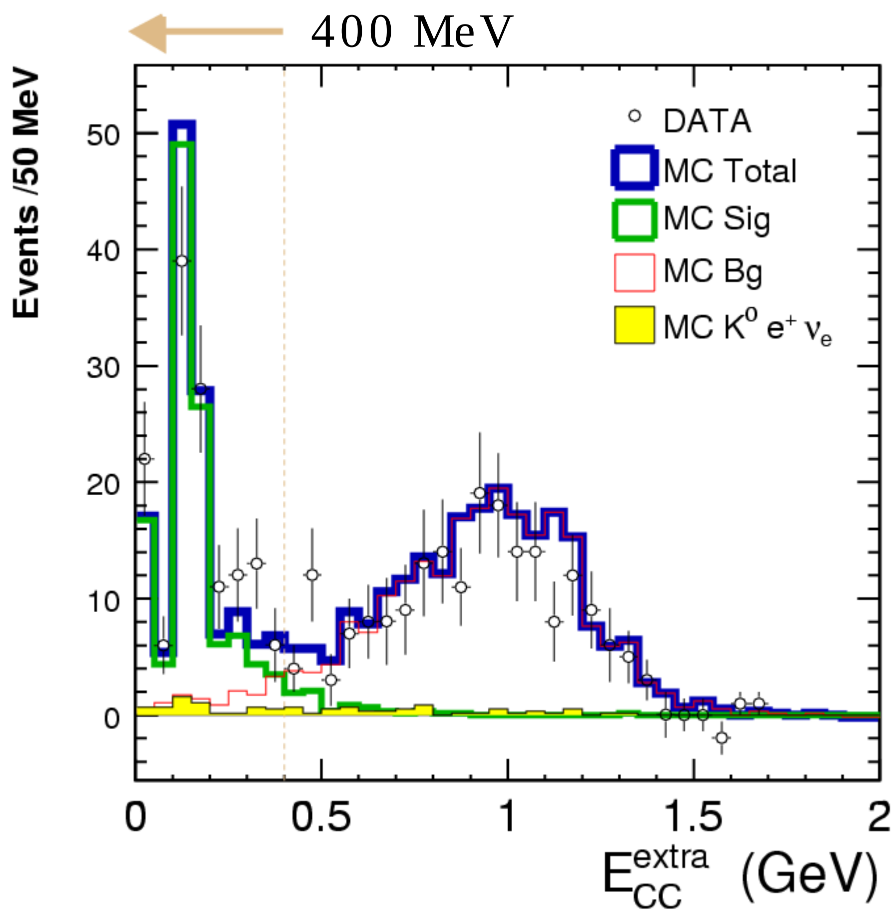
- Total of 11880±399±504 tags, after the selection on MM*^{2}.

$D_s \to \mu\nu_\mu$ and $D_s \to \tau\nu_\tau$

- $D_s^+ \to \mu^+\nu$
  - 64 signal events, 2 background, use SM to calculate $\tau\nu$ yield near 0 MM^2 based on known $\tau\nu/\mu\nu$ ratio
  - $B(D_s^+ \to \mu^+\nu) = (0.657 \pm 0.090 \pm 0.028)\%$
- $D_s^+ \to \tau^+\nu$, $\tau^+ \to \pi^+\nu$
  - Sum case (i) 0.2 > MM^2 > 0.05 GeV^2 & case (ii) MM^2 < 0.2 GeV^2. Total of 36 signal and 4.8 bkgrnd
  - $B(D_s^+ \to \tau^+\nu) = (7.1 \pm 1.4 \pm 0.03)\%$
- By summing both cases above, find
  - $f_{Ds} = 282 \pm 16 \pm 7$ MeV
  - $B^{eff}(D_s^+ \to \mu^+\nu) = (0.664 \pm 0.076 \pm 0.028)\%$
- $B(D_s^+ \to e^+\nu) < 3.1 \times 10^{-4}$

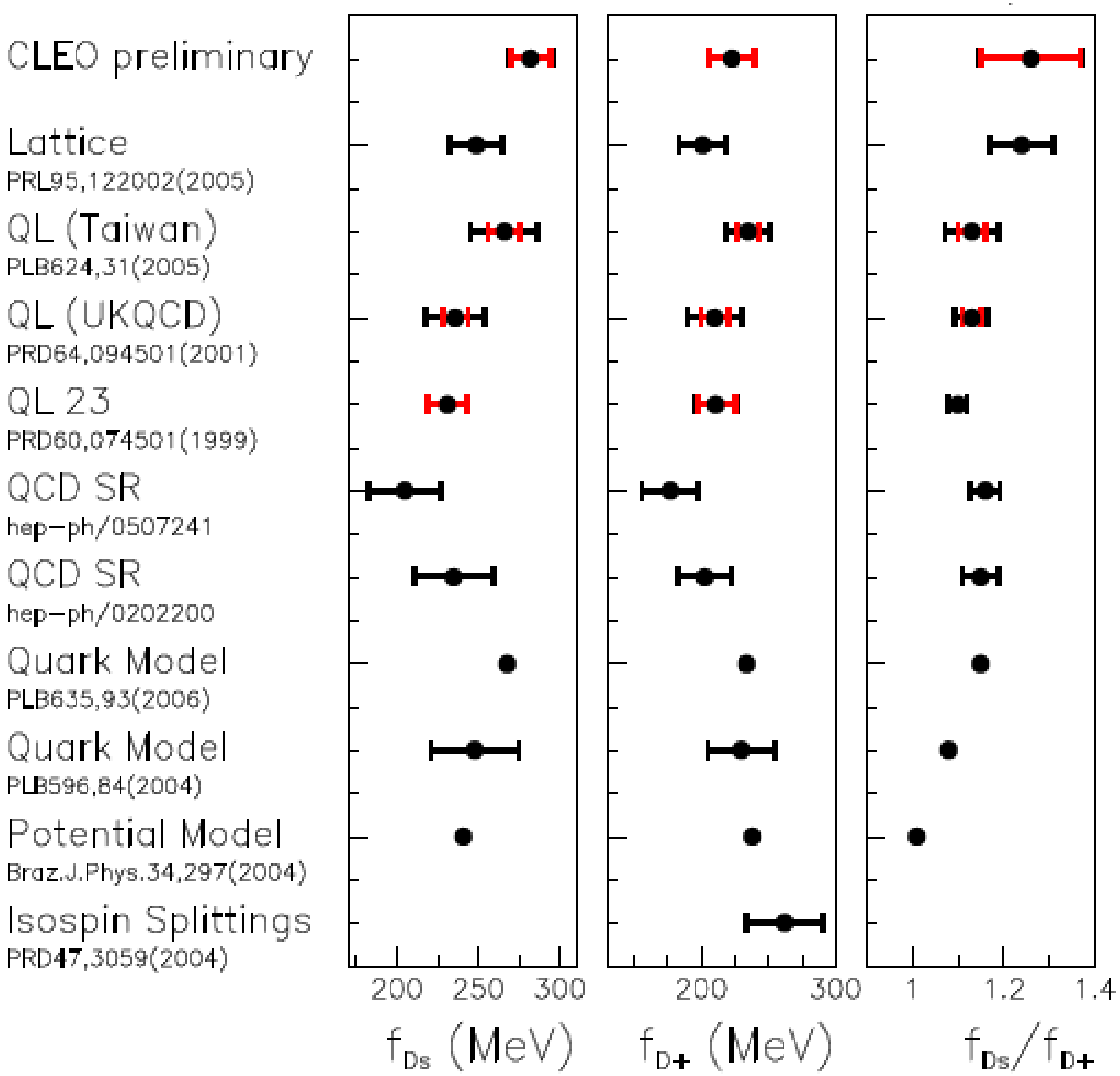
$D_s \to \tau\nu_\tau$, $\tau \to e\nu\nu$

- An alternative is to look for $D_s \to \tau\nu_\tau$, $\tau \to e\nu\nu$
- $B(D_s \to \tau\nu_\tau) \times B(\tau \to \varepsilon\nu\nu) \approx 1\%$
  - Relatively large compared to $B(D_s \to Xe\nu) \approx 8\%$
- Reconstruct tag D_s and e
- Veto extra tracks
- Look for signal with little extra energy in EM-calorimeter
- Do not need to find γ
- $B(D_s^+ \to \tau^+\nu) = (6.29 \pm 0.78 \pm 0.52)\%$
- $f_{D_s} = 278 \pm 17 \pm 12$ MeV



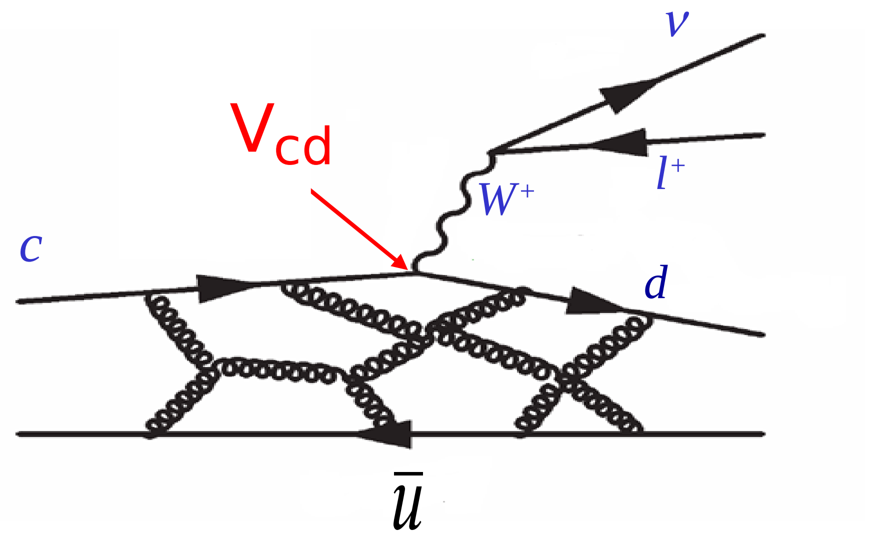
Comparison to Theory

- CLEO results consistent with most (recent) predictions.
- For precision comparisons we need more data.
- Using Lattice results for decay constants we get $|V_{cd}/V_{cs}| = 0.22 \pm 0.03$.



Semileptonic Decays

- Semileptonic decays are easier to describe theoretically than hadronic decays
  - The non-perturbative strong physics is parameterized in form factors.
  - For m_l=0 we have
    - one form factor for $D \to (K,\pi) e\nu$
    - three form factors for $D \to K^* e\nu$

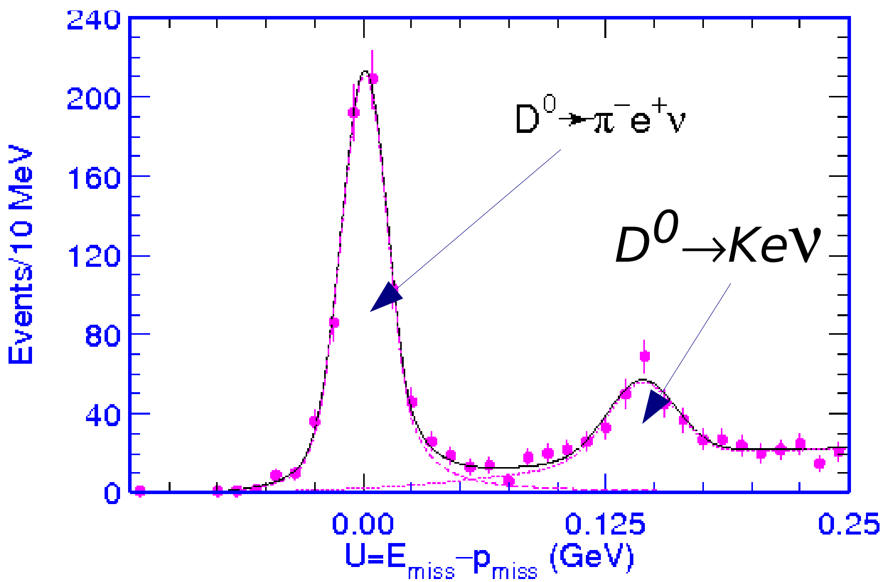


- CLEO-c measures
  - Inclusive and exclusive branching fractions
  - CKM matrix elements (V_{cd} and V_{cs})
  - Form factors
- The clean environment and excellent detector will allow the first precise studies of Cabibbo suppressed semileptonic *D* decays
- We only use electrons; muons are too soft to be cleanly identified.

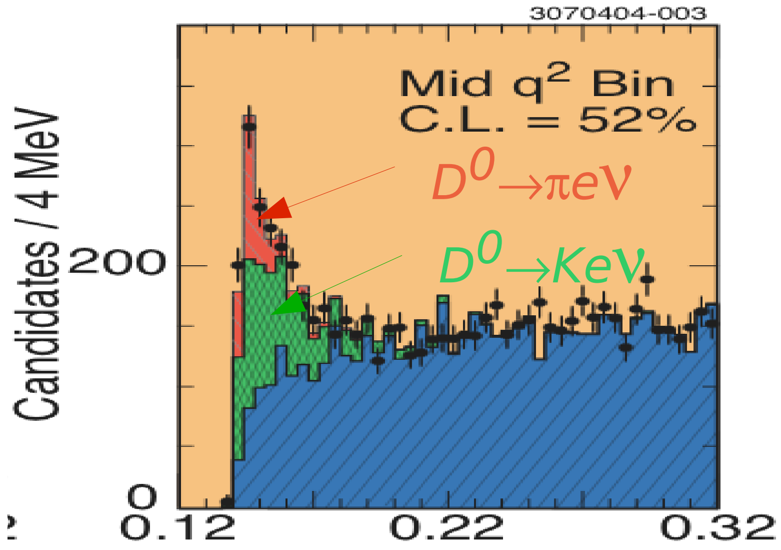
Exclusive Branching Fractions

- The exclusive decays are studied by finding an electron and reconstructing the hadronic system recoiling against a *D*-tag.
- The signal is extracted by studying the variable $U=E_{miss}-|P_{miss}|$
- For the signal events, with one missing neutrino *U* peaks at zero
- $D\to K e\nu$ and $D\to \pi e\nu$ are kinematically separated

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

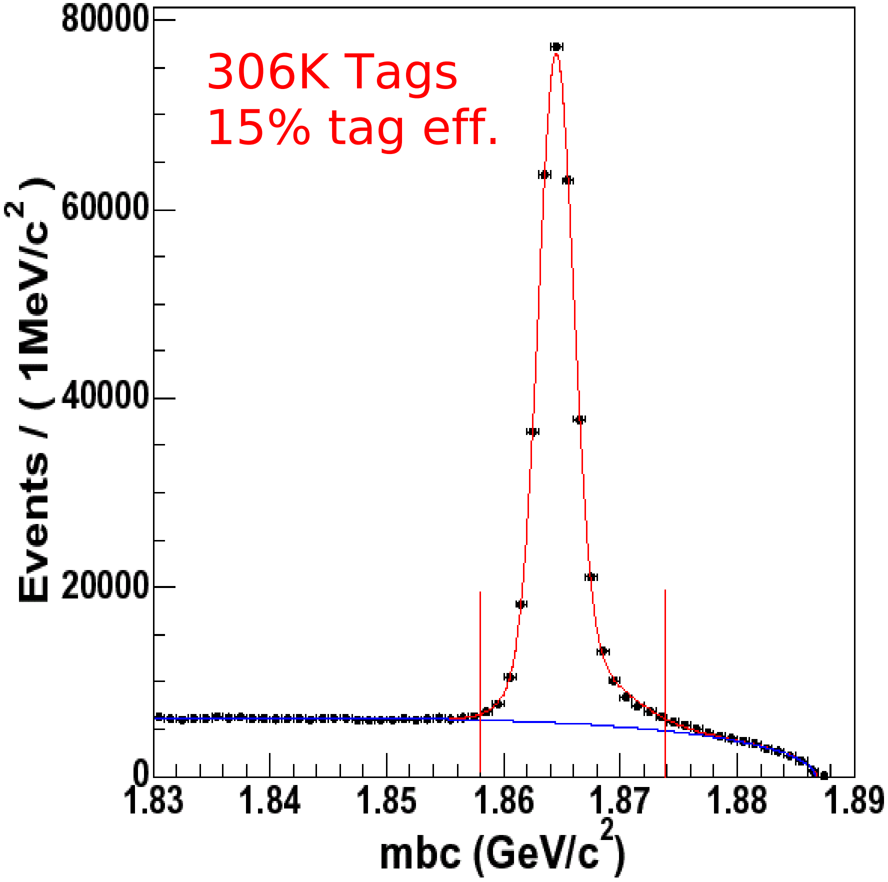


CLEO-III 7 fb^{-1} (PRL 94:011802, 2005)

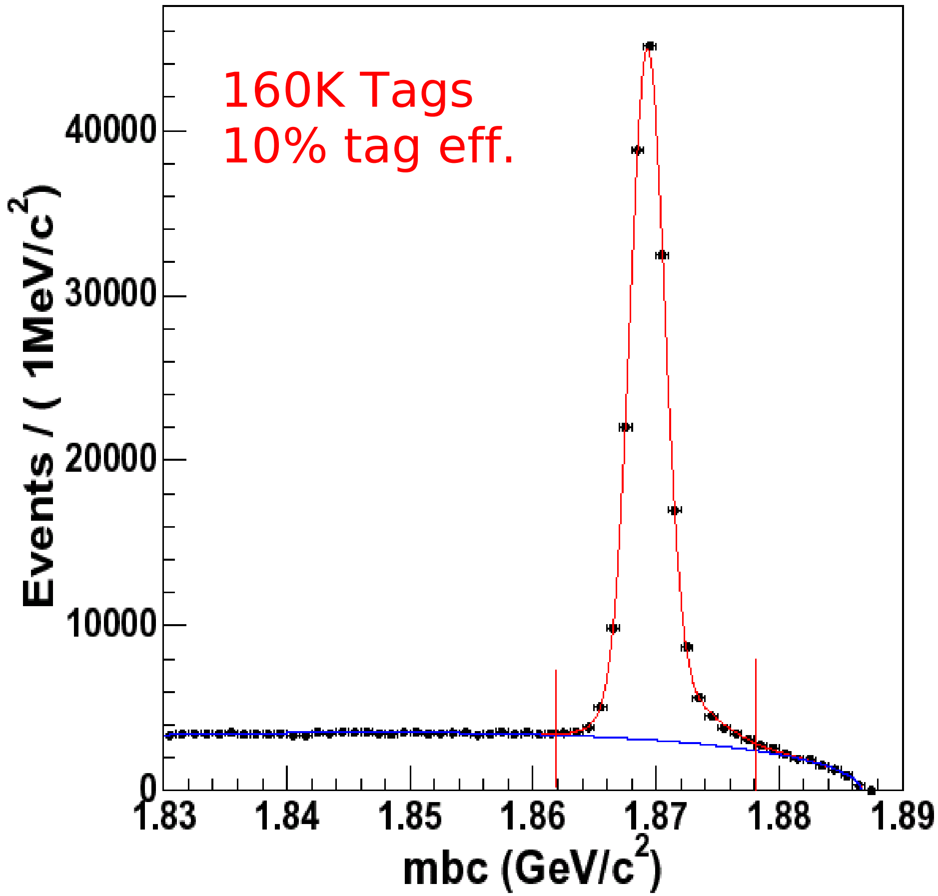


Semileptonic with Tag

D^0 Tags

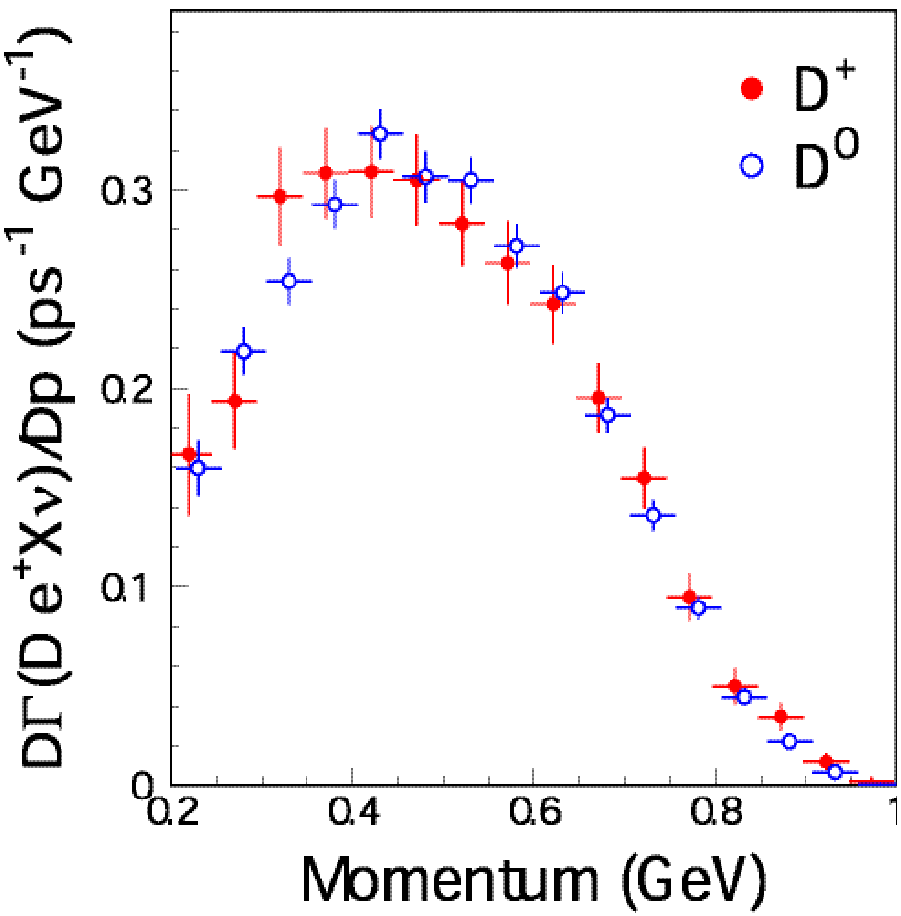


D^+ Tags



Inclusive Semileptonic *D* decays

281 fb^{-1}



(Lab frame)

- 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

$$Br(D^0 \to X e \nu_e) = (6.46 \pm 0.17 \pm 0.13)\%$$

$$Br(D^+ \to X e \nu_e) = (16.13 \pm 0.20 \pm 0.33)\%$$

- Using the measured lifetimes we obtain

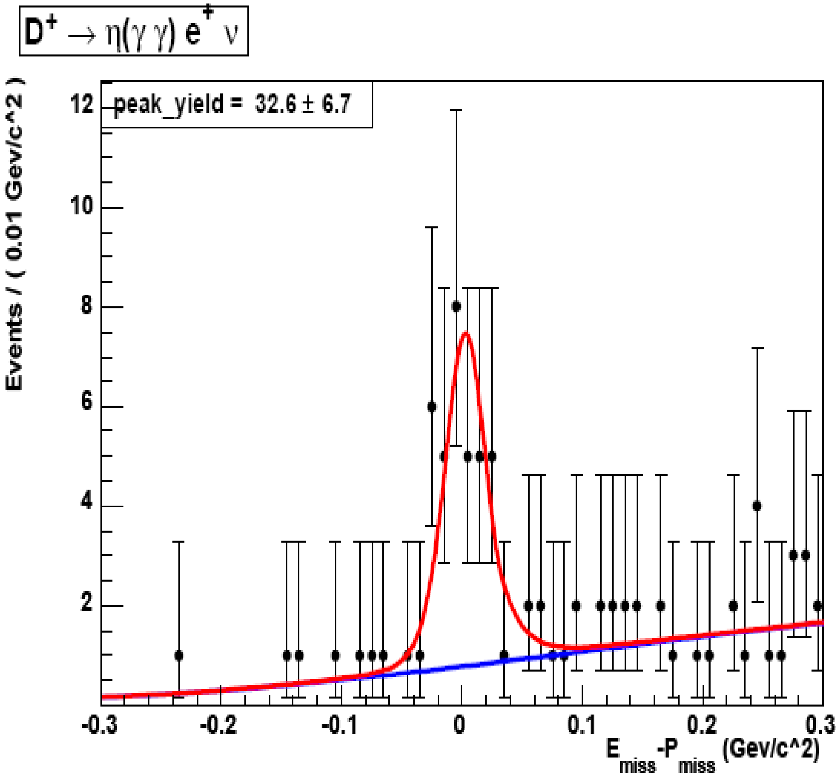
$$\frac{\Gamma(D^+ \to X e \nu_e)}{\Gamma(D^0 \to X e \nu_e)} = (0.985 \pm 0.028 \pm 0.015)$$

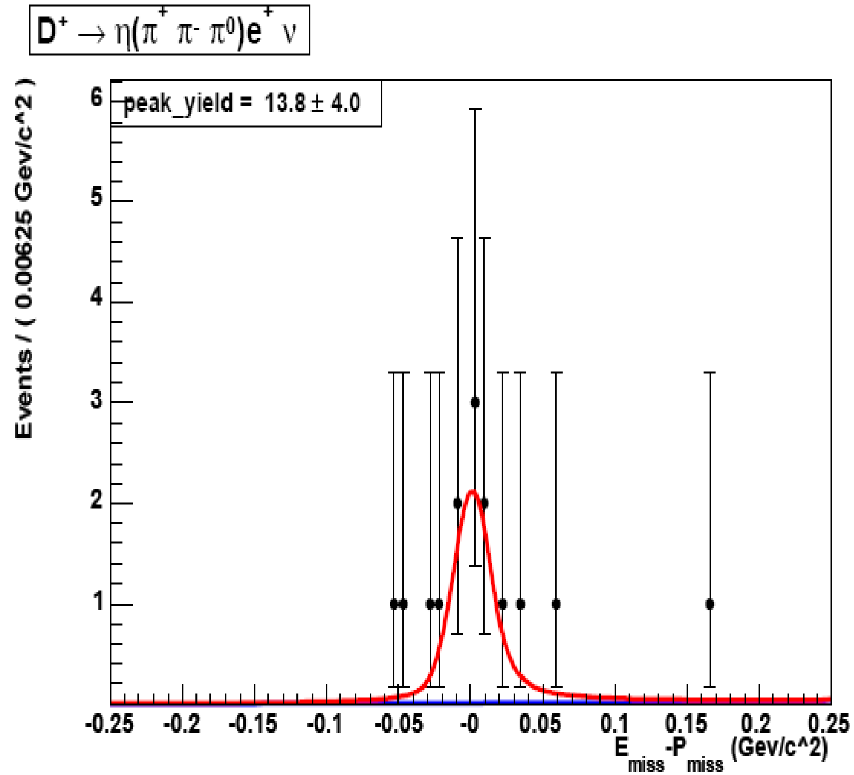
- The sum of exclusive final state

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

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

First observation of $D^+ \to \eta e^+ \nu$

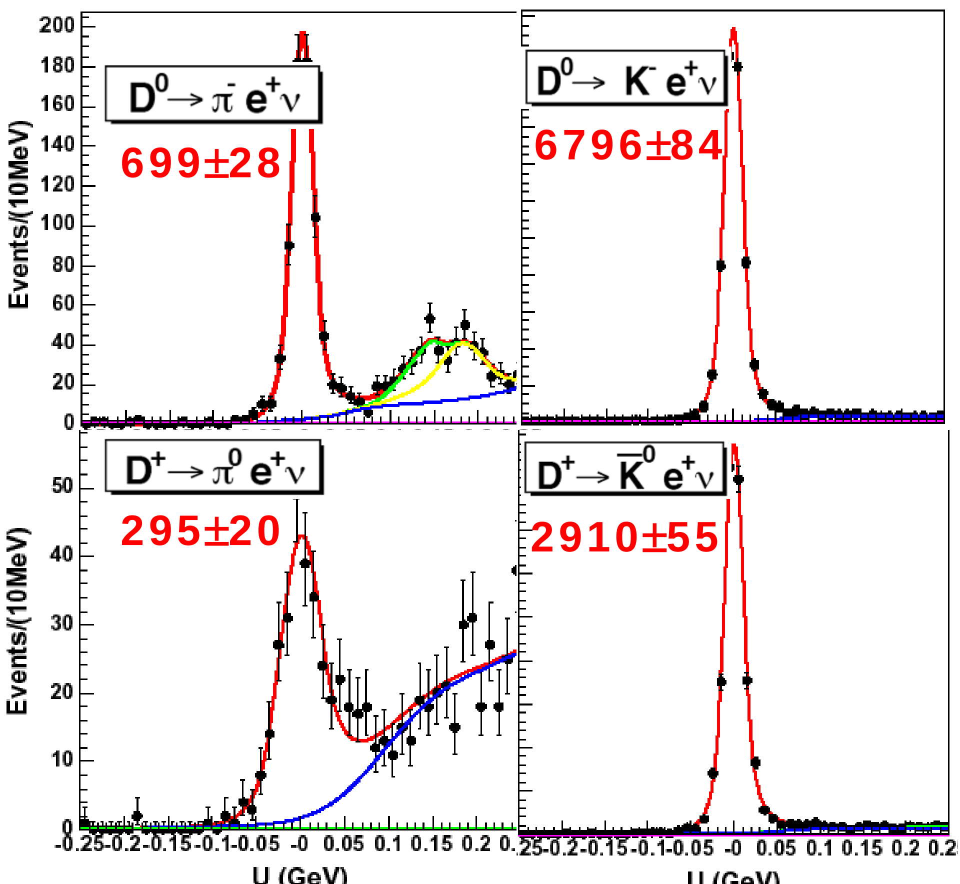


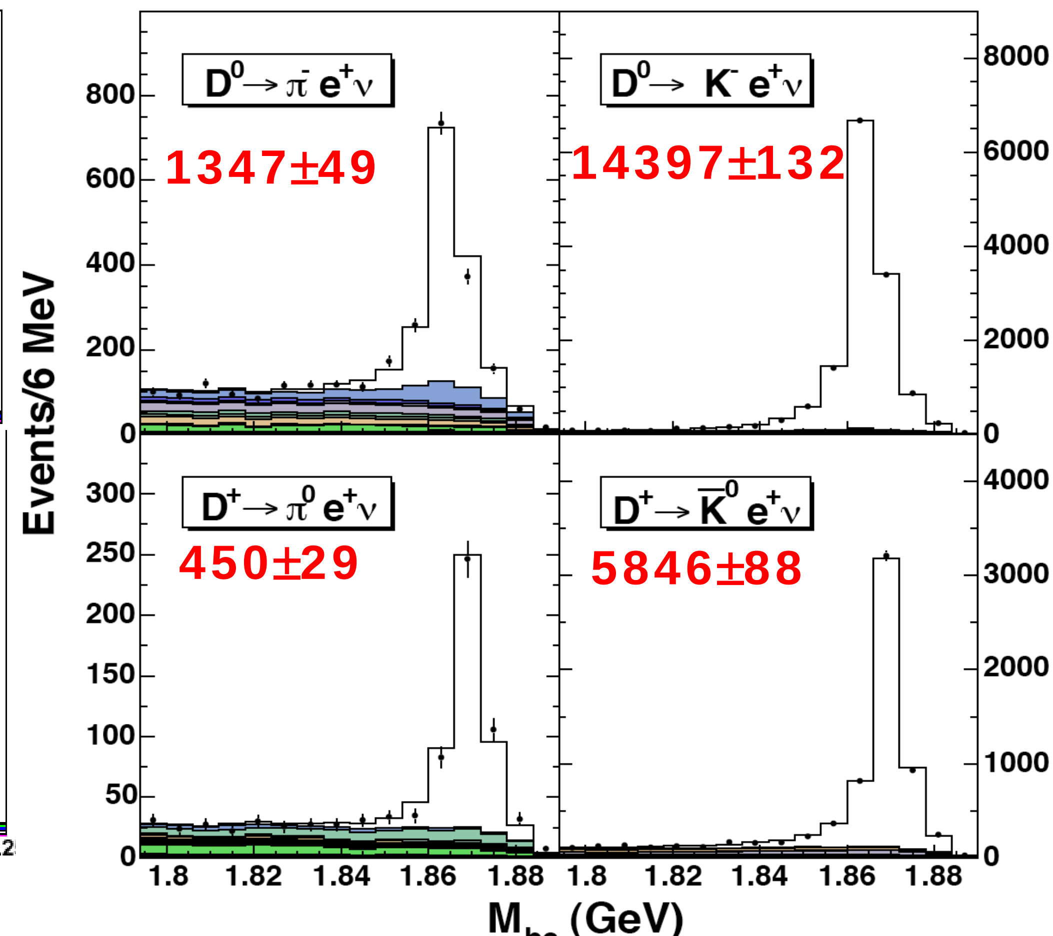


CLEO-c preliminary	PDG-2004
$B(D^+ \to \eta e^+ \nu) = (1.29 \pm 0.19 \pm 0.07) \times 10^{-3}$	$B(D^+ \to \eta l^+ \nu) < 5 \times 10^{-3} (90\% C.L.)$
$B(D^+ \to \eta' e^+ \nu)_{combined} < 3 \times 10^{-4} (90\% C.L.)$	$B(D^+ \to \eta' \mu^+ \nu) < 1.1\% (90\% C.L.)$
$B(D^+ \to \phi e^+ \nu) < 2 \times 10^{-4} (90\% C.L.)$	$B(D^+ \to \phi e^+ \nu) < 2.09\% (90\% C.L.)$

Exclusive Signals (281 pb^{-1})

Tag Preliminary **Untag**





$U = E_{miss} - |P_{miss}|$ (GeV)

Tag and Untag analysis have 40% overlap and should not be averaged

$$\Delta E = E_{K(\pi)} + E_e + |\mathbf{p}_{miss}| - E_{beam}$$

$$M_{bc} = \sqrt{E_{beam}^2 - (\mathbf{p}_{K(\pi)} + \mathbf{p}_e + \varsigma \mathbf{p}_{miss})^2}$$

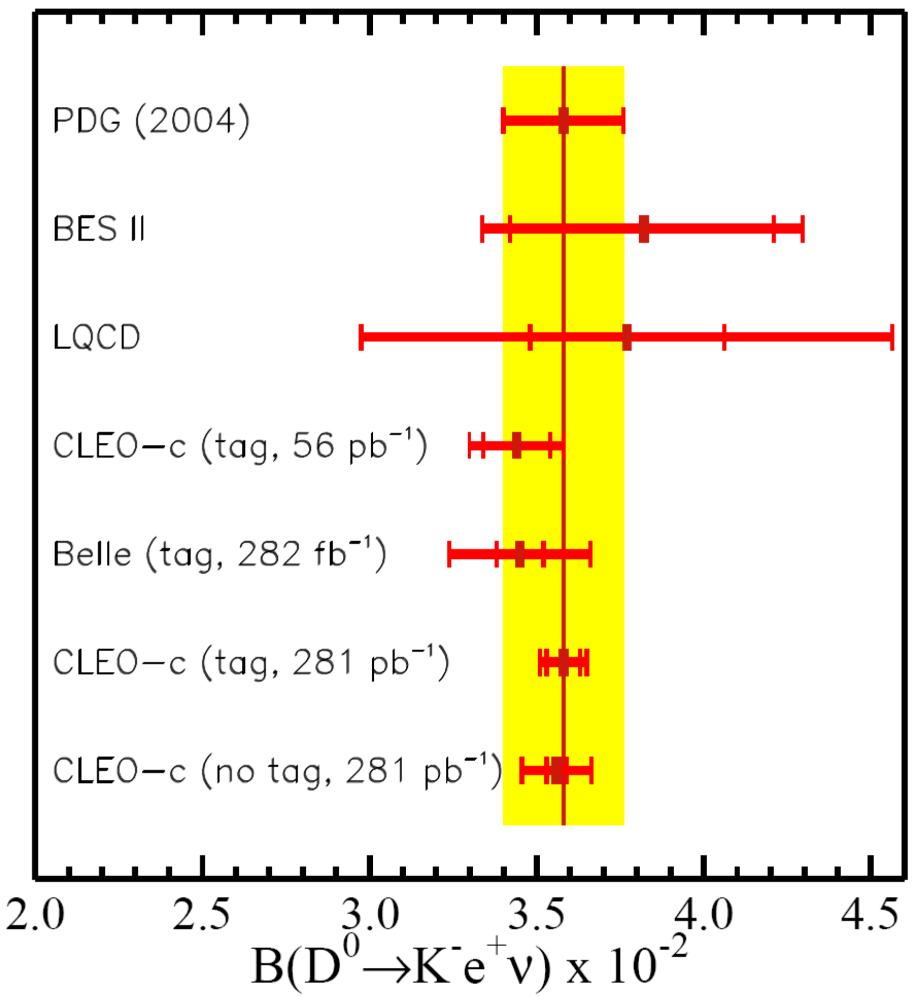
Branching Fraction Results

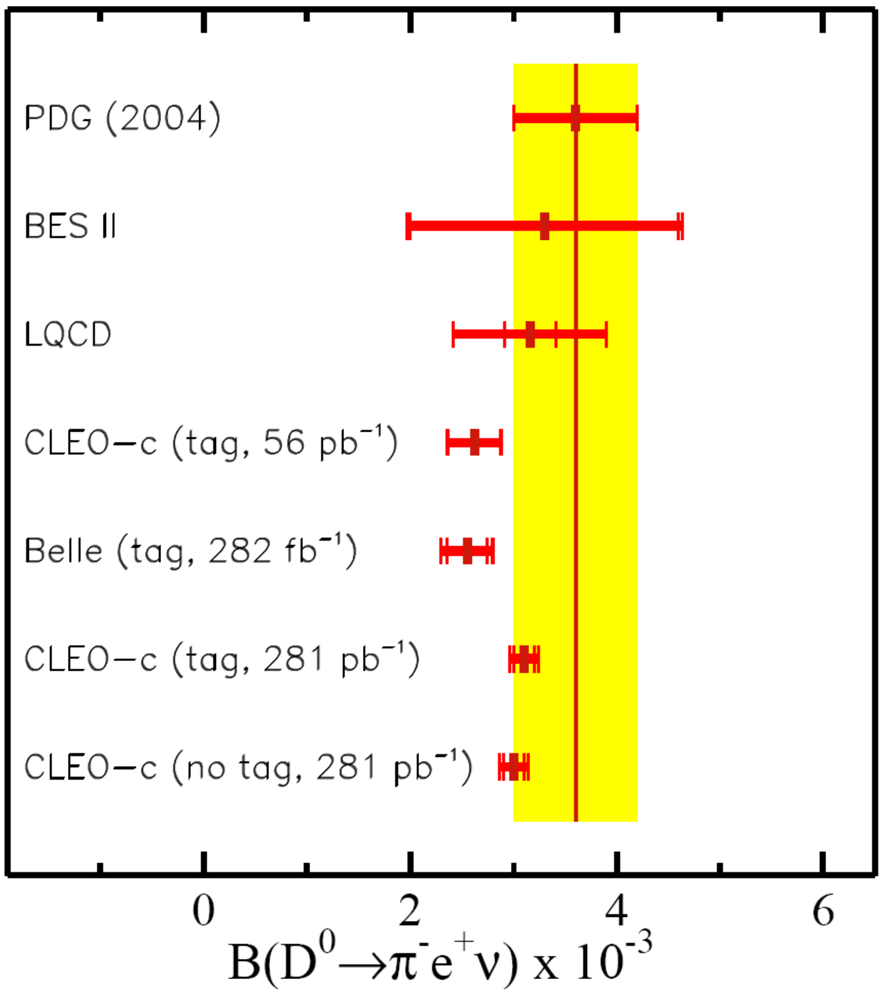
D Decay	Br. Frac. (%) Tag	Br. Frac. (%) Untag	PDG (%)
$D^0 \to K^- e^+ \nu$	3.58± 0.05± 0.05	3.56± 0.03± 0.11	3.62± 0.16
$D^0 \to \pi^- e^+ \nu$	0.309± 0.012± 0.006	0.301± 0.011± 0.010	0.311± 0.030
$D^+ \to \bar{K}^0 e^+ \nu$	8.86± 0.17± 0.20	8.75± 0.13± 0.30	7.2± 0.8
$D^+ \to \pi^0 e^+ \nu$	0.397± 0.027± 0.028	0.383± 0.025± 0.016	0.38± 0.19

Ratio	Measured (%)	PDG (%)	Ratio	Measured
$\frac{D^0 \to \pi^- e^+ \nu}{D^0 \to K^- e^+ \nu}$	8.5± 0.3± 0.1	8.6± 0.7	$\frac{\Gamma(D^0 \to \pi^- e^+ \nu)}{\Gamma(D^+ \to \pi^0 e^+ \nu)}$	1.95± 0.15± 0.14 1.99± 0.15± 0.10
$\frac{D^+ \to \pi^0 e^+ \nu}{D^+ \to \bar{K}^0 e^+ \nu}$	4.4± 0.3± 0.1	4.6± 1.4± 1.7	$\frac{\Gamma(D^0 \to K^- e^+ \nu)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu)}$	1.02± 0.02± 0.02 1.03± 0.02± 0.04

Comparison to Other Exp.

CLEO-c 281 pb^{-1} Preliminary





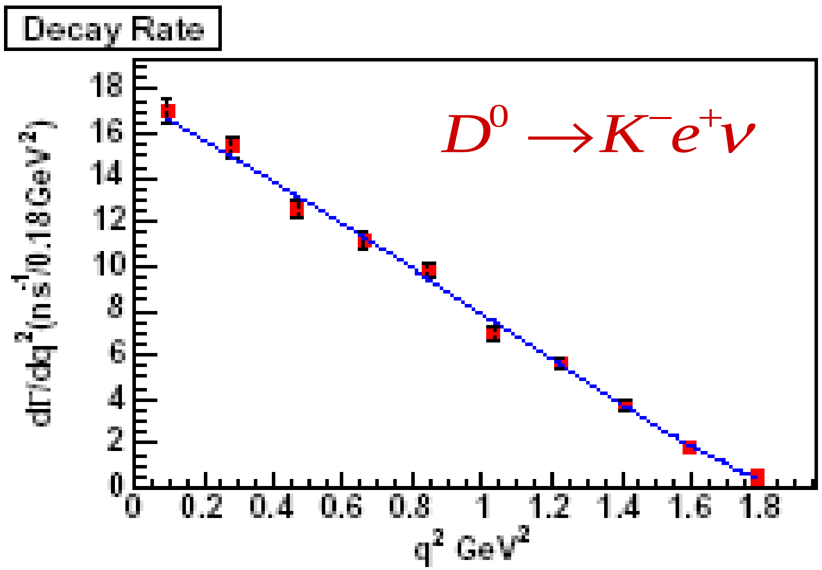
Form Factors in $D \to Ke\nu$ and $D \to \pi e\nu$

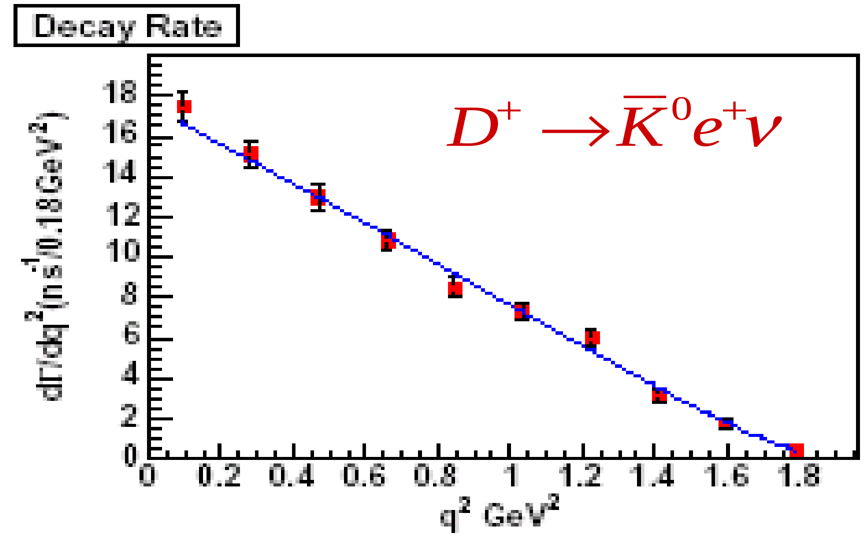
- The differential decay rate is given by

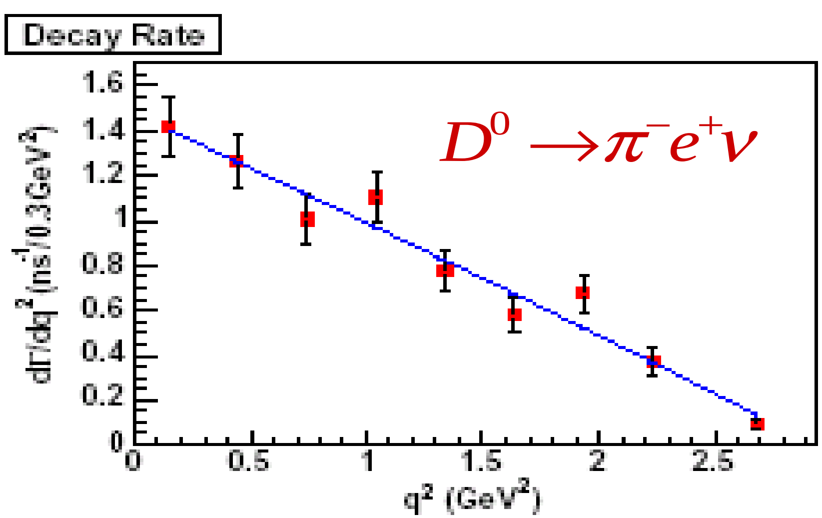
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cq}|^2 p_K^3 |f_+(q^2)|^2$$

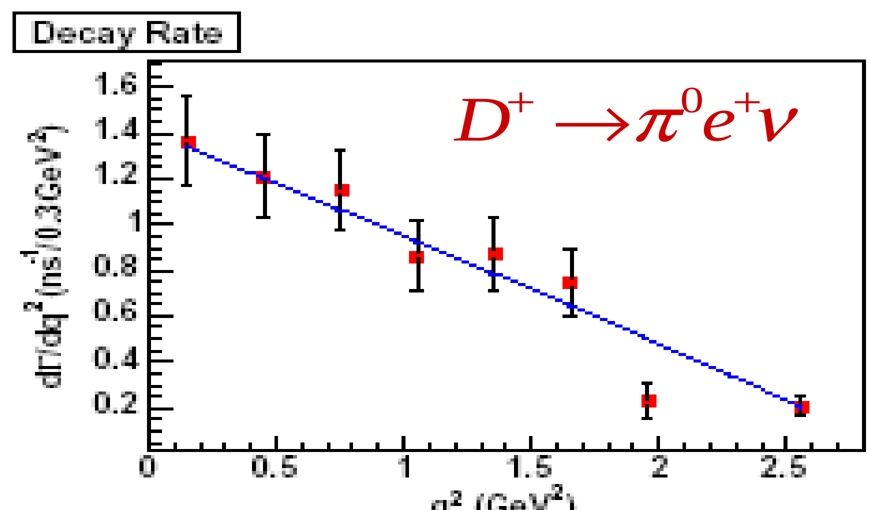
- $q^2 = m^2_{e\nu}$
- As we use electrons the form factor corresponding to a scalar *W* has a negligible contribution to the rate.
- The observed q^2 distribution is fit to extract form factor information.

Form Factor Fit (Tag)







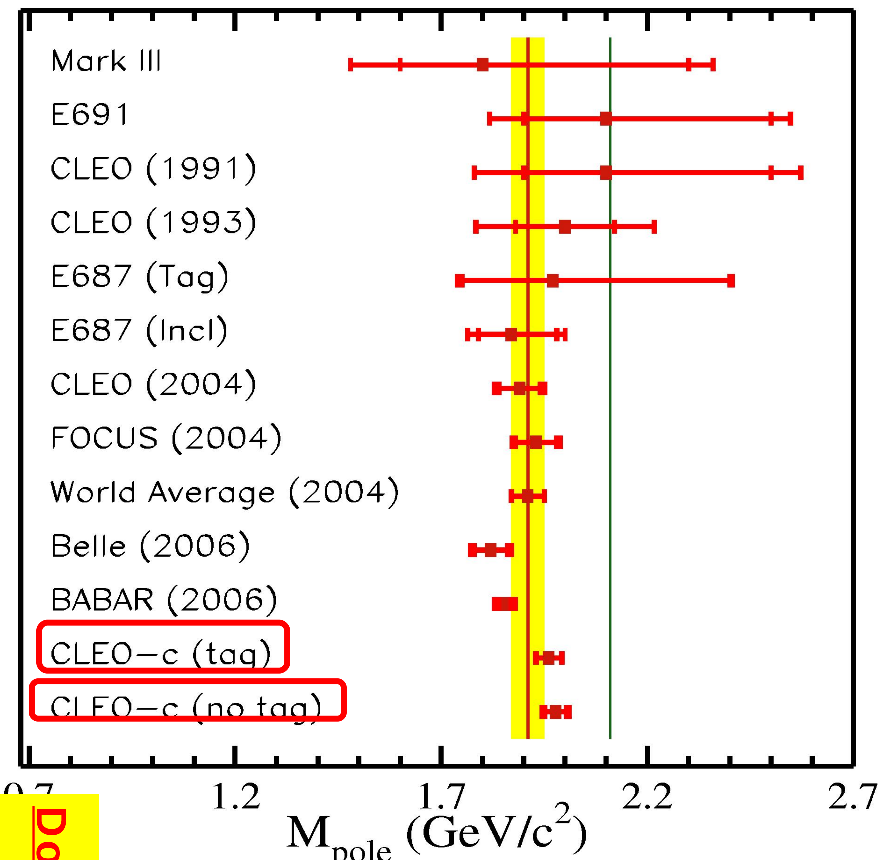


$$f_+(q^2) = \frac{f_+(0)}{1 - q^2/M_{\text{pole}}^2}$$

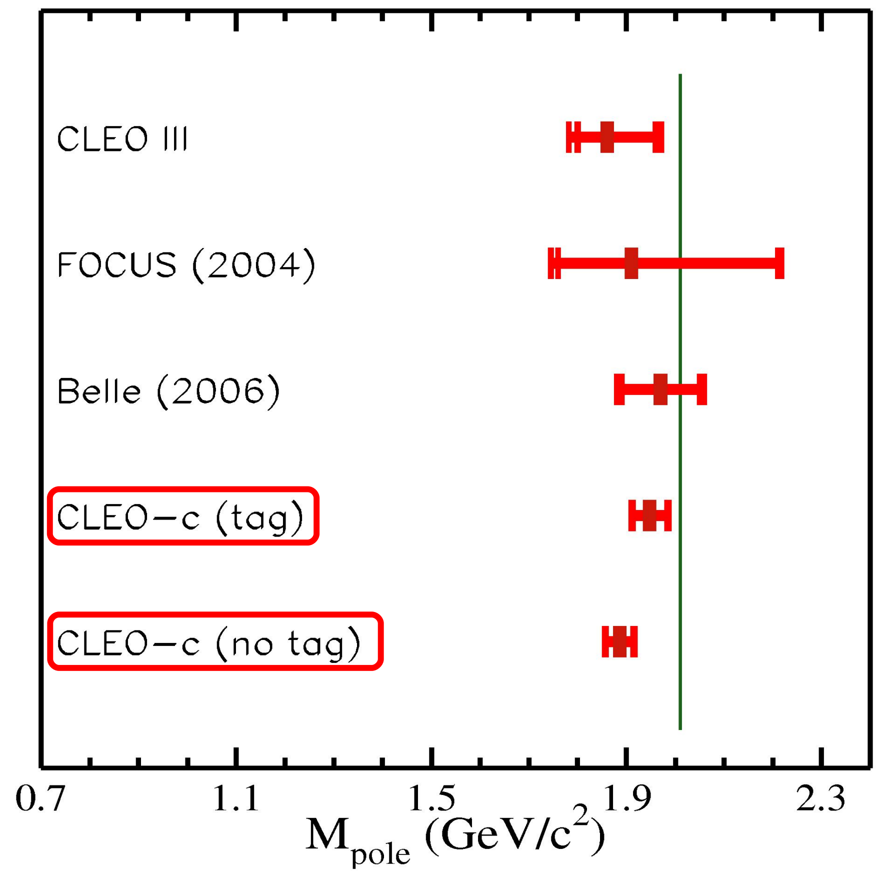
$$f_+(q^2) = \frac{f_+(0)}{1 - q^2/M_{D_{(s)}^*}^2} \times \frac{1}{1 - \alpha q^2/M_{D_{(s)}^*}^2}$$

Pole Mass

$D \to K e^+ \nu$



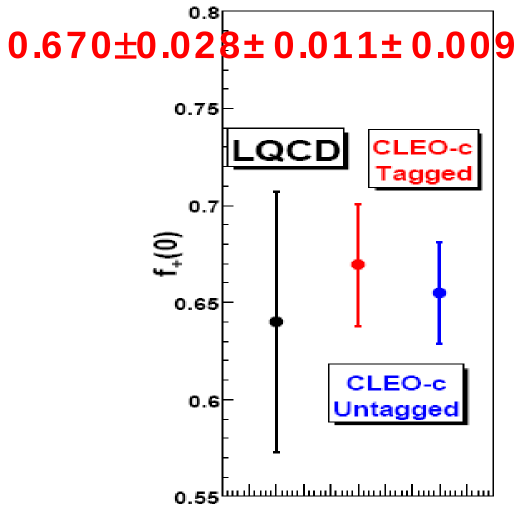
$D \to \pi e^+ \nu$

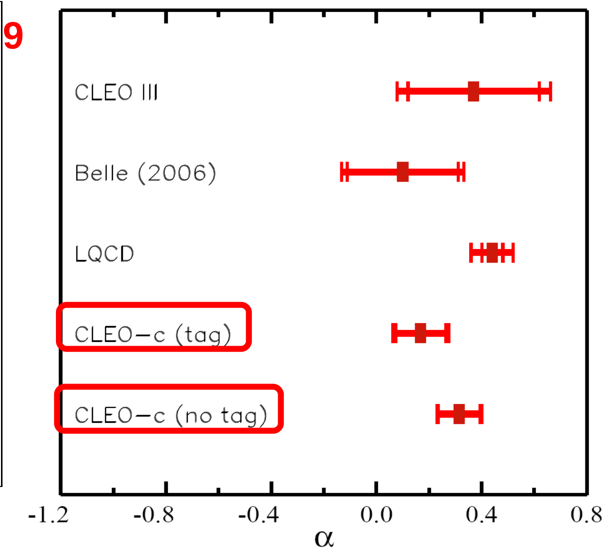


Don't average!

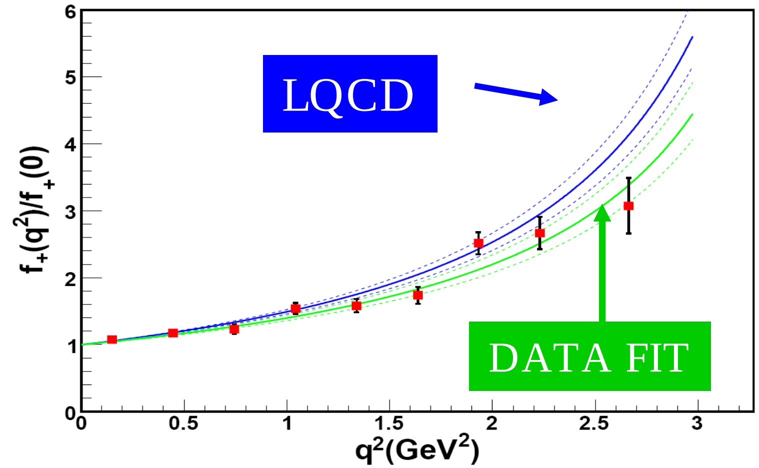
Decay Mode	Mpole (Tag)	Mpole (Untag)
$D \to K e \nu$ (av. D^0 & D^+)	1.96±0.03±0.01	1.98±0.03±0.02
$D \to \pi e \nu$ (av. D^0 & D^+)	1.95±0.04±0.02	1.88±0.03±0.02

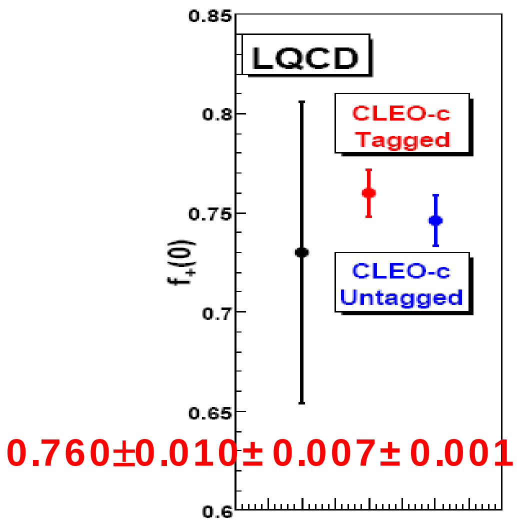
Form Factors and LQCD

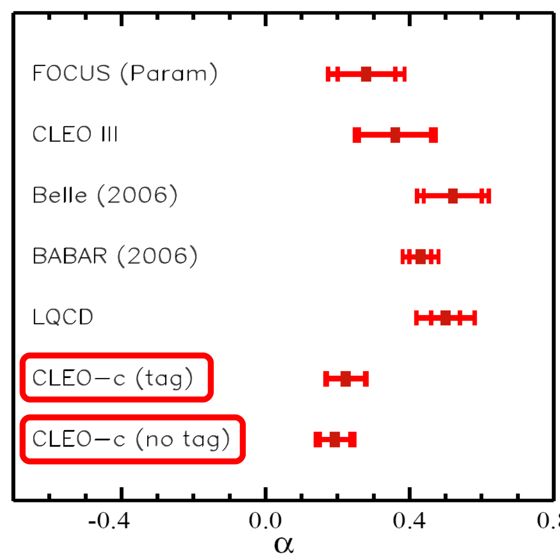




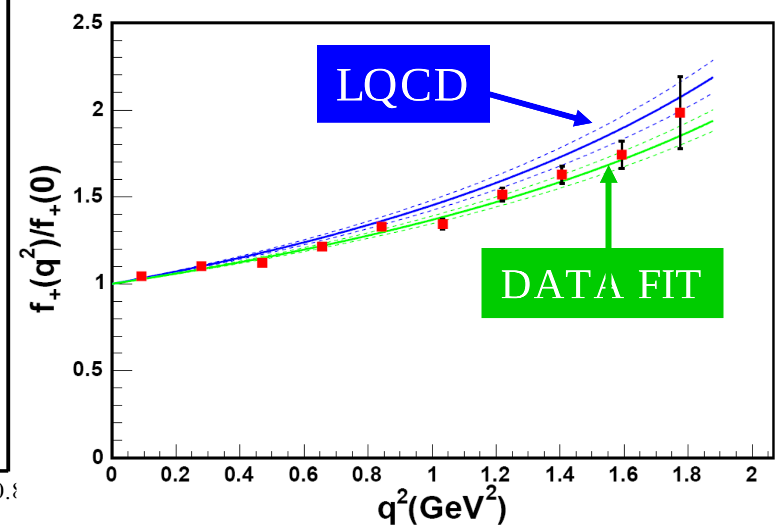
$D^0 \to \pi^- e^+ \nu$



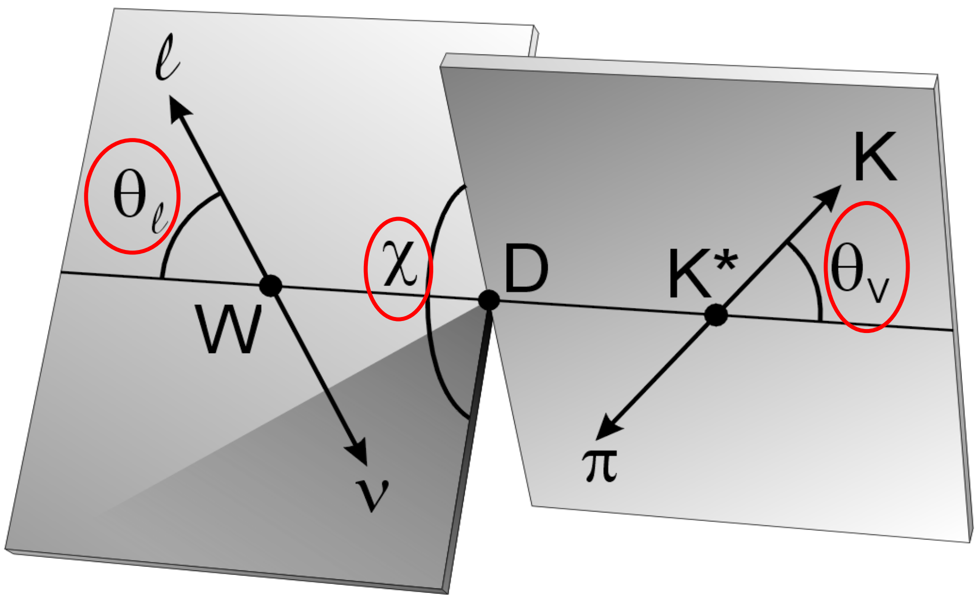




$D^0 \to K^- e^+ \nu$



$D\to$"K^*"$e\nu$ Form Factors



- Focus has seen evidence for a S-wave component of the $K\pi$.
- Fit the θ_l and θ_V distributions as a function of q^2 to extract the helicity amplitudes.

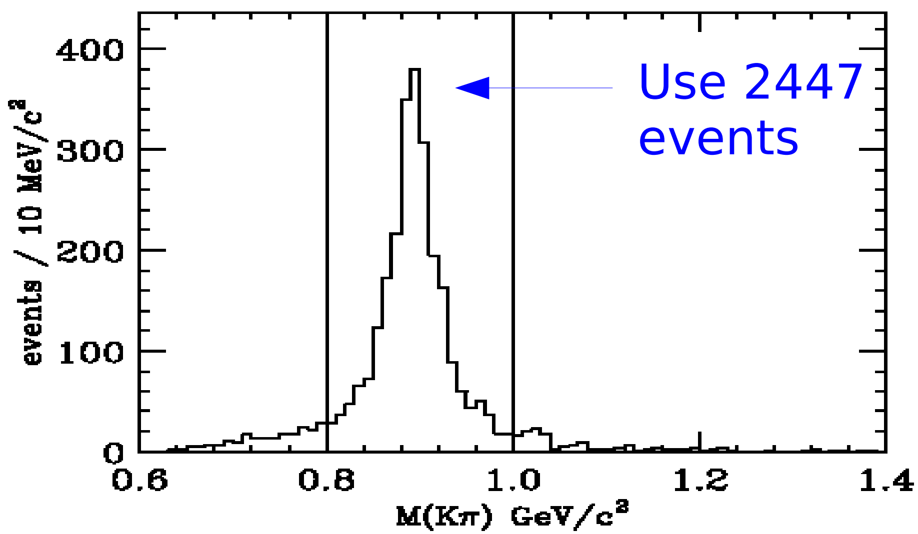
$$|A|^2 = \frac{q^2}{8}\left| \begin{array}{l} (1+\cos\theta_l)\sin\theta_V e^{i\chi}\ \mathrm{BW}\ H_+\left(q^2\right) \\ -(1-\cos\theta_l)\sin\theta_V e^{-i\chi}\ \mathrm{BW}\ H_-\left(q^2\right) \\ -2\sin\theta_l\left(\cos\theta_V\ \mathrm{BW}\ H_0\left(q^2\right) + \mathrm{A}e^{\mathrm{i}\delta} h_0\left(q^2\right)\right) \end{array} \right|^2$$

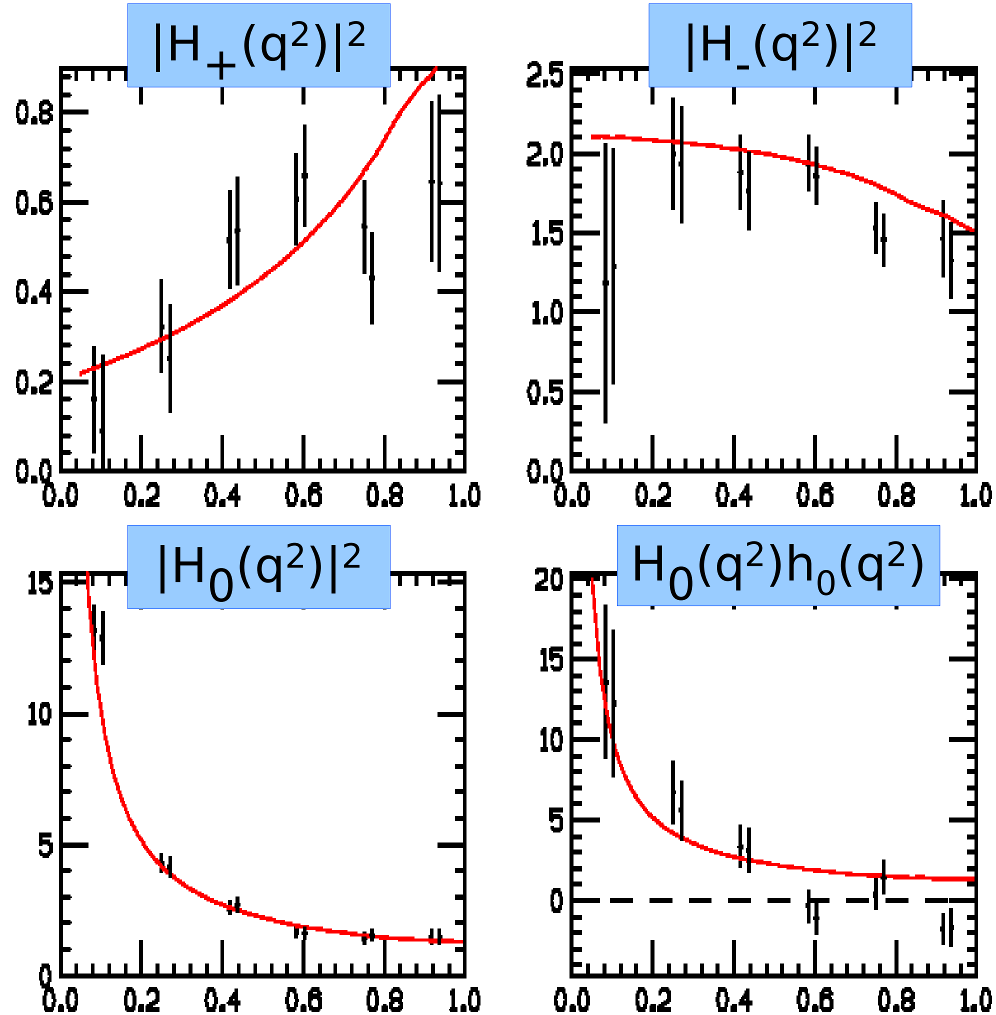
Focus found A   7% of BW peak if they assumed

$$h_0\left(q^2\right) = H_0\left(q^2\right)$$

$D\to K^{*}e\nu$ Form Factor Results

Preliminary





- Non-parametric fit
- Clear evidence for S-wave

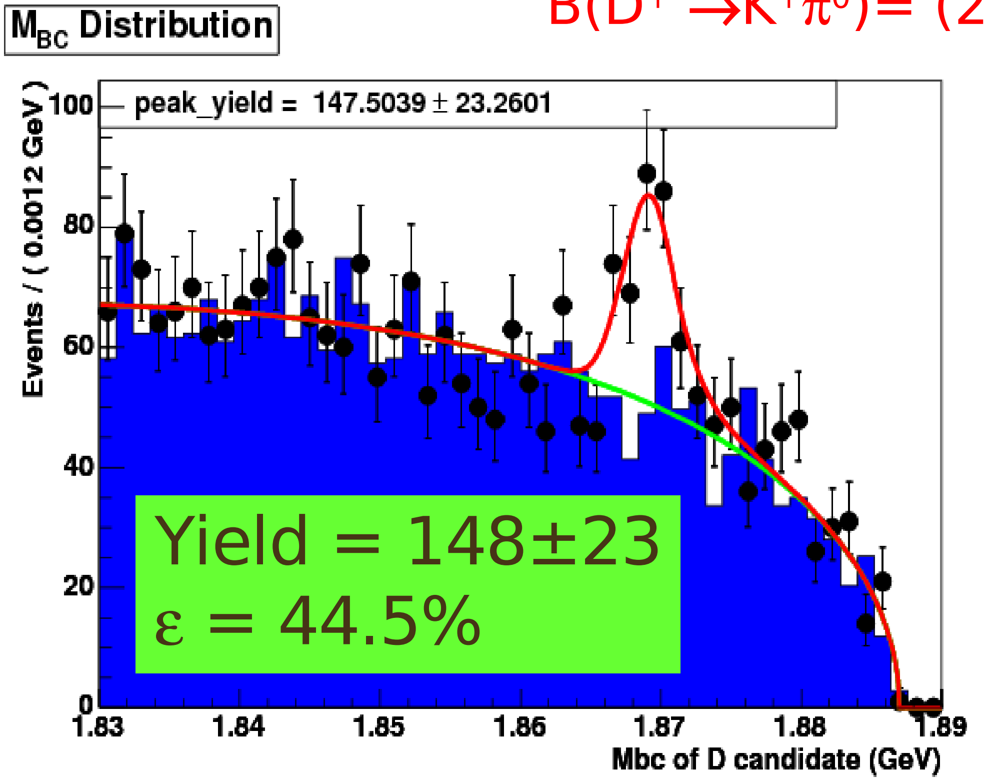
Summary-Outlook

- CLEO-c has recorded 281 pb^{-1} at $\psi(3770)$
  - Absolute hadronic branching fractions
  - Leptonic decays
  - Semileptonic decays
- Recorded ~330 pb^{-1} at $E_{cm} \approx 4170$ MeV
  - Analyzed ~200 pb^{-1} for hadronic and leptonic *Ds* decays
- Goal is to take ~750 pb^{-1} at $E_{cm} \approx 4170$ MeV and at $\psi(3770)$ before the CLEO-c run ends in April 2008.
  - Leptonic decays can make full use of statistics
  - Cabibbo favored hadronic and semileptonic decays are starting to become systematics limited at the $\psi(3770)$
  - D_s decays will remain statistics limited

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

- Reconstruct K^+ using RICH (some dE/dx), $\pi^0 \to \gamma\gamma$.
- Require $-40 < E_{cand} - E_{beam} < 35$ MeV
  - Fit M_{bc} spectrum
- Normalize to $D^+ \to K^-\pi^+\pi^+$

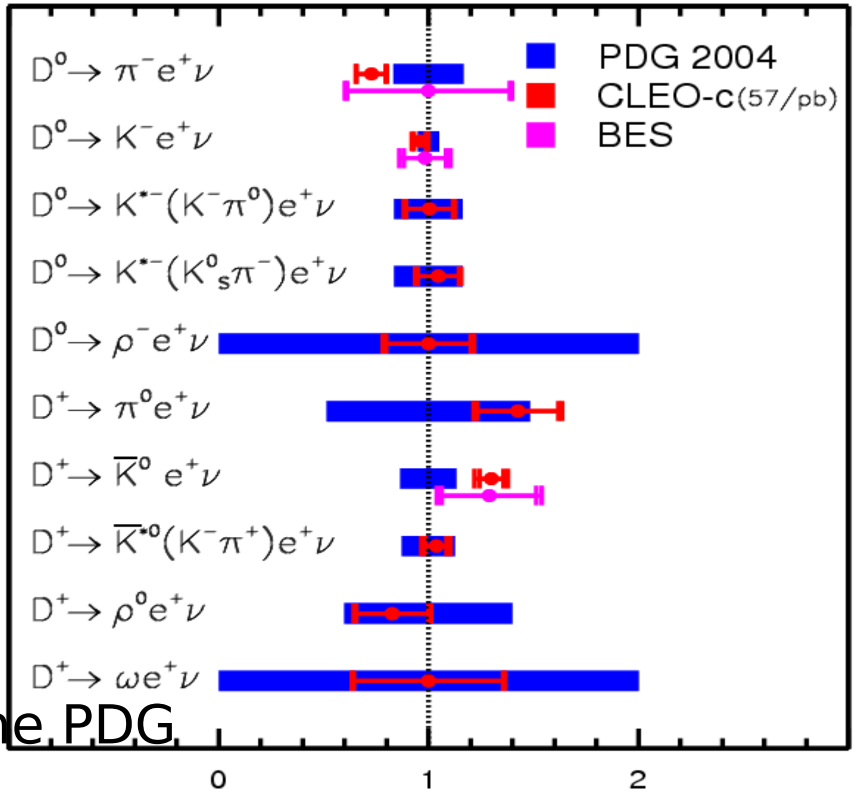
$B(D^+ \to K^+\pi^0) = (2.25 \pm 0.36 \pm 0.15 \pm 0.07) \times 10^{-4}$



BaBar (124 fb^{-1}) finds:
$B(D^+ \to K^+\pi^0) = (2.25 \pm 0.46 \pm 0.24 \pm 0.16) \times 10^{-4}$

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

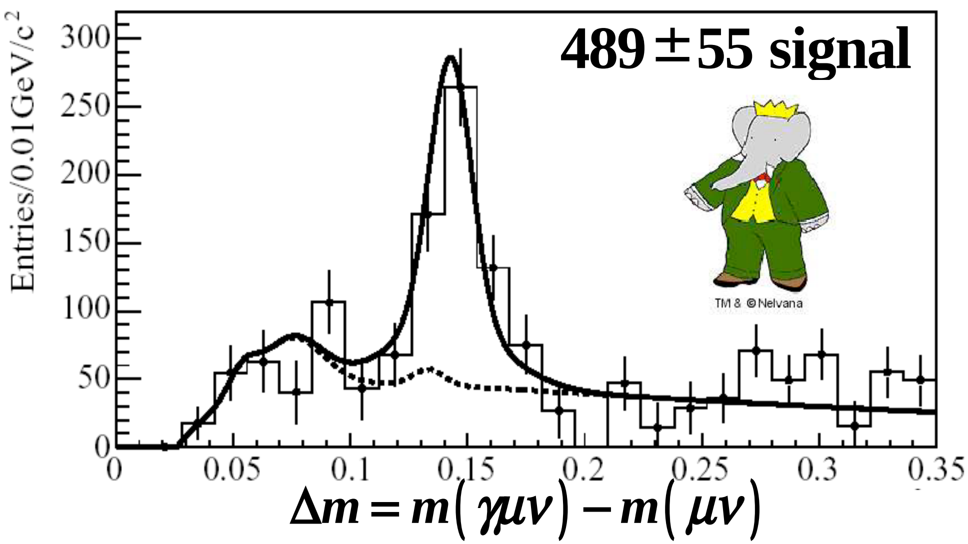
Mode	$\mathcal{B}$ (%)	$\mathcal{B}$ (%) (PDG)
$D^0 \to \pi^- e^+ \nu_e$	$0.26 \pm 0.03 \pm 0.01$	0.36 ± 0.06
$D^0 \to K^- e^+ \nu_e$	$3.44 \pm 0.10 \pm 0.10$	3.58 ± 0.18
$D^0 \to K^{*-}(K^- \pi^0) e^+ \nu_e$	$2.11 \pm 0.23 \pm 0.10$	2.15 ± 0.35
$D^0 \to K^{*-}(\bar{K}^0 \pi^-) e^+ \nu_e$	$2.19 \pm 0.20 \pm 0.11$	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
$D^+ \to \omega e^+ \nu_e$	$0.16^{+0.07}_{-0.06} \pm 0.01$	—



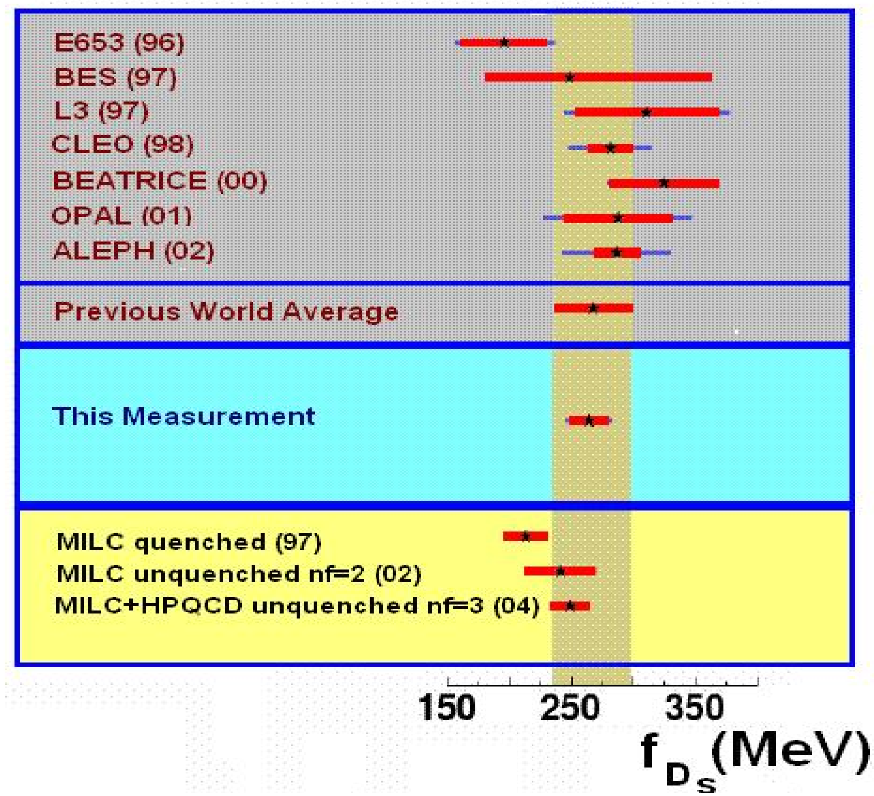
- Most modes are improvements over the PDG
  - Including two first observations
  - $D^0 \to \rho^- e^+ \nu_e$ and $D^+ \to \omega e^+ \nu_e$
- Most systematics can be reduced with more data
- Updating analysis to 281 pb^{-1}

$D_s \to \mu\nu_\mu$

- Current best measurement from BaBar (230 fb^{-1})
- Use D^0, D^+, D_s tags to get clean $e^+e^- \to cc$ sample
- Have 489±55 $D_s \to \mu\nu_\mu$ candidates



From P. Patteri (Babar)

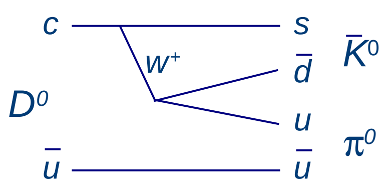


$$f_{D_s}^{BaBar} / f_{D+}^{CLEO} = 1.25 \pm 0.14$$

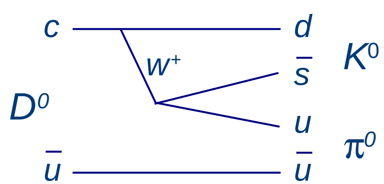
(As expected from LQCD)

$D^0 \to K_S \pi^0$ and $D^0 \to K_L \pi^0$

- 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



Cabibbo- suppressed

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

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

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

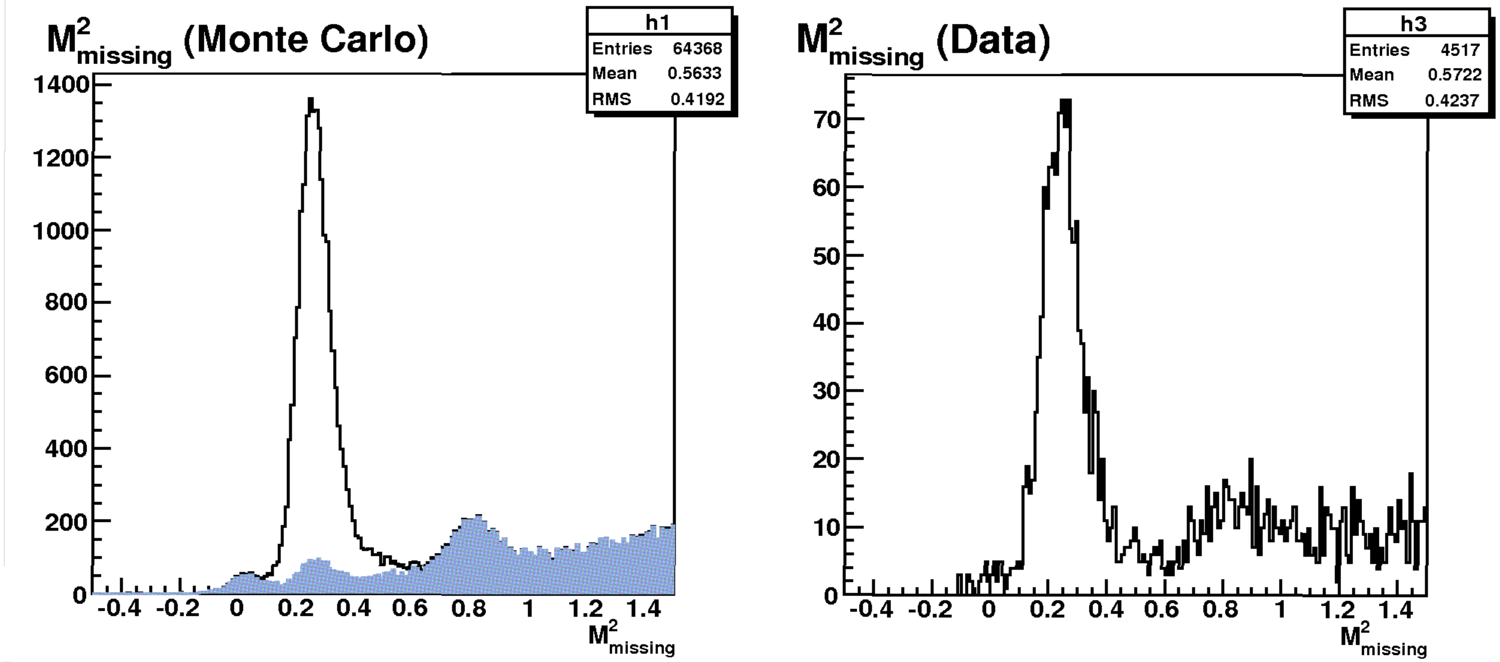
Based on factorization Bigi and Yamamoto (PLB 349, 363 (1995))
Predict

$$\frac{\Gamma(D^0 \to K_S) - \Gamma(D^0 \to K_L)}{\Gamma(D^0 \to K_S) + \Gamma(D^0 \to K_L)} \approx 0.1$$

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



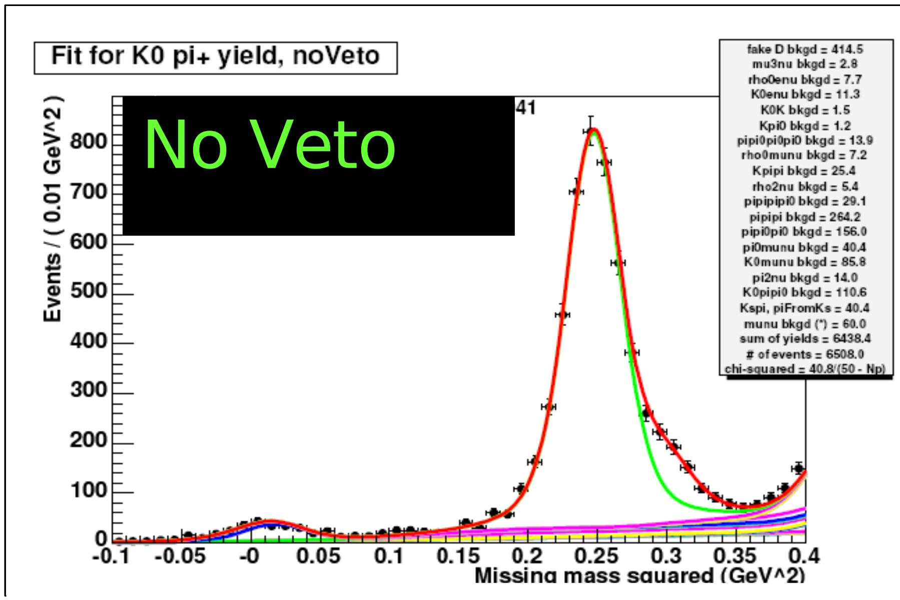
- Correcting for Quantum Correlations
- $B(D^0 \to K_L^0 \pi^0) = (0.940 \pm 0.046 \pm 0.032)\%$
- $B(D^0 \to K_S^0 \pi^0) = (1.212 \pm 0.016 \pm 0.039)\%$

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

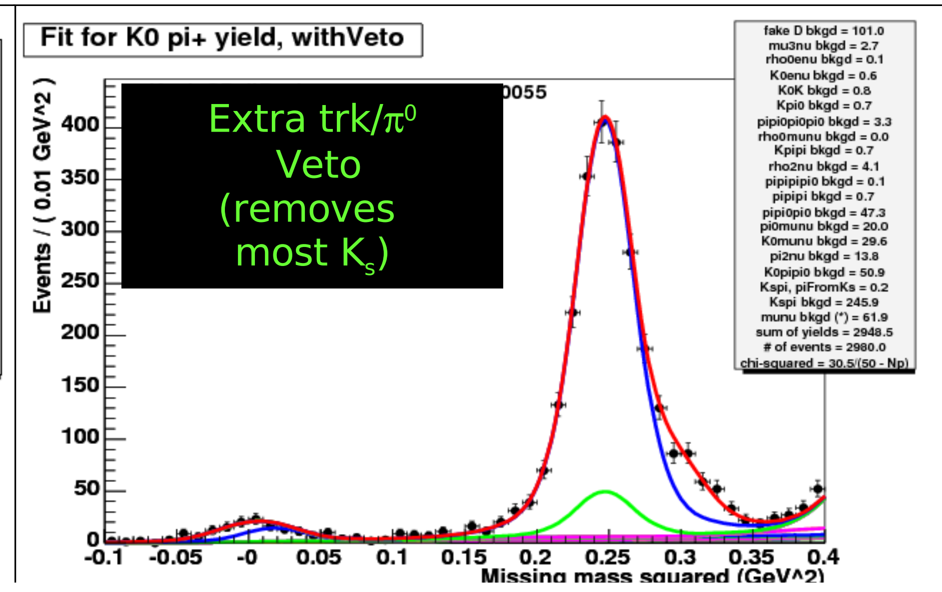
In agreement with theory (factorization)

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

- 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

$$\frac{\Gamma(D^+ \to K_S) - \Gamma(D^+ \to K_L)}{\Gamma(D^+ \to K_S) + \Gamma(D^+ \to K_L)} = 0.030 \pm 0.023 \pm 0.025$$