Physics at the ψ(3770)

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for the
CLEO Collaboration
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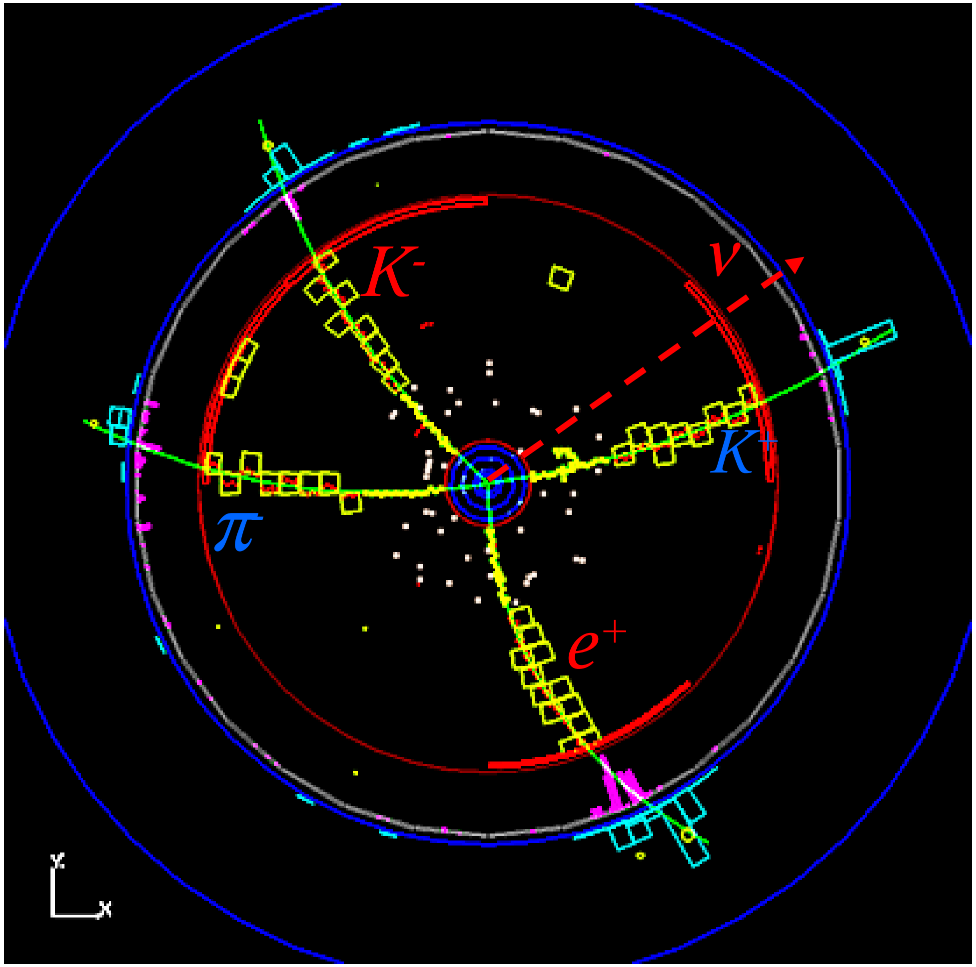
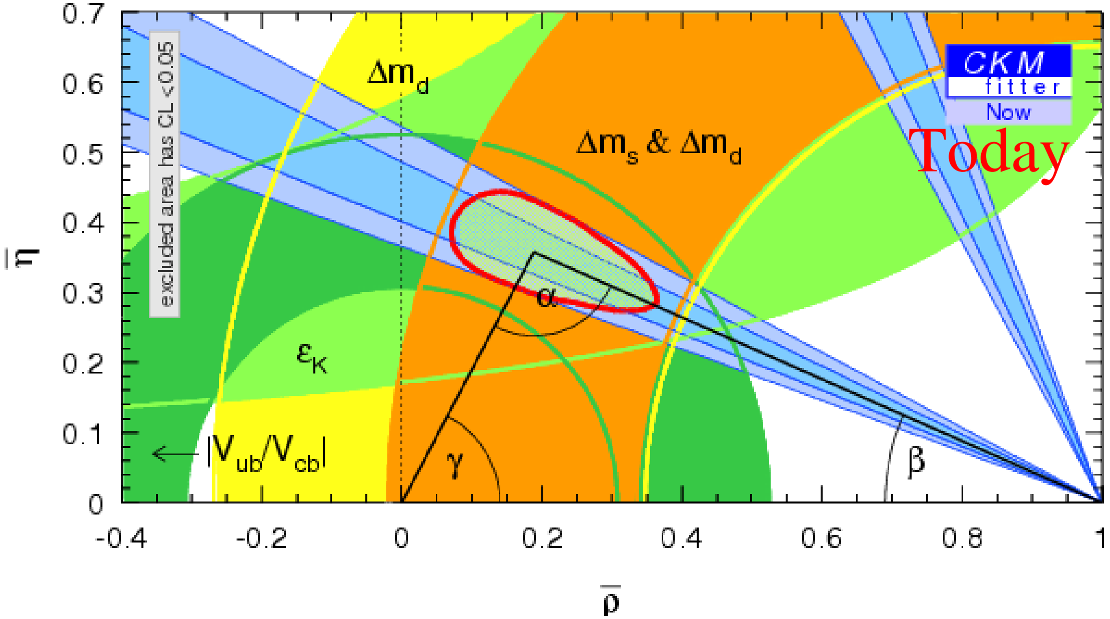
$$e^+e^- \to c\,\overline{c} \to D^0\,\overline{D}^0$$

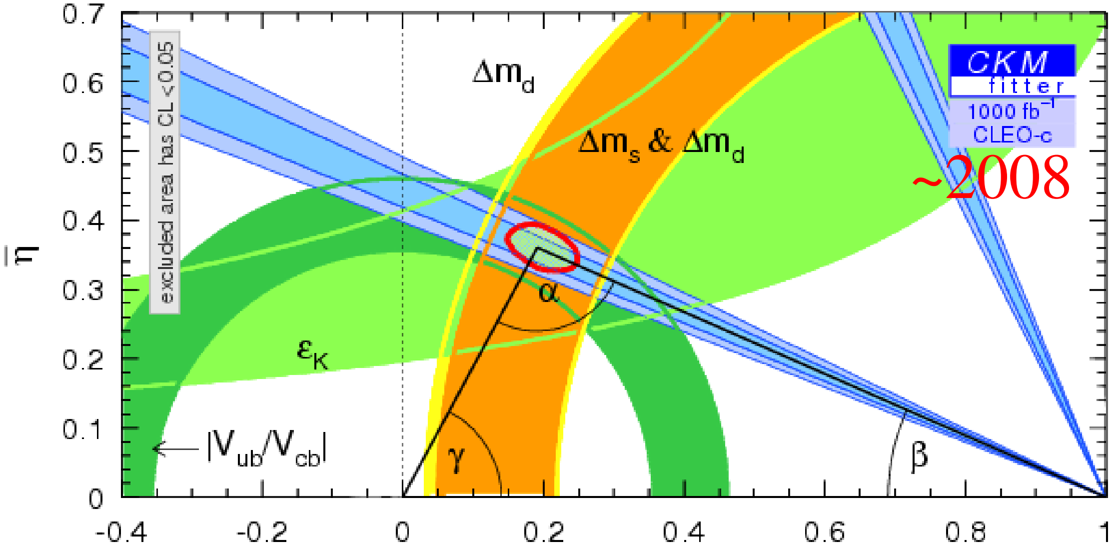
$$\overline{D}^0 \to K^+\pi^-,\ D^0 \to K^- e^+ \overline{\nu}$$



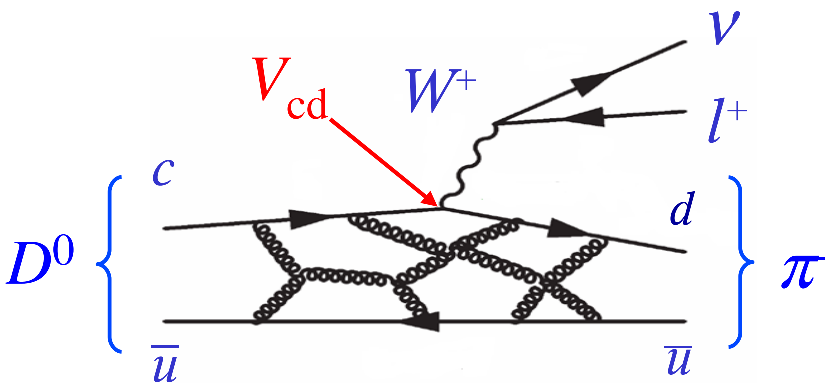
Testing the Quark Mixing (CKM) Matrix

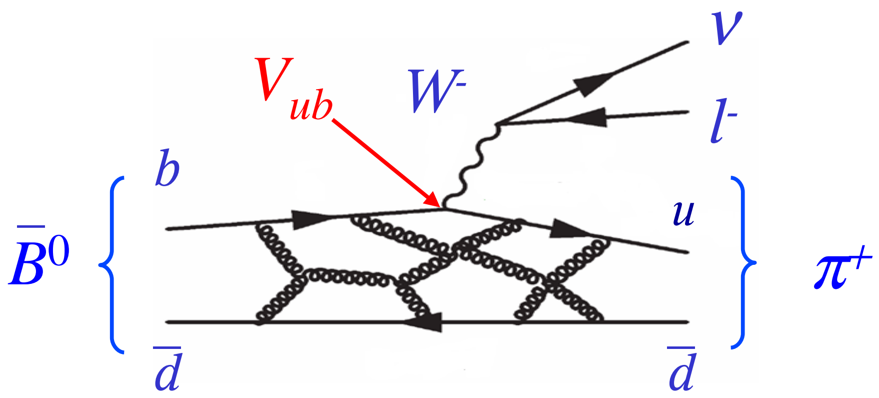
- The CKM matrix provides the only mechanism for CP violation in the SM.
- It is an important goal of flavor physics to measure – and overconstrain – the parameters in the CKM matrix.
- Non-perturbative strong effects limit our ability to extract the fundamental parameters from the measurements.
- CLEO-c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





Testing Theories of Strong Interactions

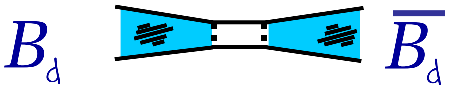




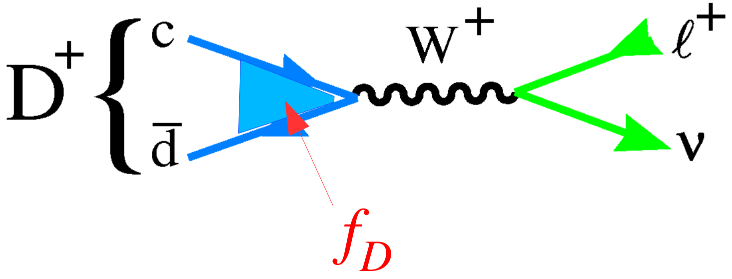
- Measure form factors in $D \to \pi l \nu$ and validate theoretical calculations
  - Can then use this to extract $|V_{ub}|$ from $B \to \pi l \nu$

- 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



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



Outline

- Experimental technique
- Hadronic branching fractions
  - Reference branching fractions
  - Cabibbo suppressed decays
- Semileptonic decays
  - Inclusive branching fractions
  - Exclusive branching fractions
  - Form factors
- Leptonic decays
- Rare decays
- Conclusions

Normalization Br. Fr.
Systematics

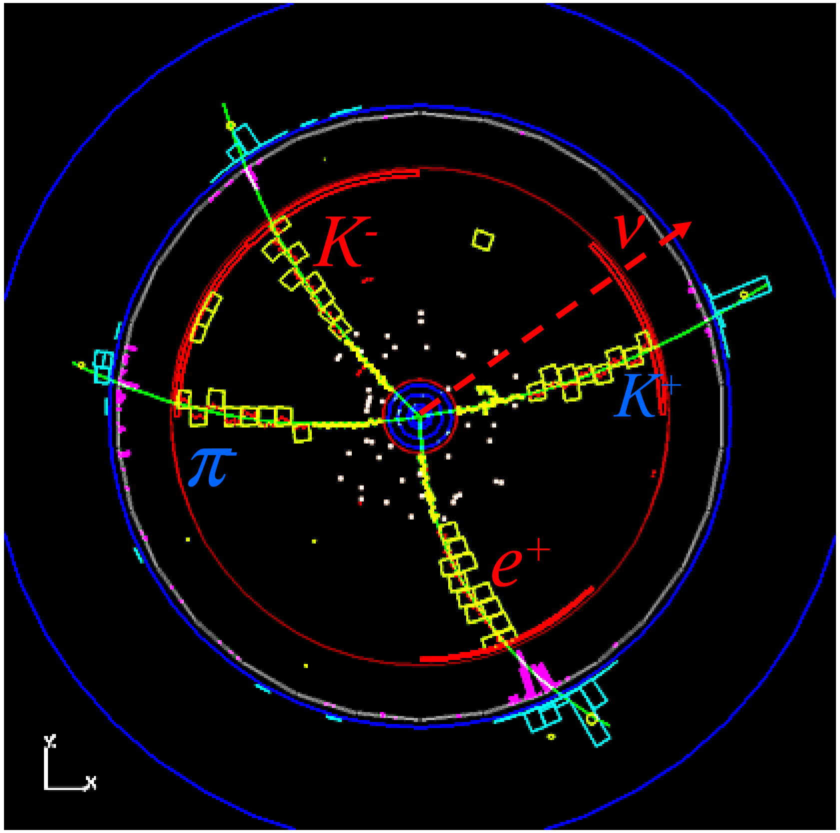
Tests of theory for
strong physics:
f_D, form factors

Physics at $c\bar{c}$ Threshold

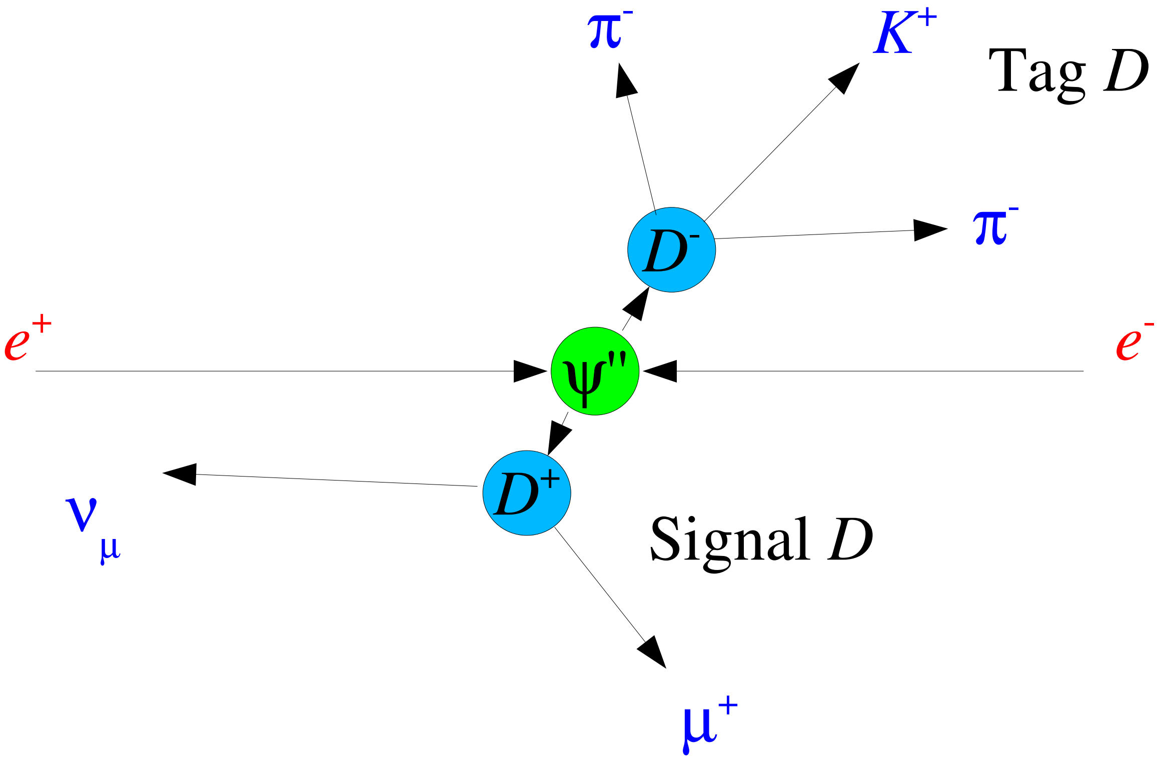
- We run at E_{cm}=3.77 GeV
  - the ψ(3770) resonance.
- Producing $D\bar{D}$ pairs
  - and no other pions.
- Makes this a very clean experiment for studies of charm decays.
- Most analyses use a tagging technique
  - one of the produced D mesons is fully reconstructed.

$$e^+e^- \to c\bar{c} \to D^0\bar{D}^0$$

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



Analysis Technique



Tag *D* – fully reconstructed

Signal *D*

- Detect muon and make sure it recoiled against neutrino.
  - Extract signal in M^2_{miss} which peaks at 0.
- Slightly different use of tags in different analyses

Data Samples at $\psi(3770)$

- Analyses presented are based on two data samples
  - 56 pb^{-1} recorded Dec '03 - Apr '04
  - 281 pb^{-1} recorded Dec '03 – Apr '05 (include the 56 pb^{-1})
  - We project that we will have 750 pb^{-1} by April 2008.
- We have final results from 281 pb^{-1} for $D^+ \rightarrow \mu^+ \nu_\mu$
- Many other analyses are being finalized
  - Systematics studies need to be done in detail for many analyses

Tag Reconstruction

- Fully reconstructed *D*-tag candidates are built from
  - Charged kaons, good tracks from IP with particle identification
  - Charged pions, good tracks from IP with particle identification
  - π^0 ($\gamma\gamma$)
  - K_s ($\pi^+\pi^-$), no flight significance cut applied.
- To extract yields we typically cut on $\Delta E = E_{\mathrm{Reco}} - E_{\mathrm{beam}}$
  - Cut is mode (and analysis) dependent
- and fit the m_{BC} distribution
- We reconstruct a D^0 tag with ~17% eff. and D^+ tag with ~10% eff.
  - Different analyses use different tag modes.

Hadronic *D*-decays

- Hadronic decays of D mesons are important as they set the branching fraction scale of many B and D decays.
- The PDG '04 is dominated by measurements based on the tagging of a D^* by the presence of a slow pion (CLEO and LEP experiments)
  - D^+ branching fractions are less well known, as a slow π^0 is not a clean tag.
  - Systematics limited.
  - Our systematics are orthogonal.
- As the double tag technique we use determines the number of $D\bar{D}$ pairs we can also calculate the cross-section for D^+D^- and $D^0\bar{D}^0$ production.

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

- In order to measure the cross section and absolute branching fractions we need to determine the number of produced $D\overline{D}$ events
  - Use a 'double tag' technique, pioneered by MARK III

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

$$N_{ii} = \epsilon_{ii} B_i^2 N_{D\overline{D}}$$

$$N_{D\overline{D}} = \frac{N_i^2}{4\mathrm{N}_{ii}} \frac{\epsilon_{ii}}{\epsilon_i^2}$$

- 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.).

Initial State Radiation

- We run at E_{cm}=3.77 GeV to produce the ψ(3770)
  - The spread in E_{cm} is about 2 MeV
  - The width of the ψ(3770) is about 25 MeV
- However, the beam particles can radiate a photon and produce the ψ(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:

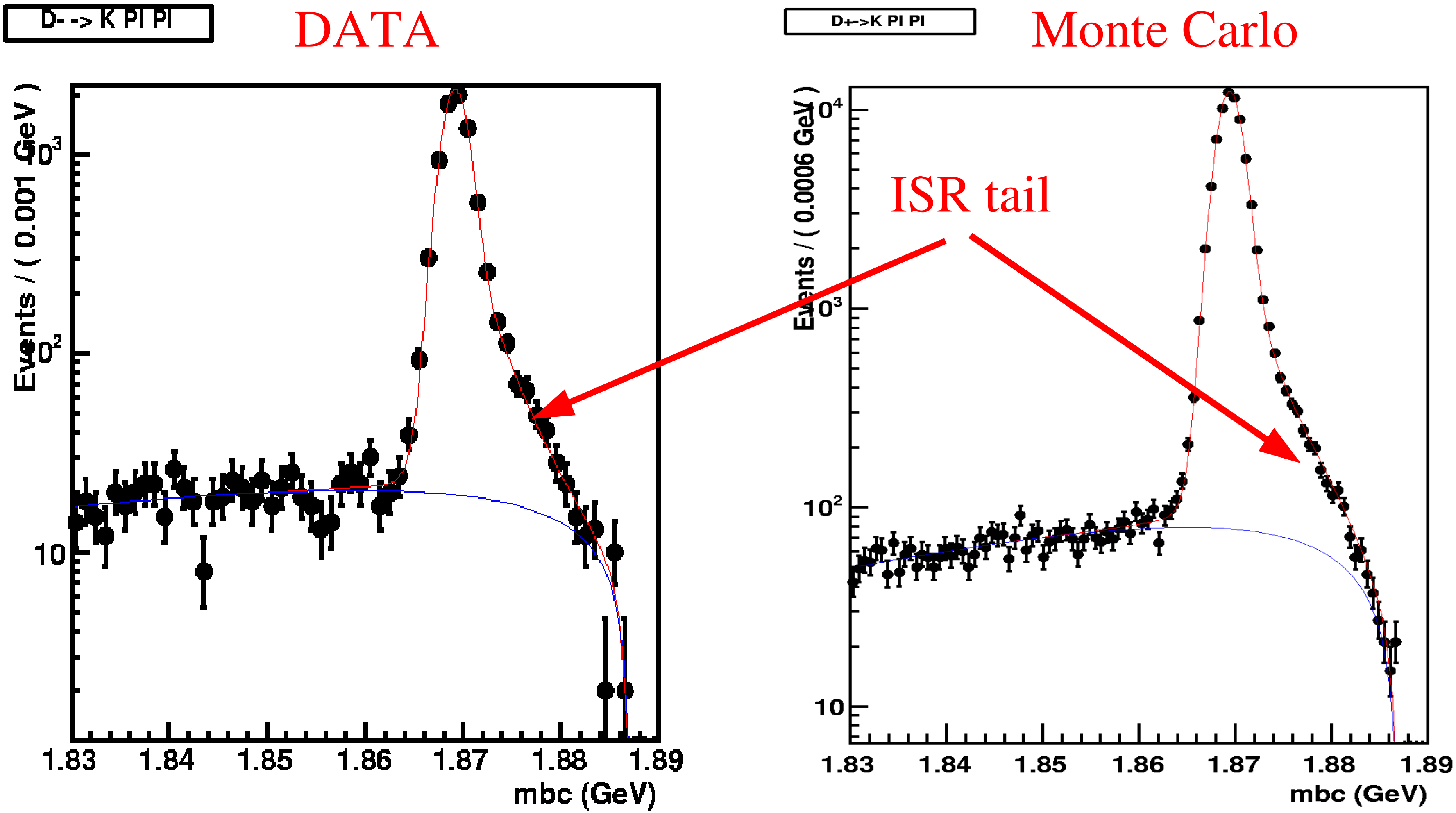
$$f(E_\gamma) \propto E_\gamma^{\beta-1}$$

$$\beta = \frac{2\alpha}{\pi}\left[2\ln\frac{E_{cm}}{m_e} - 1\right] \approx 0.07$$

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

ISR in Data *vs.* MC

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



DATA

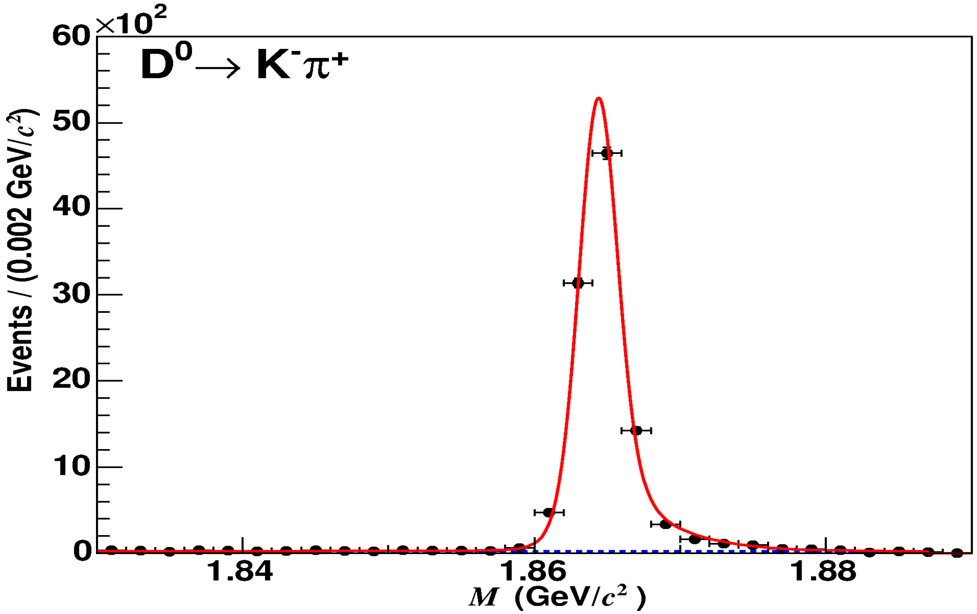
Monte Carlo

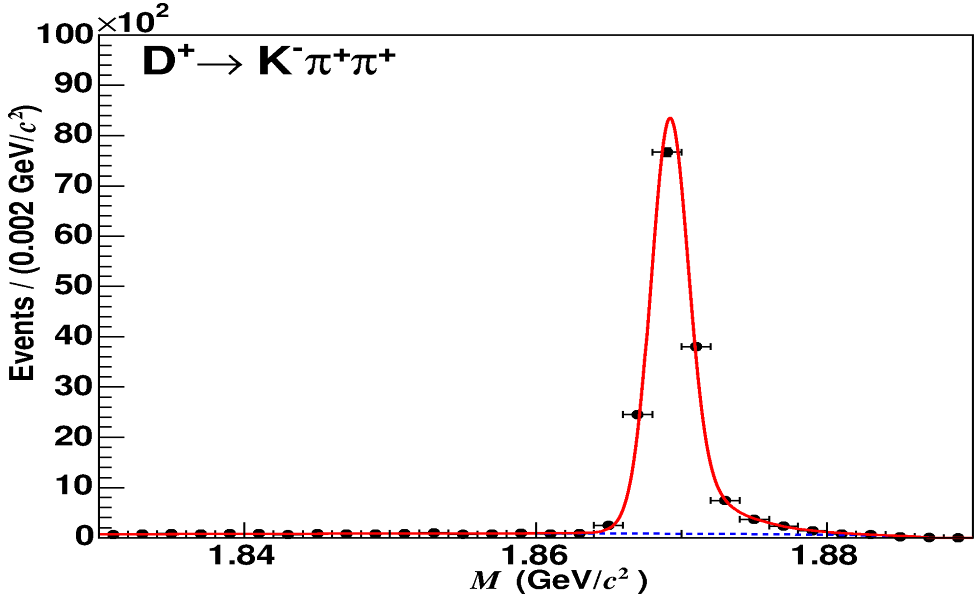
ISR tail

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

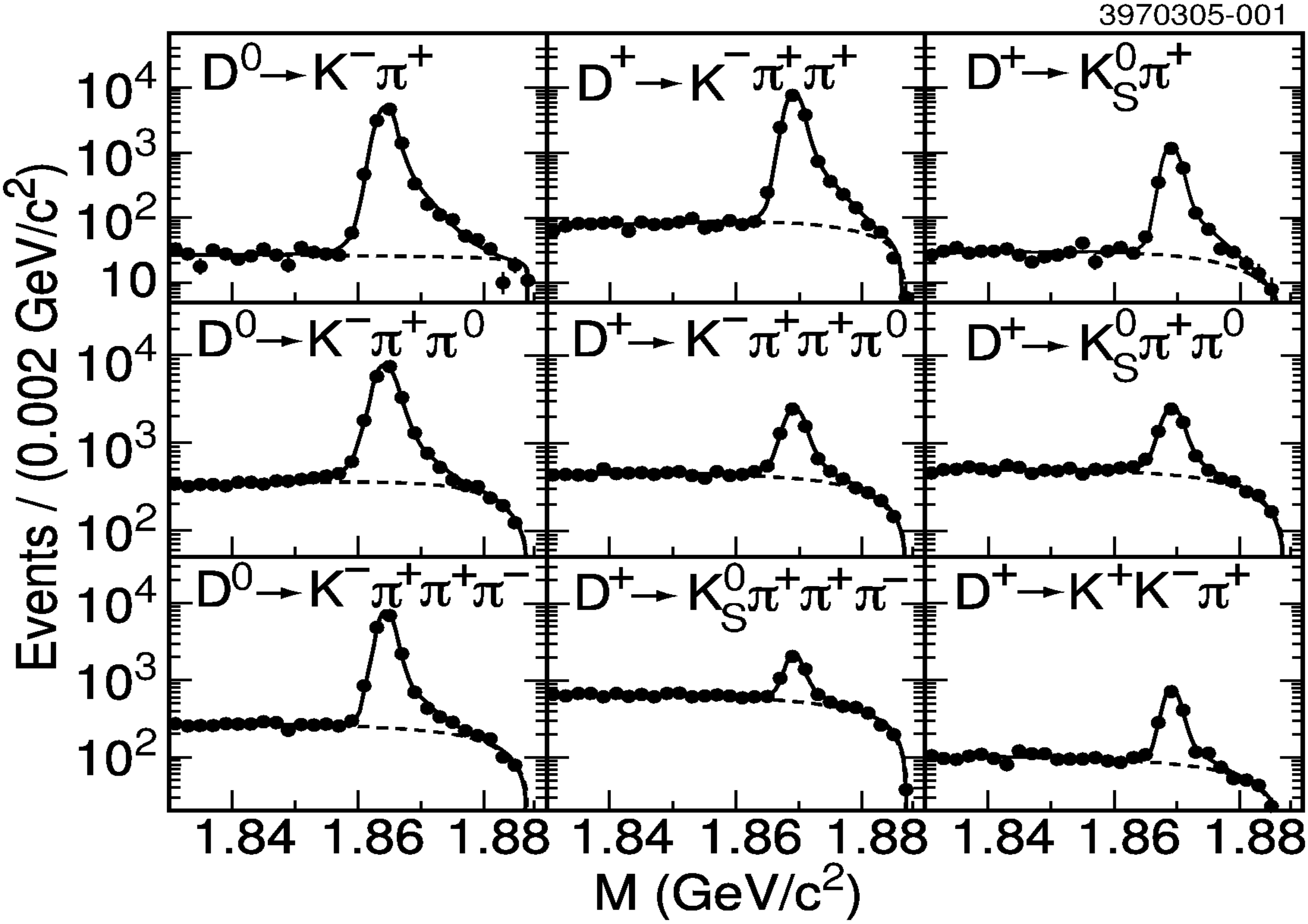
Single Tag Yields (56 pb^{-1})

D or $\bar{D}$ Mode	Yield (10^3)	Efficiency (%)
$D^0 \to K^-\pi^+$	5.11 ± 0.07	64.6 ± 0.3
$\bar{D}^0 \to K^+\pi^-$	5.15 ± 0.07	65.6 ± 0.3
$D^0 \to K^-\pi^+\pi^0$	9.51 ± 0.11	31.4 ± 0.1
$\bar{D}^0 \to K^+\pi^-\pi^0$	9.47 ± 0.11	31.8 ± 0.1
$D^0 \to K^-\pi^+\pi^+\pi^-$	7.44 ± 0.09	43.6 ± 0.2
$\bar{D}^0 \to K^+\pi^-\pi^-\pi^+$	7.43 ± 0.09	43.9 ± 0.2
$D^+ \to K^-\pi^+\pi^+$	7.56 ± 0.09	50.7 ± 0.2
$D^- \to K^+\pi^-\pi^-$	7.56 ± 0.09	51.3 ± 0.2
$D^+ \to K^-\pi^+\pi^+\pi^0$	2.45 ± 0.07	25.7 ± 0.2
$D^- \to K^+\pi^-\pi^-\pi^0$	2.39 ± 0.07	25.7 ± 0.2
$D^+ \to K^0_S\pi^+$	1.10 ± 0.04	45.5 ± 0.4
$D^- \to K^0_S\pi^-$	1.13 ± 0.04	45.9 ± 0.4
$D^+ \to K^0_S\pi^+\pi^0$	2.59 ± 0.07	22.4 ± 0.2
$D^- \to K^0_S\pi^-\pi^0$	2.50 ± 0.07	22.4 ± 0.2
$D^+ \to K^0_S\pi^+\pi^+\pi^-$	1.63 ± 0.06	31.1 ± 0.2
$D^- \to K^0_S\pi^-\pi^-\pi^+$	1.58 ± 0.06	31.3 ± 0.2
$D^+ \to K^+K^-\pi^+$	0.64 ± 0.03	41.4 ± 0.5
$D^- \to K^+K^-\pi^-$	0.61 ± 0.03	40.8 ± 0.5

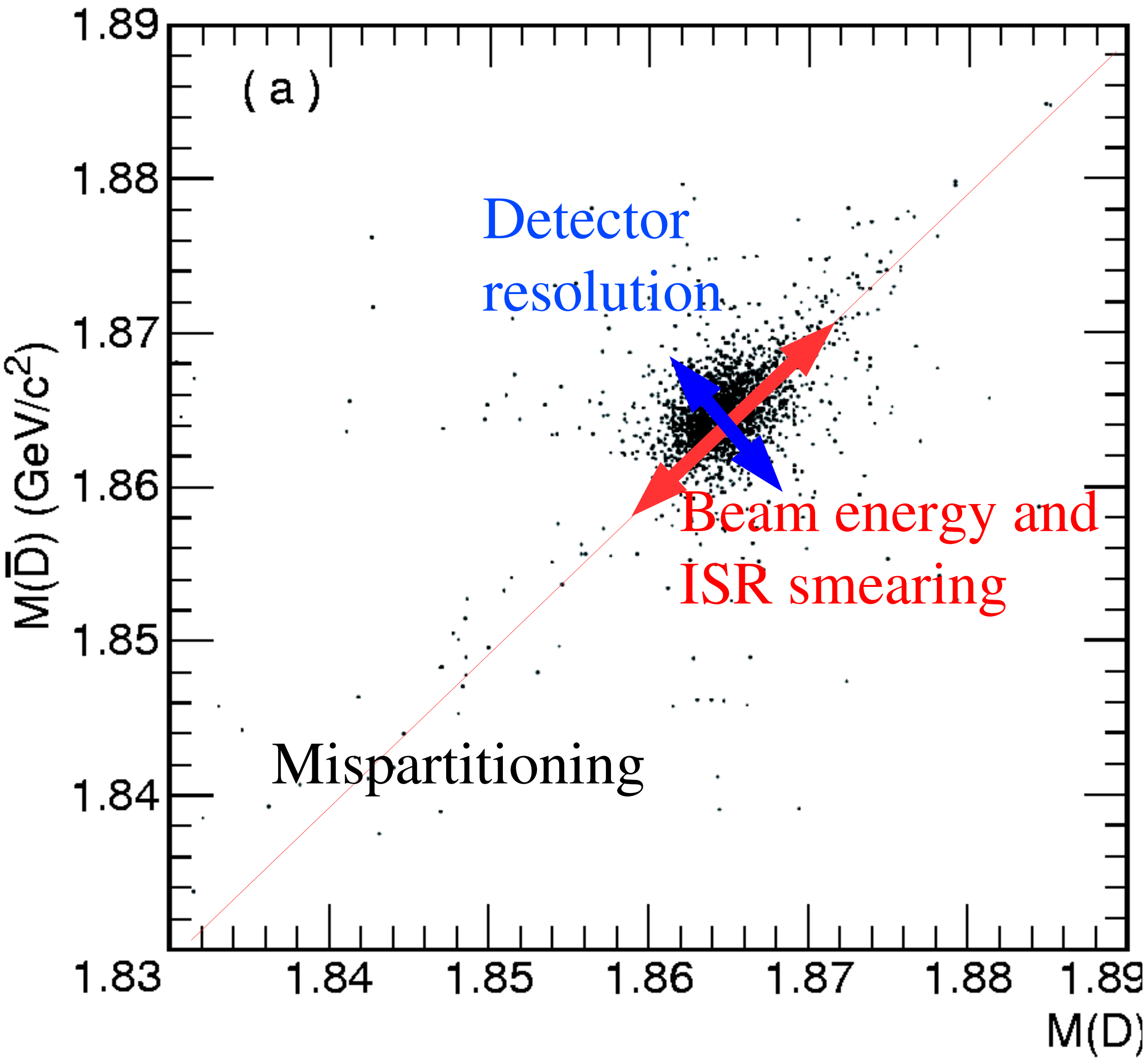




Single Tag Yields (56 pb^{-1})



Double Tag Fits



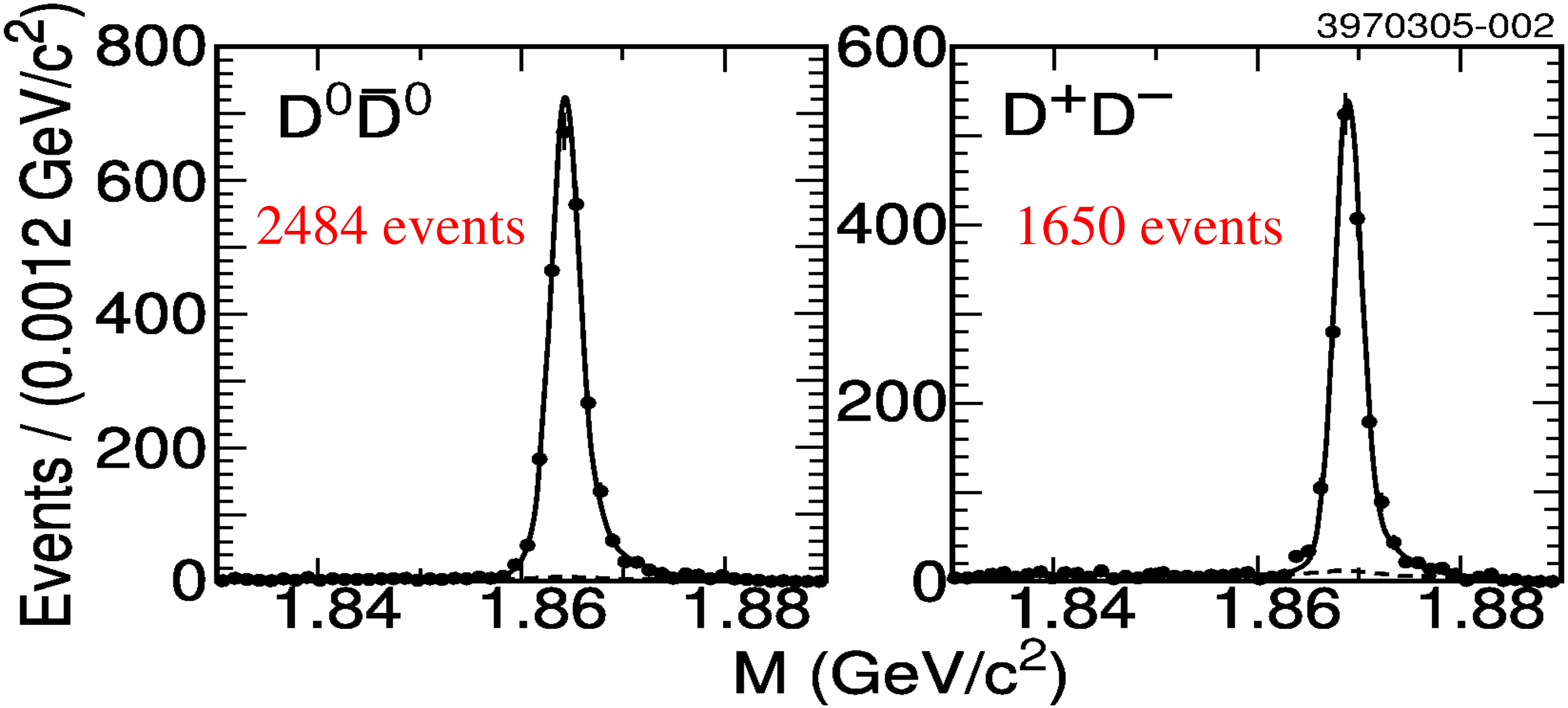
- Beam energy spread and ISR causes a correlated shift in the mass of the two *D*-mesons
- Resolution is uncorrelated among the two *D*-mesons
- A two dimensional fit allow us to separate the effects of beam energy smearing and detector resolution.

MC $\sigma_E = (2.08 \pm 0.01)\,\text{MeV}$

Data $\sigma_E = (2.11 \pm 0.02)\,\text{MeV}$

- MC width comes from machine parameters

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 56 pb^{-1}

Parameter	Fitted Value	Δ_{FSR}	PDG 2004*
$N_{D^0\bar{D}^0}$	$(2.01 \pm 0.04 \pm 0.02) \times 10^5$	-0.2%	
$\mathcal{B}(D^0 \to K^-\pi^+)$	$(3.91 \pm 0.08 \pm 0.09)\%$	-2.0%	$\epsilon=(95.43\pm0.04)\%$
$\mathcal{B}(D^0 \to K^-\pi^+\pi^0)$	$(14.9 \pm 0.3 \pm 0.5)\%$	-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%	$(9.2\pm0.6)\%$
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+\pi^0)$	$(6.0 \pm 0.2 \pm 0.2)\%$	-0.6%	
$\mathcal{B}(D^+ \to K_S^0\pi^+)$	$(1.55 \pm 0.05 \pm 0.06)\%$	-1.8%	
$\mathcal{B}(D^+ \to K_S^0\pi^+\pi^0)$	$(7.2 \pm 0.2 \pm 0.4)\%$	-0.8%	
$\mathcal{B}(D^+ \to K_S^0\pi^+\pi^+\pi^-)$	$(3.2 \pm 0.1 \pm 0.2)\%$	-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, PDG values are not

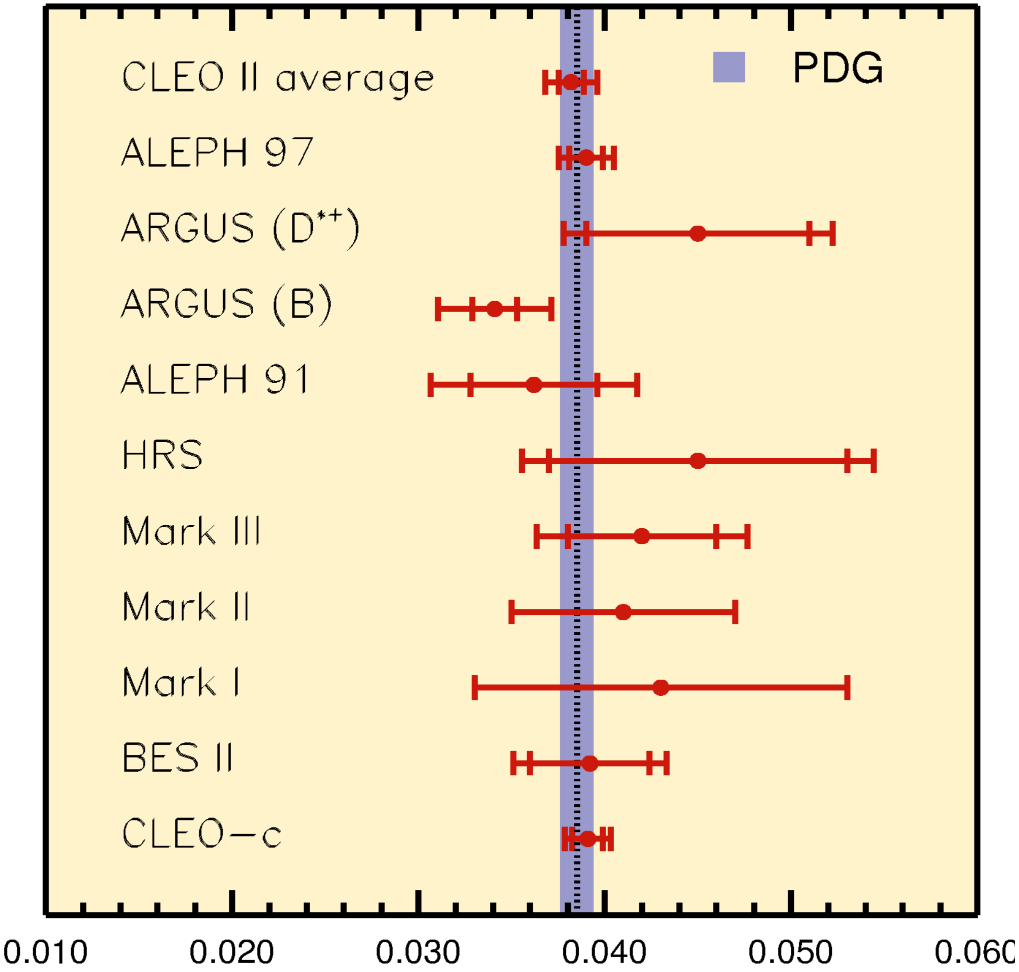
Using our measured luminosity of $55.8\pm0.6\ \mathrm{pb}^{-1}$ we obtain:

$\sigma(D^0\bar{D}^0)=(3.60\pm0.07\pm0.07)\,\mathrm{nb}$ $\sigma(D^+D^-)=(2.79\pm0.07\pm0.10)\,\mathrm{nb}$

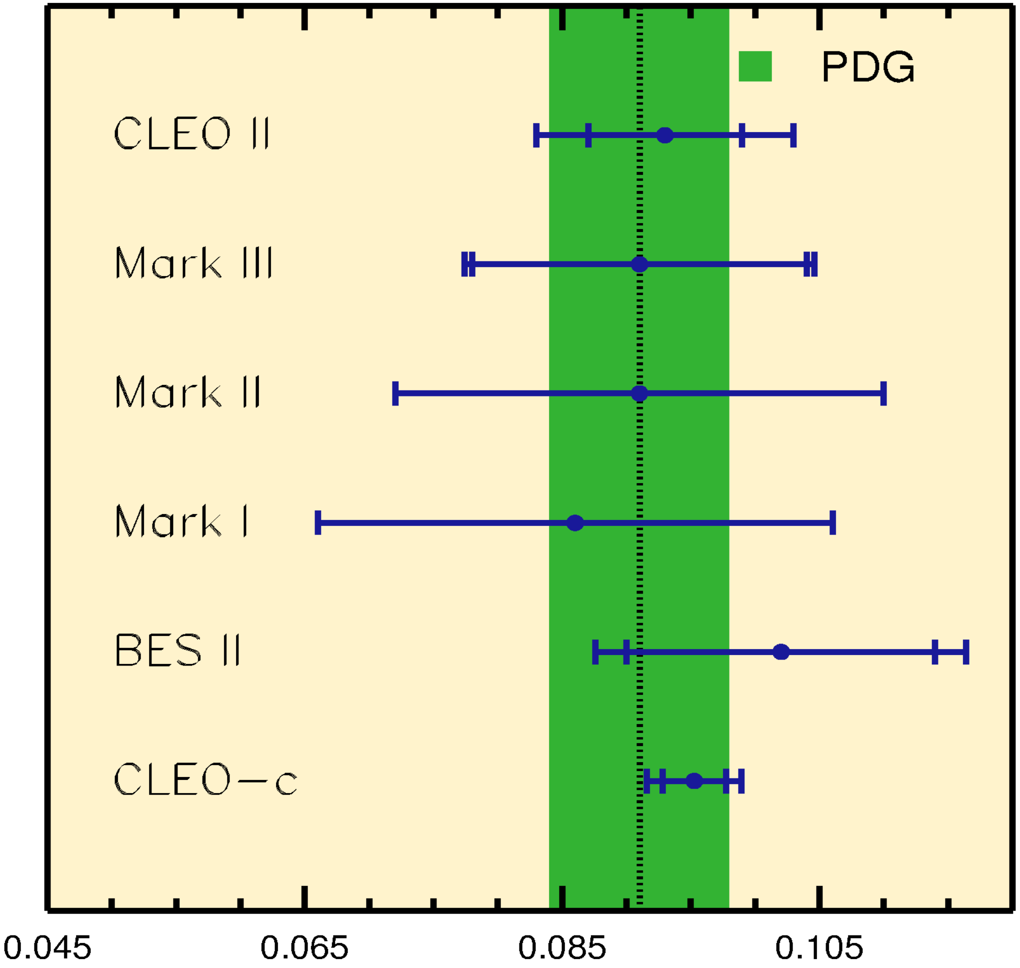
$\sigma(D\bar{D})=(6.39\pm0.10\pm0.17)\,\mathrm{nb}$

Comparison with Other Exp.

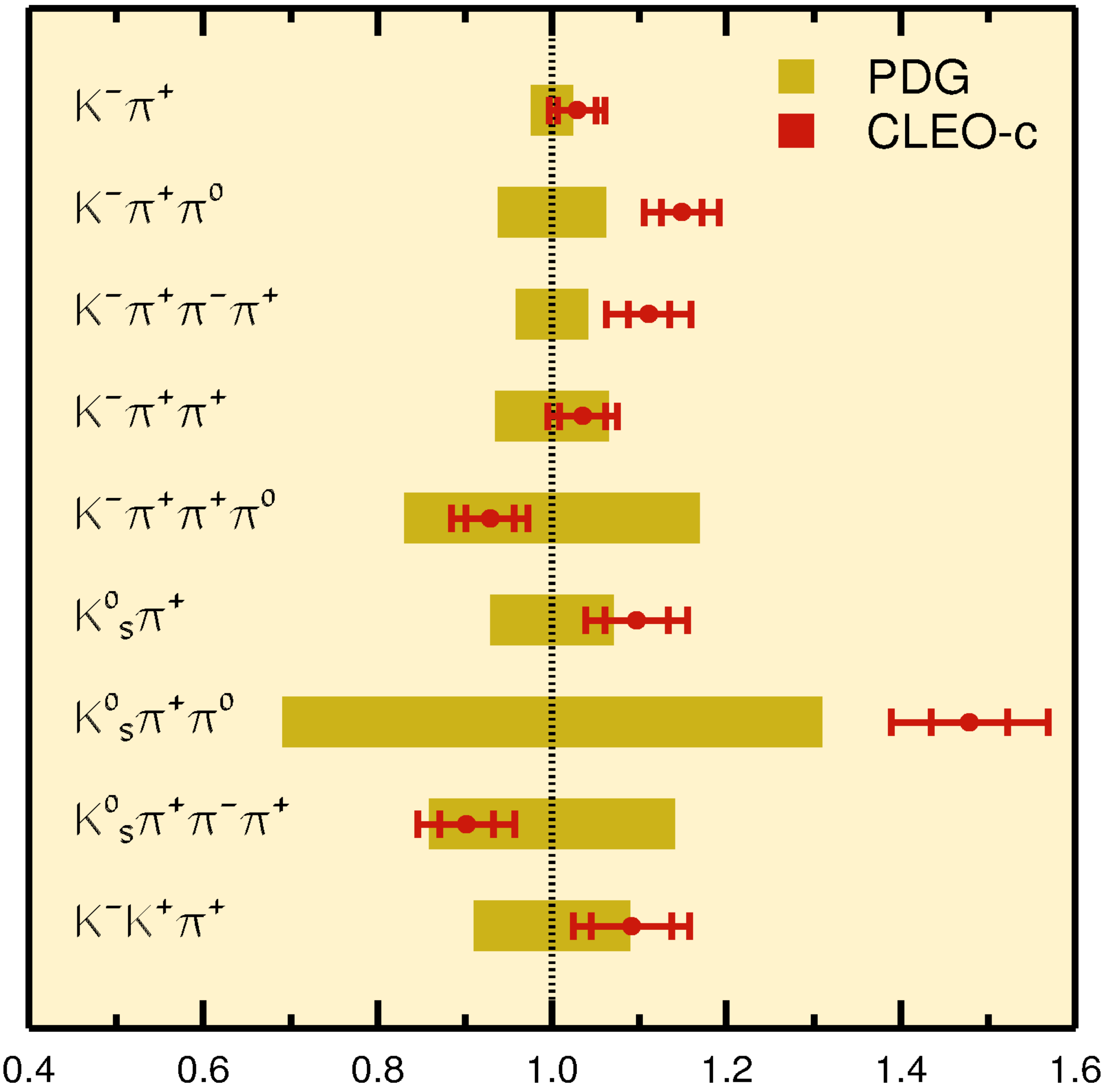
$Br(D^0 \to K^- \pi^+)$



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

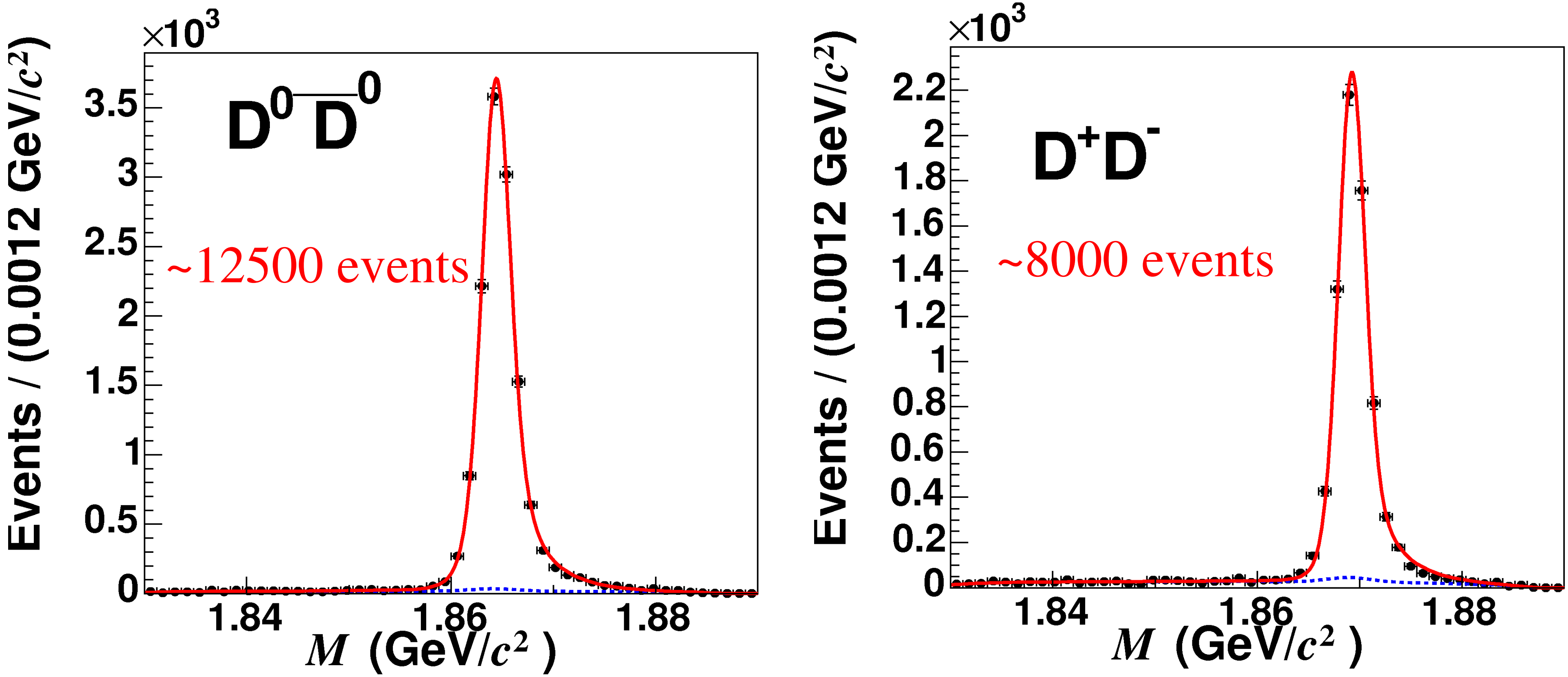


Comparison to PDG



Projections

- These results were based on 56 pb^{-1} (PRL 95, 121801 (2005))
- We are now analyzing the 281 pb^{-1} sample



- Statistical uncertainties about 1% in the 281 pb^{-1} sample!

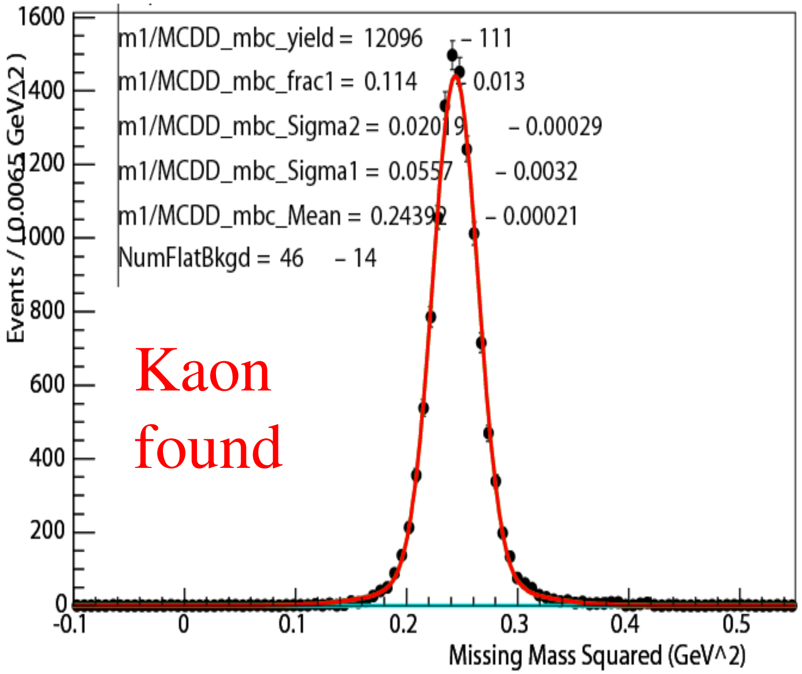
$D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ Systematics

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%

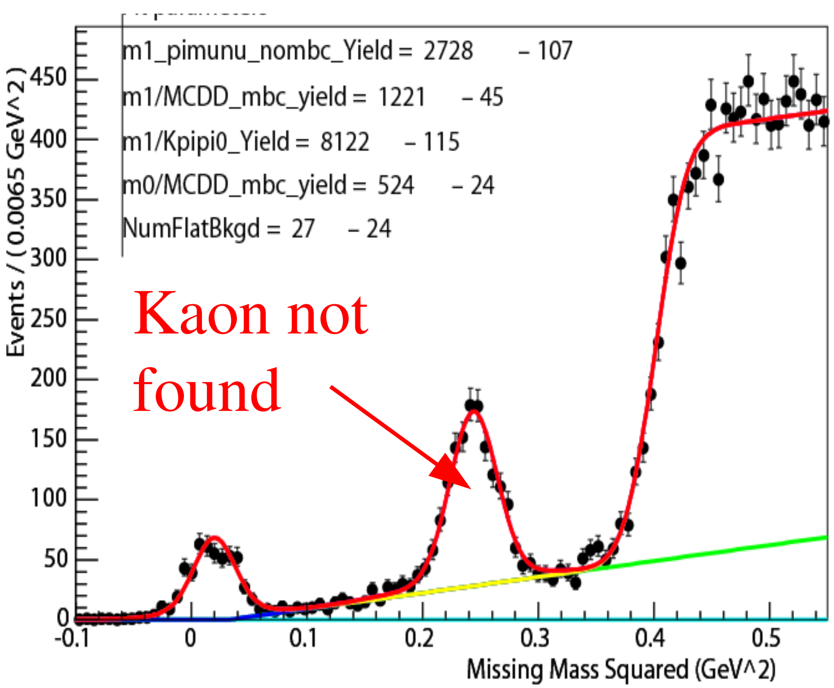
- Systematics limited at 281 pb^{-1}
  - Some systematics should improve with additional statistics

Tracking Efficiencies

- Events that can be fully reconstructed can be used for very clean studies of tracking efficiencies.
- We have used *DD* events and ψ(2S)→*J*/ψ $\pi^+\pi^-$ events
- Look at recoil mass against D^0-tag and pion – see how often kaon is found
  - In data we find ε=(90.8±0.4)%



Kaon found

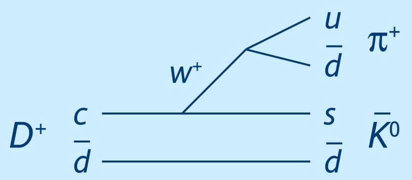


Kaon not found

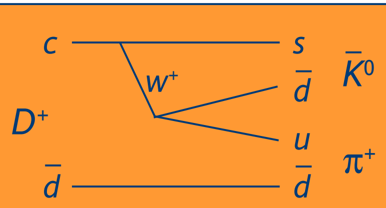
Other Hadronic Modes

- There are many analyses underway that involves hadronic *D*-decays
- Dalitz plot and quantum correlation analyses are discussed in talk by D. Asner
- I will briefly discuss two other analyses
  - $D^+ \to K_{L,S}\pi^+$ where we have interference from Cabibbo allowed and suppressed amplitudes.
  - Cabibbo suppressed decays to pions.

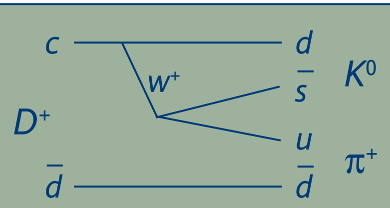
$D^+\to K_{L,S}\pi^+$



Cabibbo-favored



Color-suppressed



DCS and color-suppressed

Interfere destructively
(Long D^+ lifetime)

$$f(E_\gamma)\propto E_\gamma^{\beta-1}$$

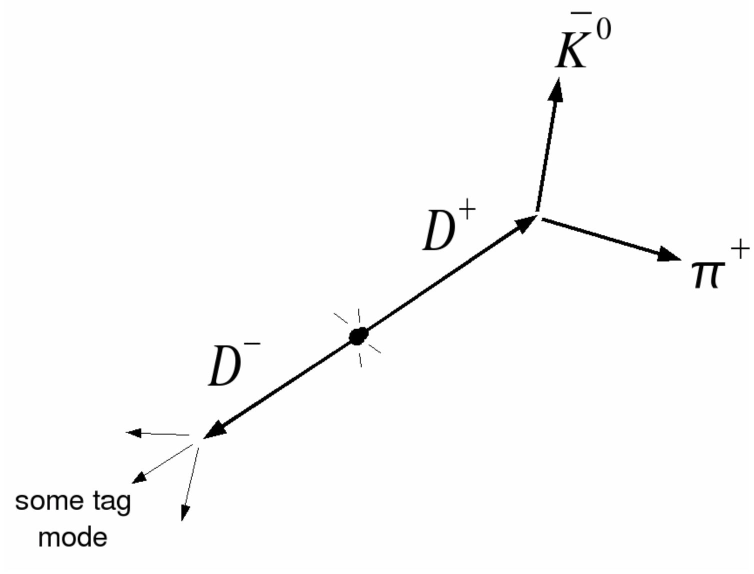
$$K^0=\frac{1}{\sqrt{2}}(K_S^0+K_L^0)$$

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

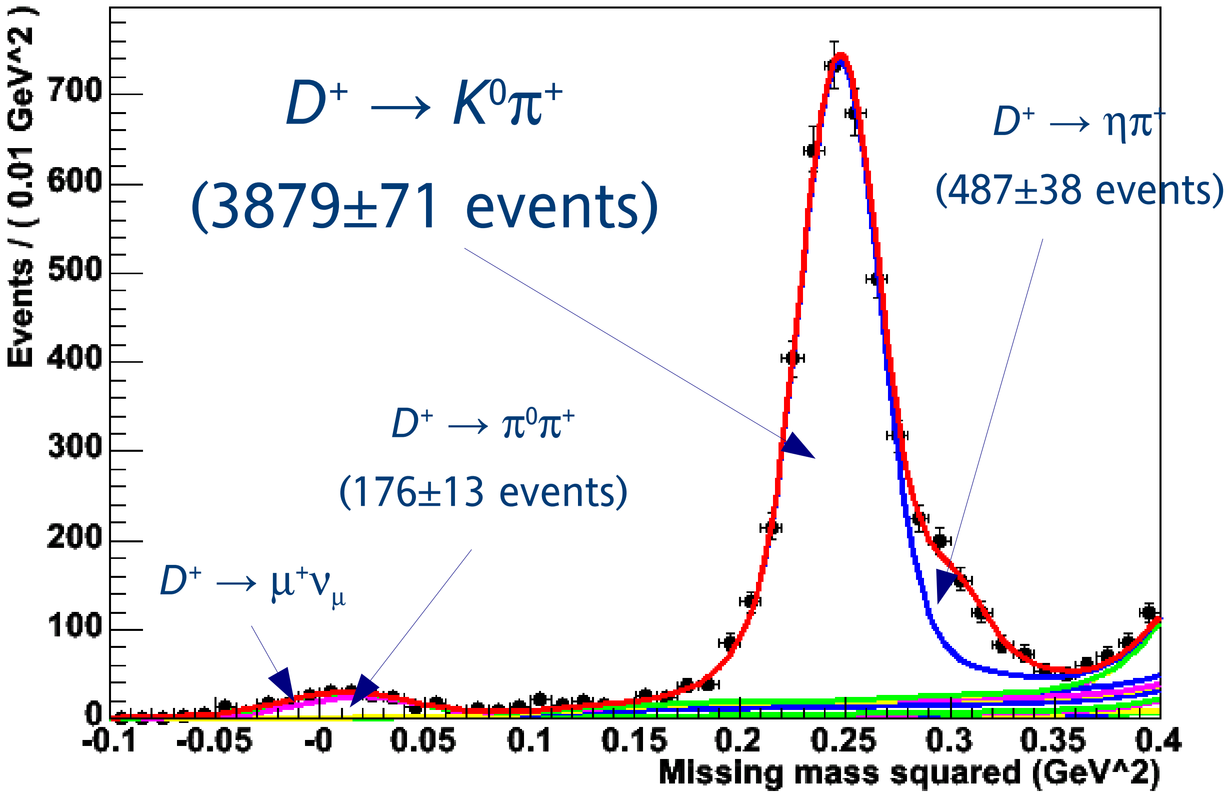
$$\frac{\Gamma(D^+\to K_L)-\Gamma(D^+\to K_S)}{\Gamma(D^+\to K_L)+\Gamma(D^+\to K_S)}\approx 10\,\%$$

Preliminary Results



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

281 fb^{-1}

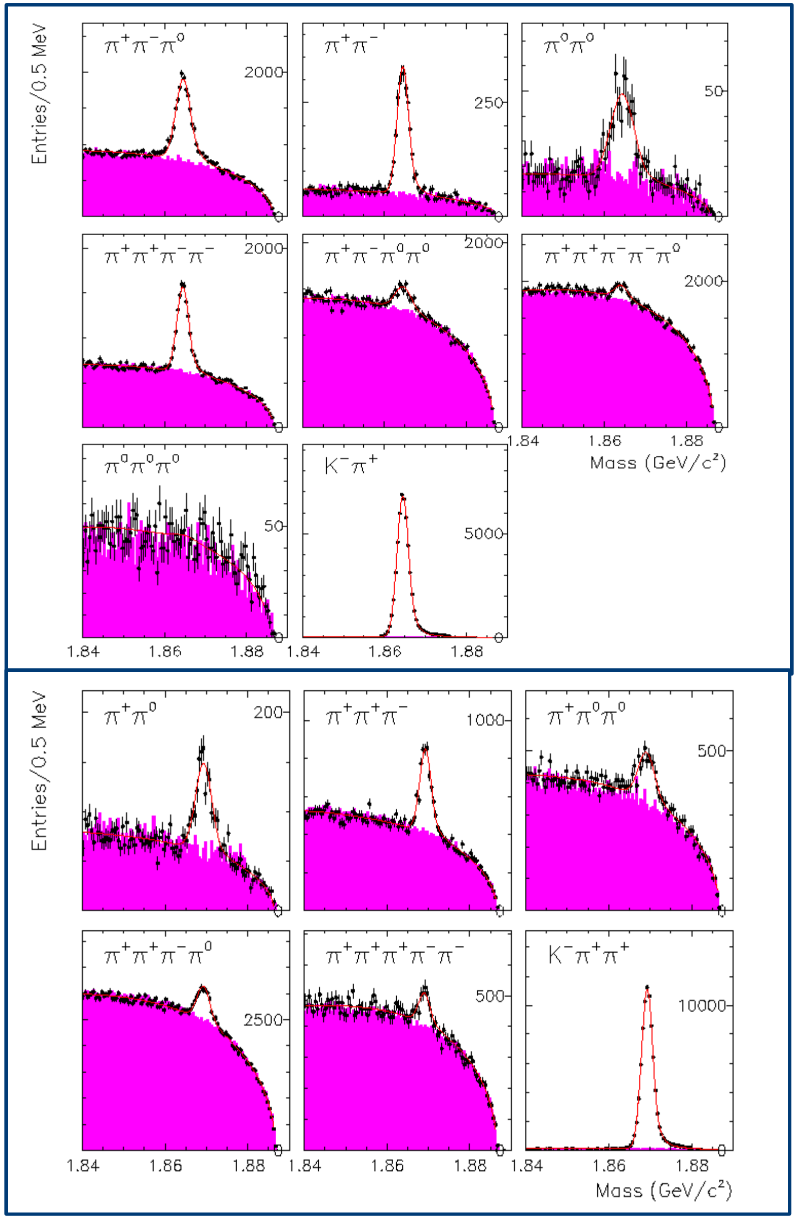


- $\mathcal{B}(D^+ \rightarrow K^0_S\pi^+) + \mathcal{B}(D^+ \rightarrow K^0_L\pi^+) = (3.06 \pm 0.06 \pm 0.16)\%$
- Asymmetry = $(K^0_L - K^0_S)/(K^0_L + K^0_S) = -0.01 \pm 0.04 \pm 0.07$
  - Consistent with 10% prediction.
- $\mathcal{B}(D^+ \rightarrow \eta\pi^+) = (0.39 \pm 0.03 \pm 0.03)\%$ [PDG2004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

$D\rightarrow n(\pi^{\pm})m(\pi^{0})$ (Preliminary)

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

Mode	$\mathcal{B}$ (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	---

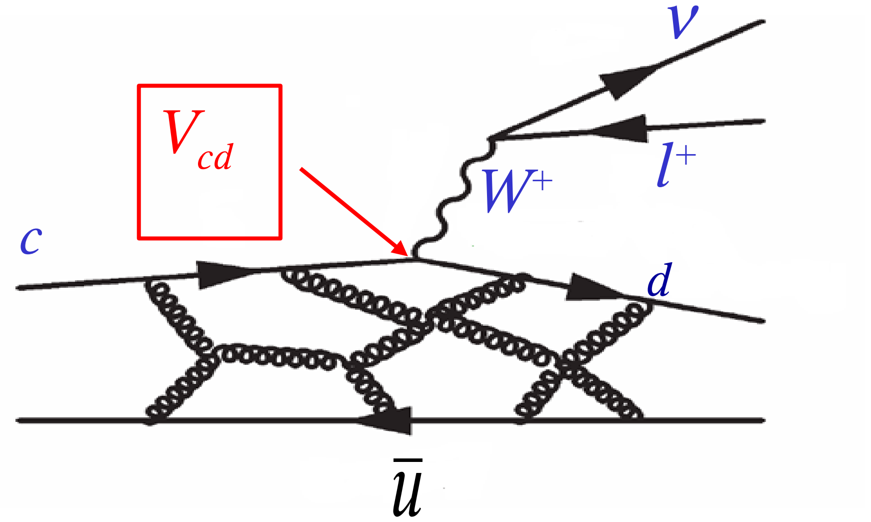


Summary of Hadronic Decays

- We understand how to do analyses based on *D*-tags.
  - We have tuned up the detector simulation to have good data-MC agreement to allow precision measurements.
- The reference modes $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ are measured at the (1.5 to 2.0)% level in 281 pb^{-1}
  - Systematics dominated – some improvements still possible, but hard to predict how much the systematics can be reduced.
- The extremely clean environment allows us to study basically all *D*-decays – we should dominate practically all entries in the PDG!

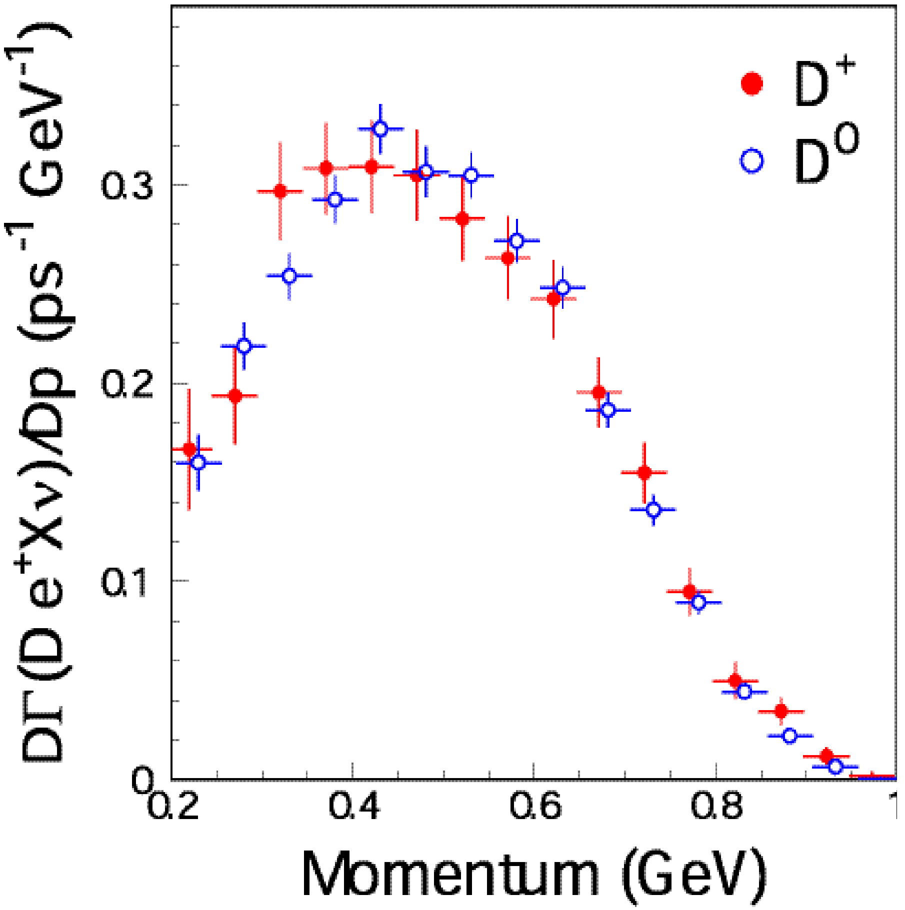
Semileptonic Decays

- Semileptonic decays are easier to describe theoretically
  - 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 will measure
  - 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.



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

$$Br(D^0 \to X e \nu_e) = (6.45 \pm 0.17 \pm 0.15)\%$$

$$Br(D^+ \to X e \nu_e) = (16.19 \pm 0.20 \pm 0.36)\%$$

- Using the measured lifetimes we obtain

$$\frac{\Gamma(D^+ \to X e \nu_e)}{\Gamma(D^0 \to X e \nu_e)} = (1.01 \pm 0.03 \pm 0.03)$$

- The sum of exclusive final state

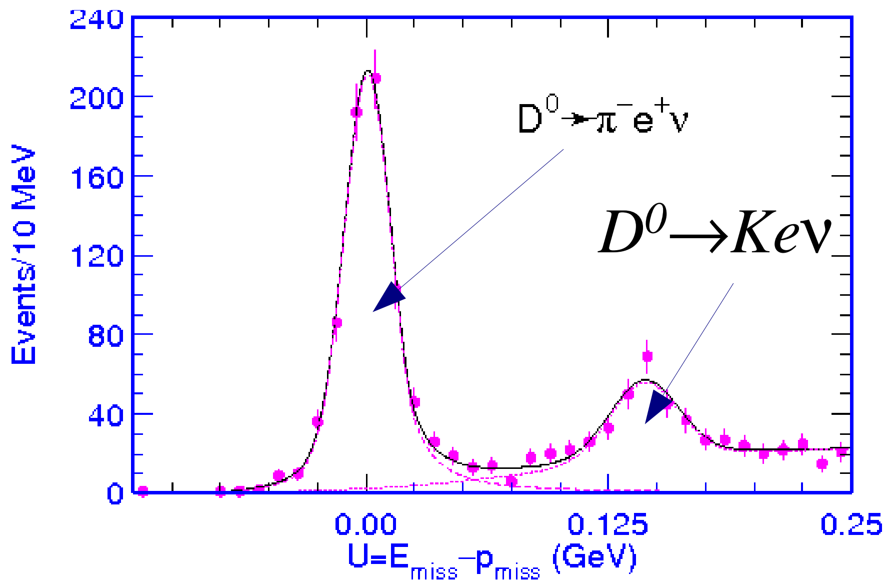
$$\sum_i Br(D^0 \to X_i e \nu_e) = (6.1 \pm 0.2 \pm 0.2)\%$$

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

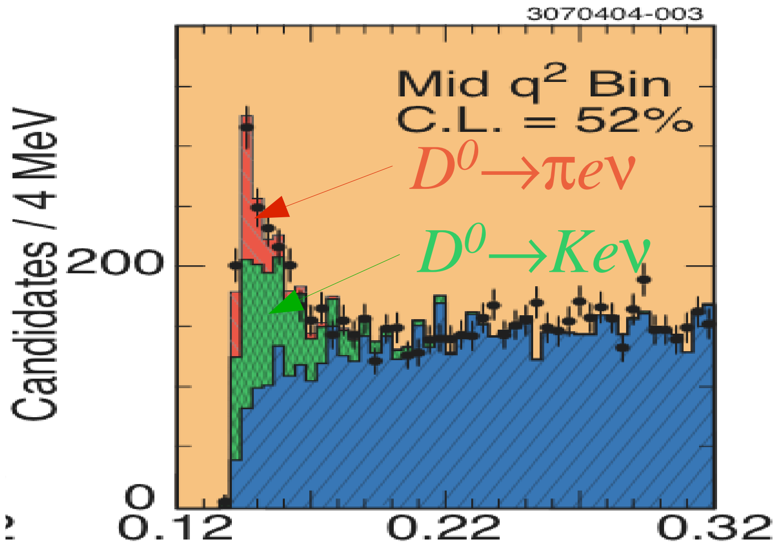
Exclusive Branching Fractions

- 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 $U=E_{\mathrm{miss}}-|P_{\mathrm{miss}}|$
- For the signal events, with one missing neutrino *U* peaks at zero
- $D\to Ke\nu$ and $D\to\pi e\nu$ are kinematically separated

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



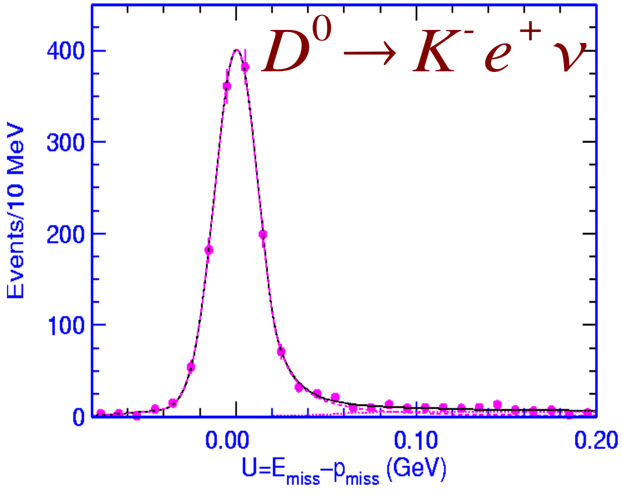
CLEO-III 7 fb^{-1} (PRL 94:011802, 2005)

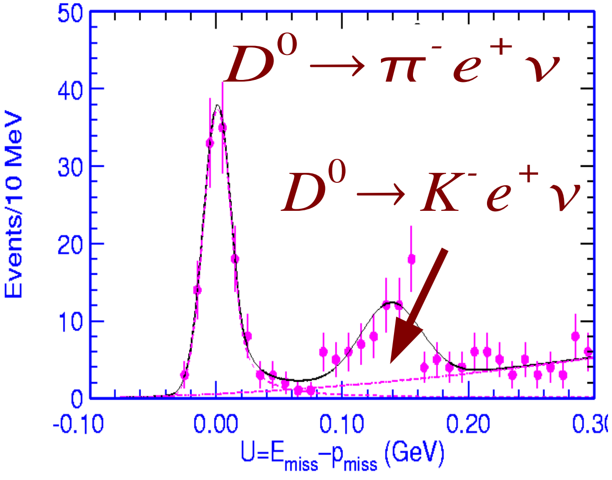


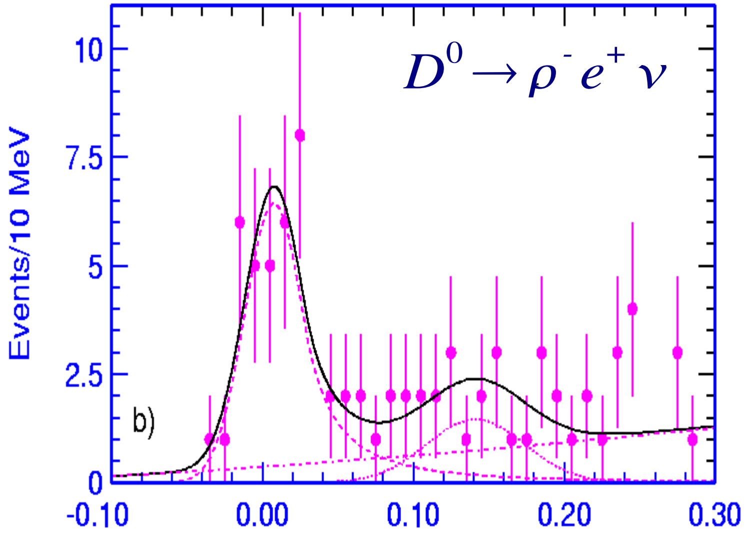
Semileptonic D^0-decays in 56 pb^{-1}

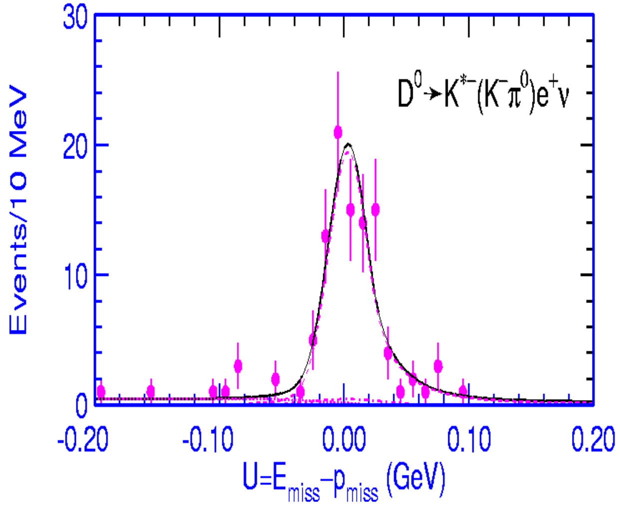
PRL 95, 181802, 2005

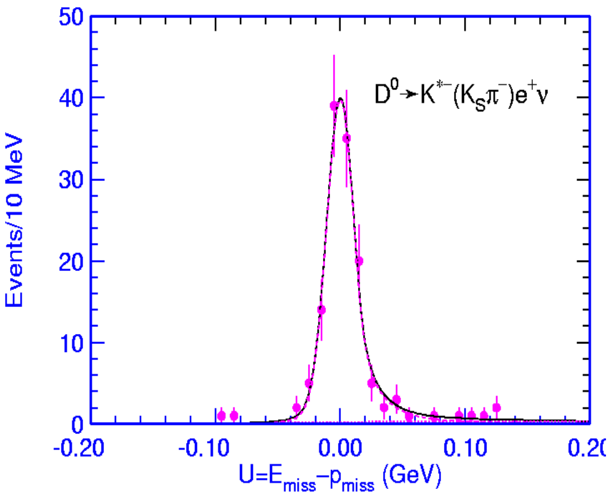
First observation





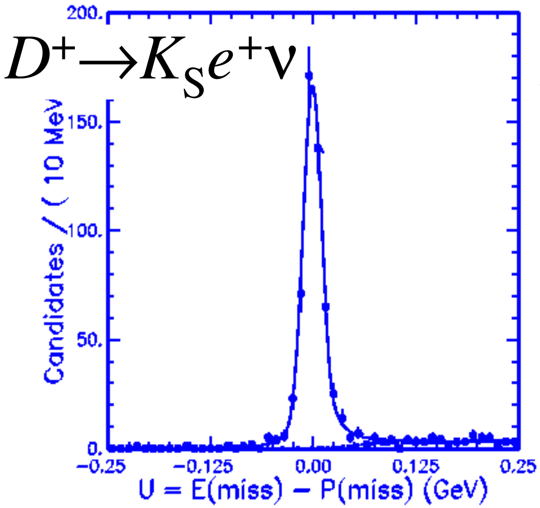




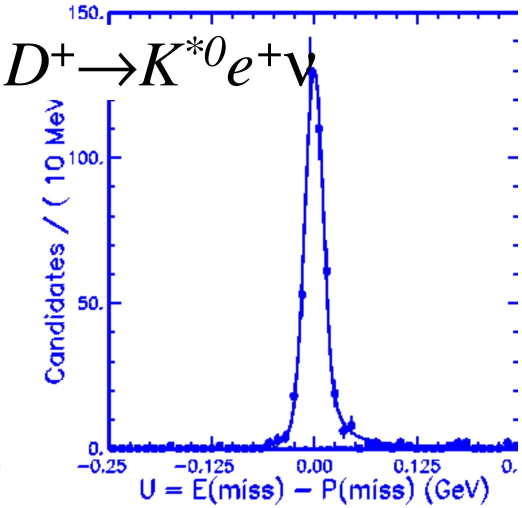


Semileptonic D^+-decays in 56 pb^{-1}

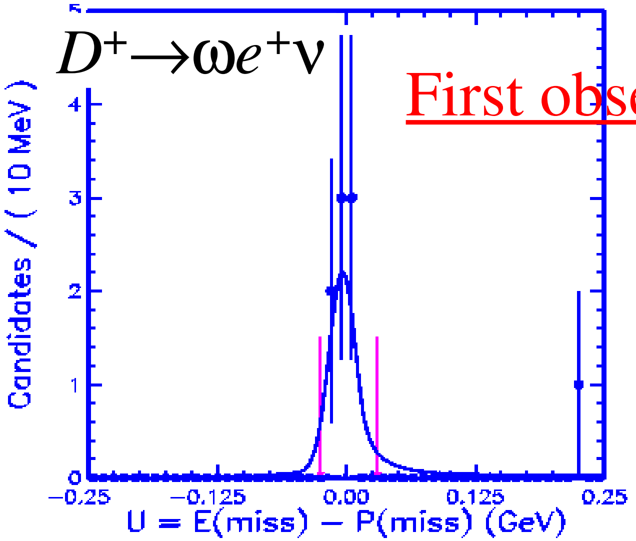
PRL 95, 181801, 2005



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

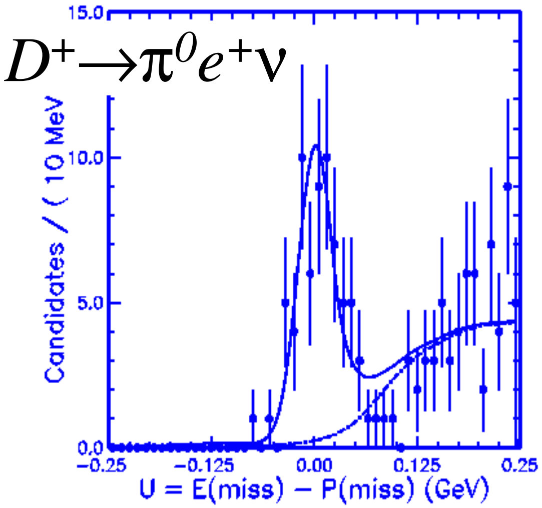


$D^+ \to K^{*0} e^+ \nu$

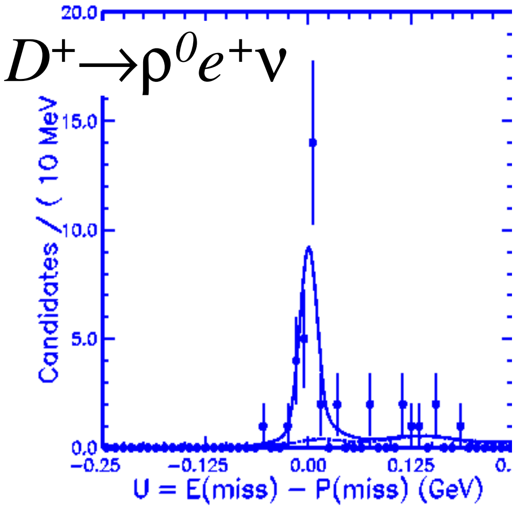


$D^+ \to \omega e^+ \nu$

First observation



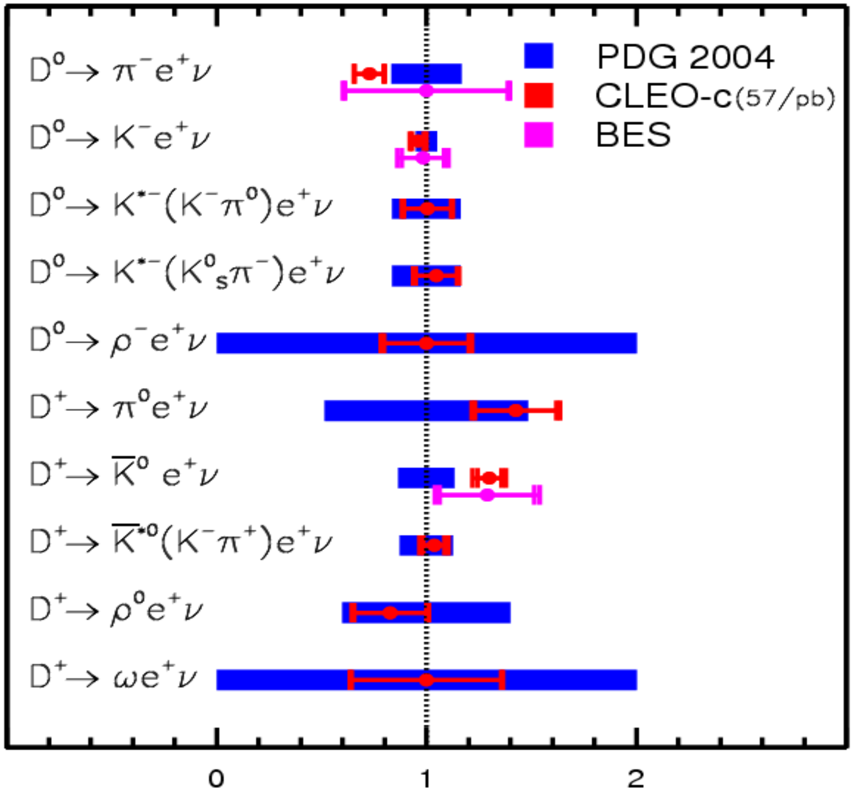
$D^+ \to \pi^0 e^+ \nu$



$D^+ \to \rho^0 e^+ \nu$

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

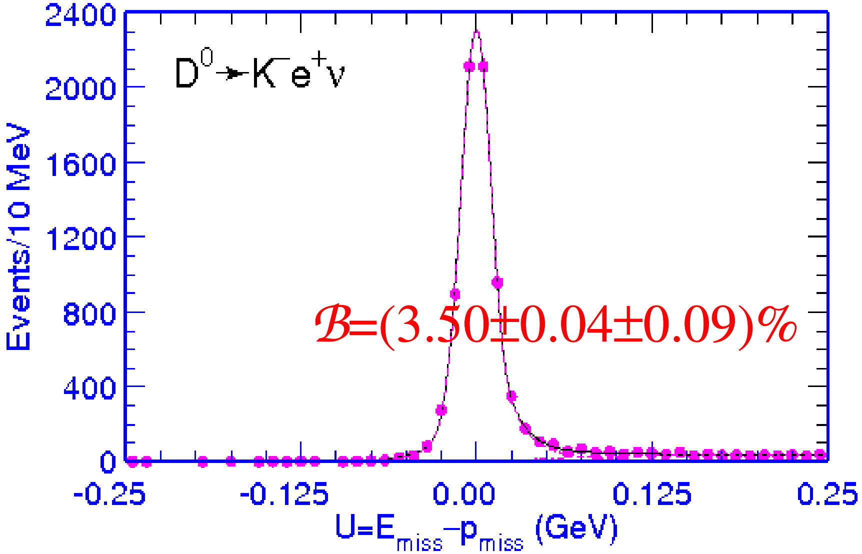
Mode	$\mathcal{B}$ (%)	$\mathcal{B}$ (%) (PDG)
$D^0 \to \pi^- e^+ \nu_e$	$0.26 \pm 0.03 \pm 0.01$	0.36 ± 0.06
$D^0 \to K^- e^+ \nu_e$	$3.44 \pm 0.10 \pm 0.10$	3.58 ± 0.18
$D^0 \to K^{*-}(K^- \pi^0) e^+ \nu_e$	$2.11 \pm 0.23 \pm 0.10$	2.15 ± 0.35
$D^0 \to K^{*-}(\bar{K}^0 \pi^-) e^+ \nu_e$	$2.19 \pm 0.20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



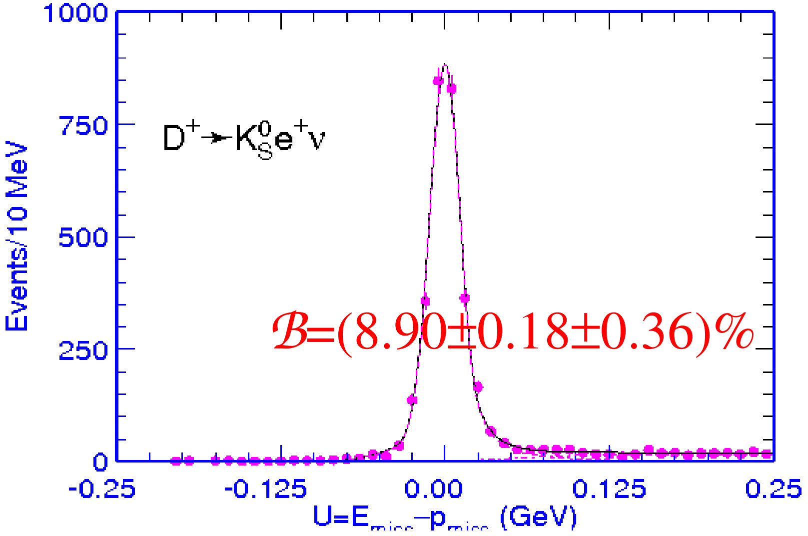
- Most modes are improvements over the PDG
  - Including two first observations
  - $D^0 \to \rho^- e^+ \nu_e$ and $D^+ \to \omega e^+ \nu_e$
- Most systematics can be reduced with more data
- Updating analysis to 281 pb^{-1}

Exclusive Signals (281 pb^{-1})

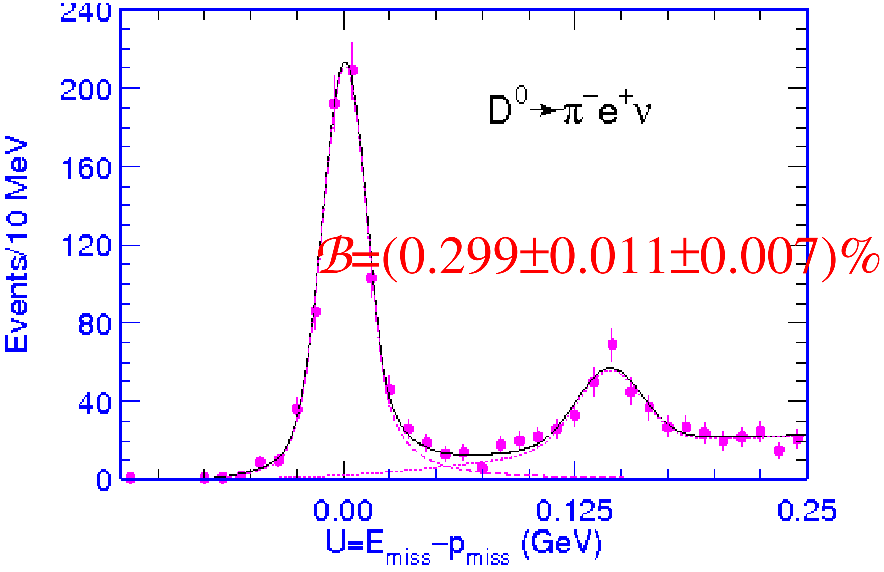
Preliminary



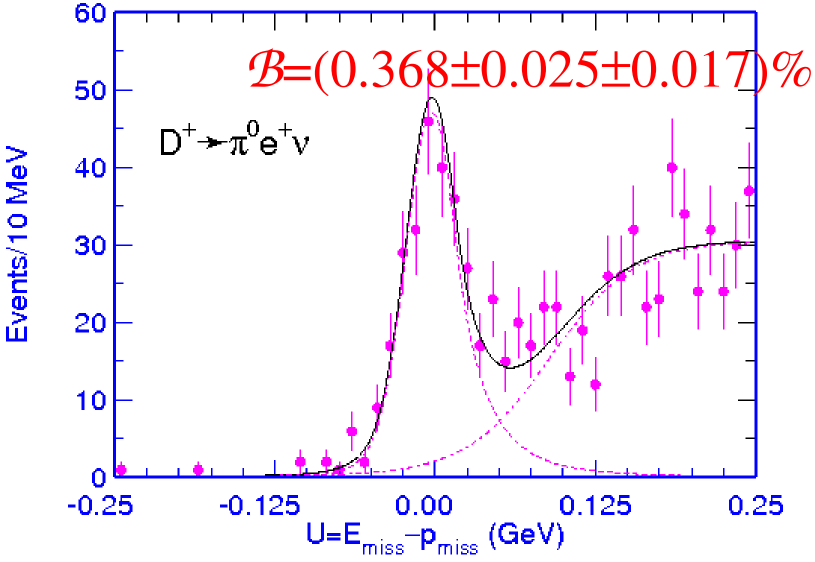
$\mathcal{B}=(3.50\pm0.04\pm0.09)\%$



$\mathcal{B}=(8.90\pm0.18\pm0.36)\%$



$\mathcal{B}=(0.299\pm0.011\pm0.007)\%$



$\mathcal{B}=(0.368\pm0.025\pm0.017)\%$

V_{cd} and V_{cs} Determination (281 pb^{-1})

Using LQCD (PRL 94, 011601 (2005))

- $f_+^K(0) = 0.73 \pm 0.03 \pm 0.07$ and $f_+^\pi(0) = 0.64 \pm 0.03 \pm 0.06$

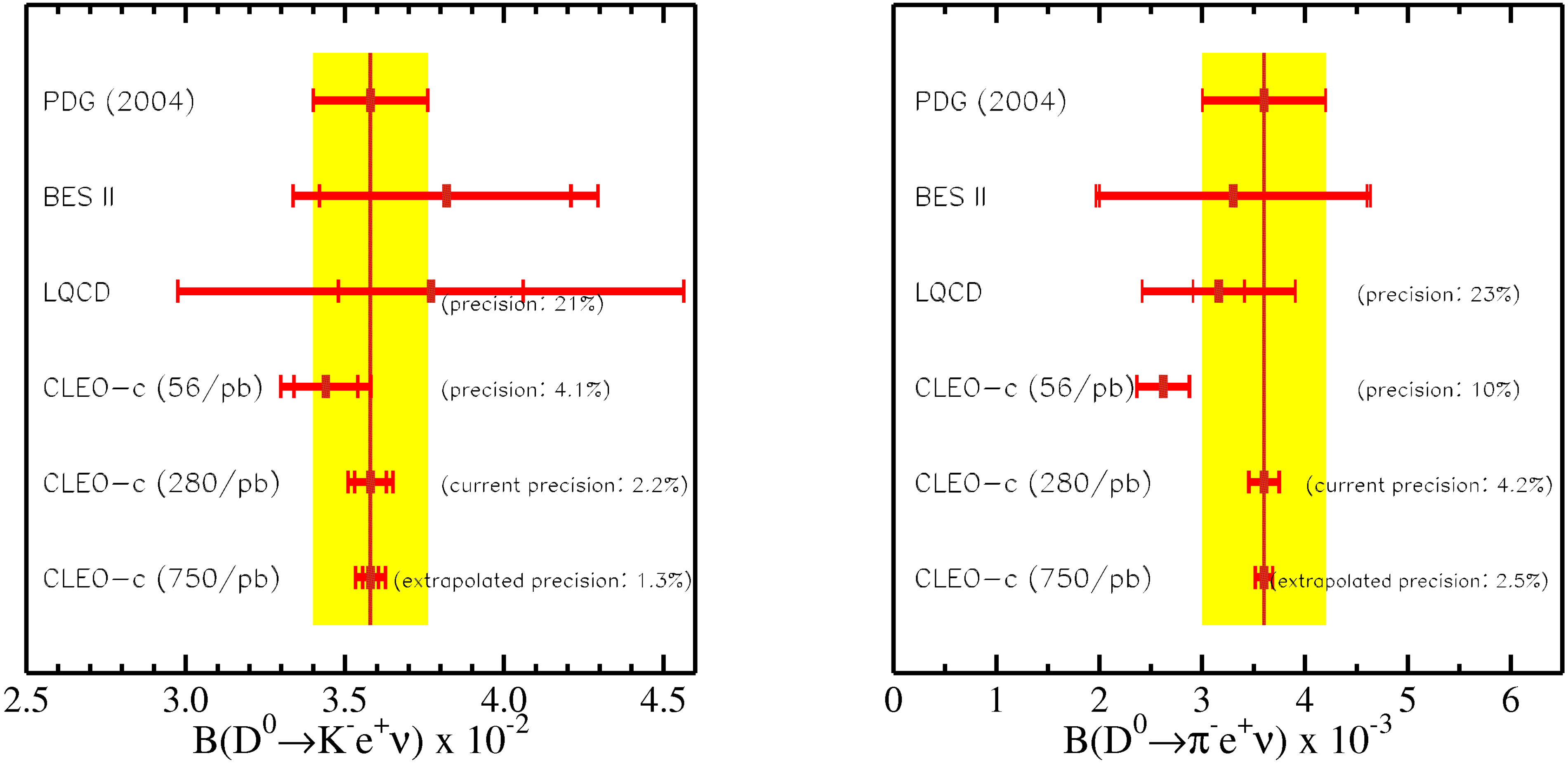
We obtain

- $D^0 \to K^- e^+ \nu$ $|V_{cs}|=0.977 \pm 0.102(\mathrm{LQCD}) \pm 0.009(\alpha) \pm 0.011(\mathcal{B})$
- $D^+ \to K_S e^+ \nu$ $|V_{cs}|=0.975 \pm 0.102(\mathrm{LQCD}) \pm 0.009(\alpha) \pm 0.015(\mathcal{B})$
- $D^0 \to \pi^- e^+ \nu$ $|V_{cd}|=0.227 \pm 0.024(\mathrm{LQCD}) \pm 0.006(\alpha) \pm 0.005(\mathcal{B})$
- $D^+ \to \pi^0 e^+ \nu$ $|V_{cd}|=0.221 \pm 0.023(\mathrm{LQCD}) \pm 0.006(\alpha) \pm 0.009(\mathcal{B})$

Or using $|V_{cs}|=0.976 \pm 0.014$ and $|V_{cd}|=|V_{us}|=0.2252 \pm 0.0008 \pm 0.0021$

- $D^0 \to K^- e^+ \nu$ $f_+^K(0)=0.731 \pm 0.006(\alpha) \pm 0.010(\mathcal{B}) \pm 0.010(V_{cs})$
- $D^+ \to K_S e^+ \nu$ $f_+^K(0)=0.729 \pm 0.006(\alpha) \pm 0.011(\mathcal{B}) \pm 0.010(V_{cs})$
- $D^0 \to \pi^- e^+ \nu$ $f_+^\pi(0)=0.645 \pm 0.017(\alpha) \pm 0.014(\mathcal{B}) \pm 0.006(V_{us})$
- $D^+ \to \pi^0 e^+ \nu$ $f_+^\pi(0)=0.629 \pm 0.017(\alpha) \pm 0.026(\mathcal{B}) \pm 0.006(V_{us})$

Projections



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

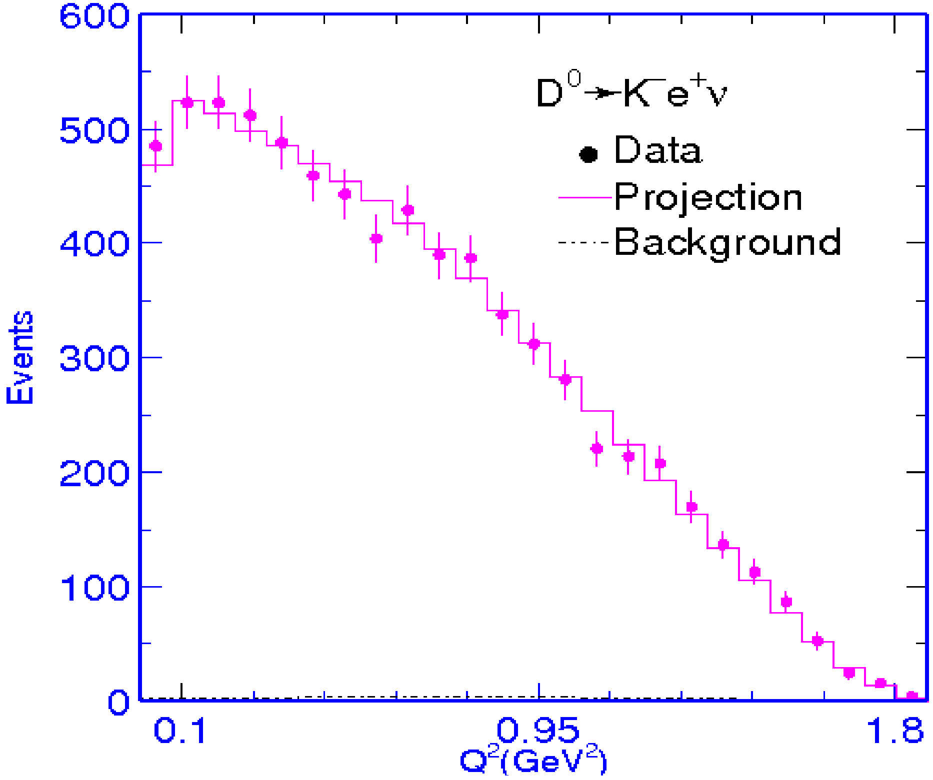
- The differential decay rate is given by

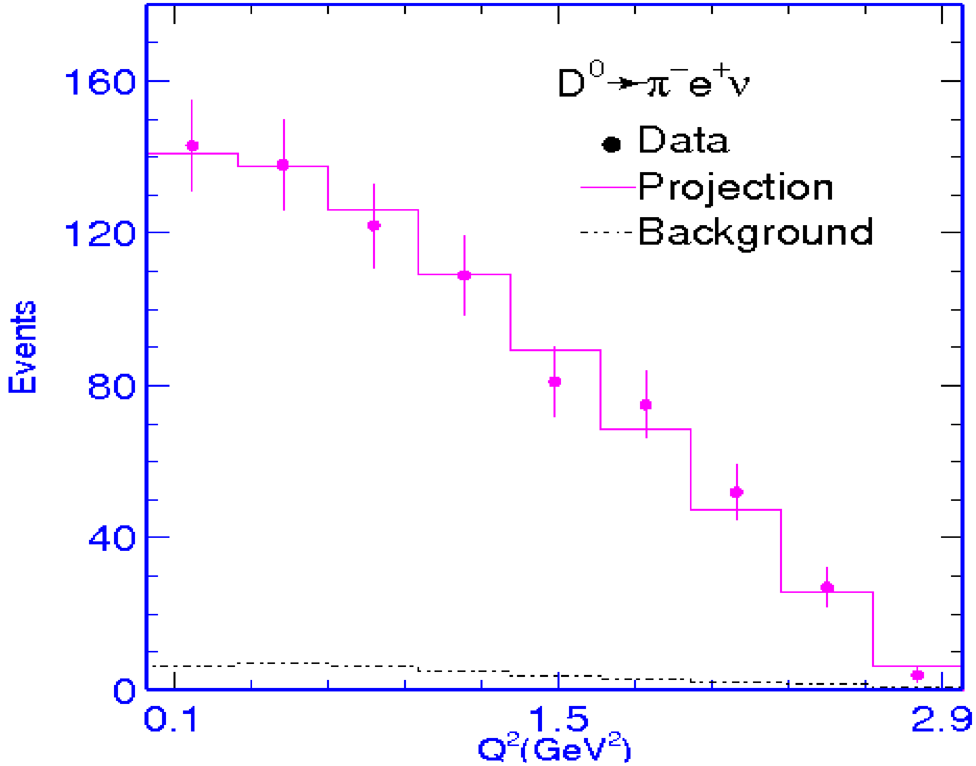
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cq}|^2 p_K^3 |f_+(q^2)|^2$$

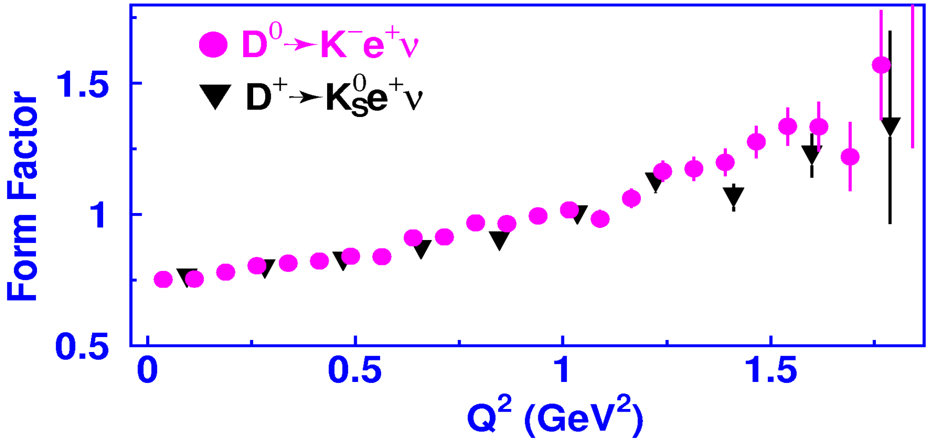
- $q^2 = m^2_{e\nu}$
- As we use electrons the form factor corresponding to a scalar W has a negligible contribution to the rate.
- The observed q^2 distribution is fit to extract form factor information.

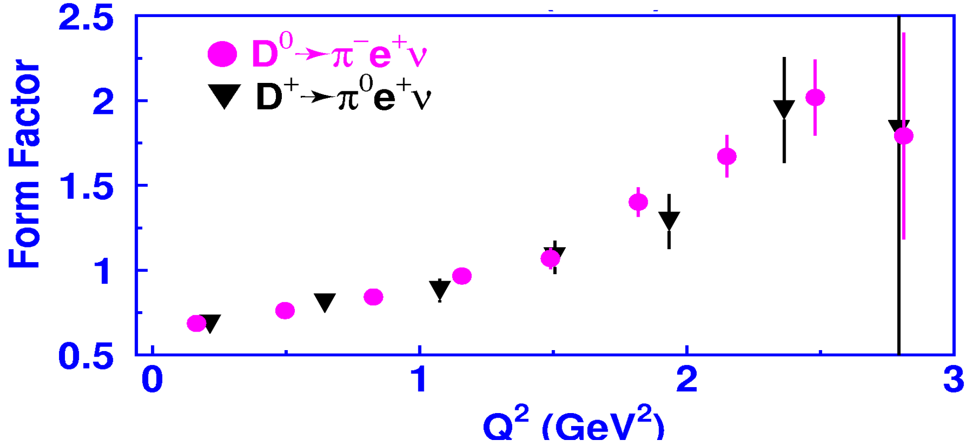
q^2 Distributions (281 pb^{-1})

Preliminary









$D\to(K,\pi)e\nu$ Form Factors

- We fit the observed q^2 distribution to a simple pole form

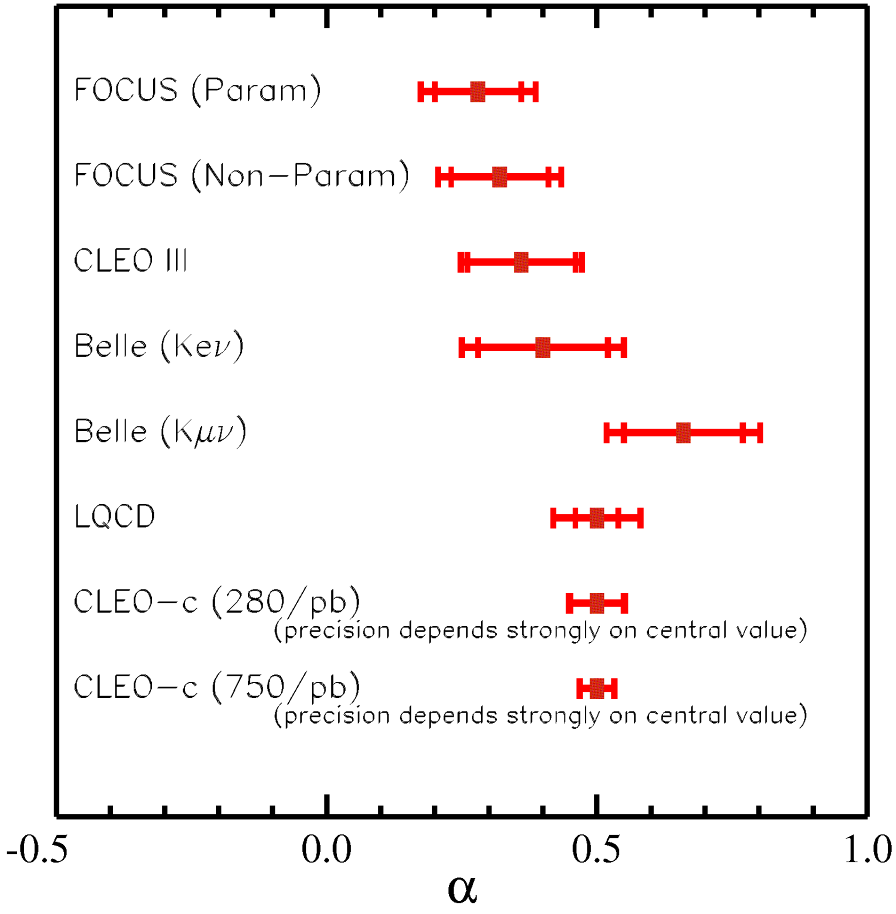
$$f_+(q^2)=\frac{f_+(0)}{1-q^2/M^2_{\mathrm{pole}}}$$

- or a modified pole form (BK)

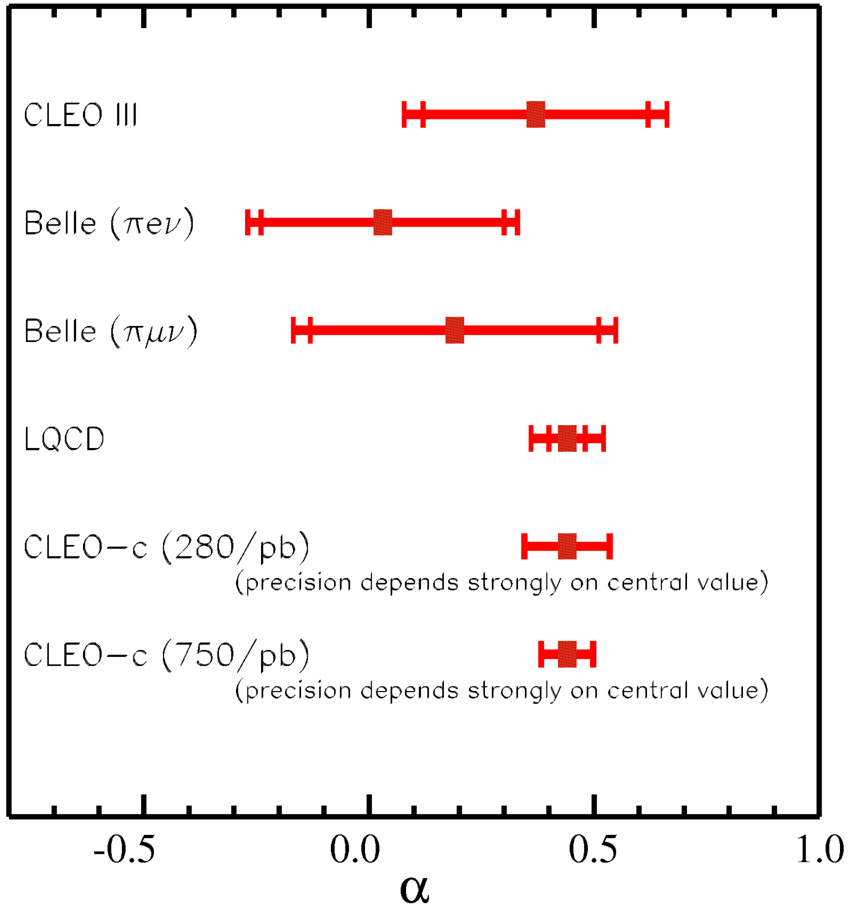
$$f_+(q^2)=\frac{f_+(0)}{1-q^2/M^2_{D^*_{(s)}}}\times\frac{1}{1-\alpha q^2/M^2_{D^*_{(s)}}}$$

Form Factor Precision

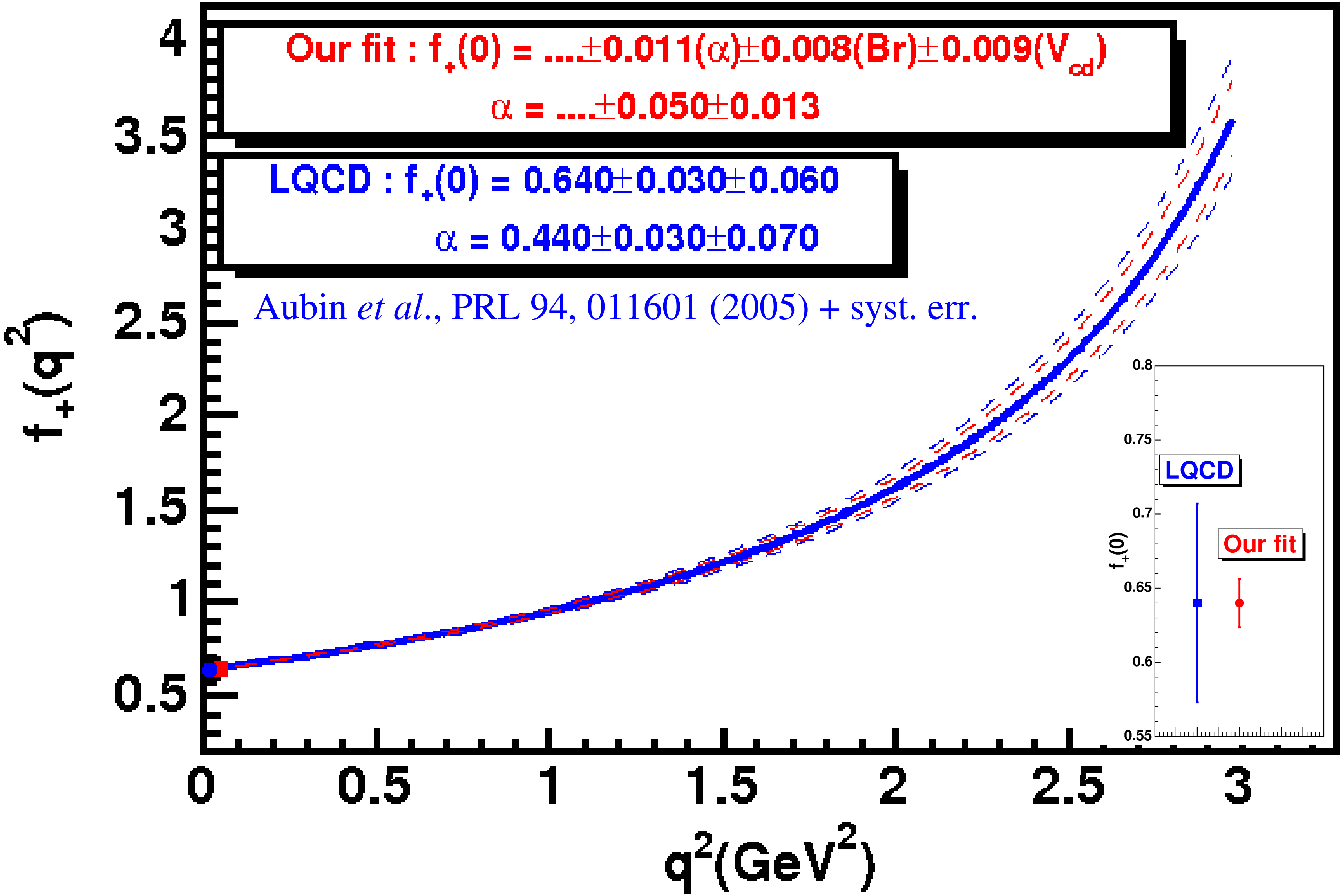
$D \rightarrow Ke\nu$



$D \rightarrow \pi e\nu$

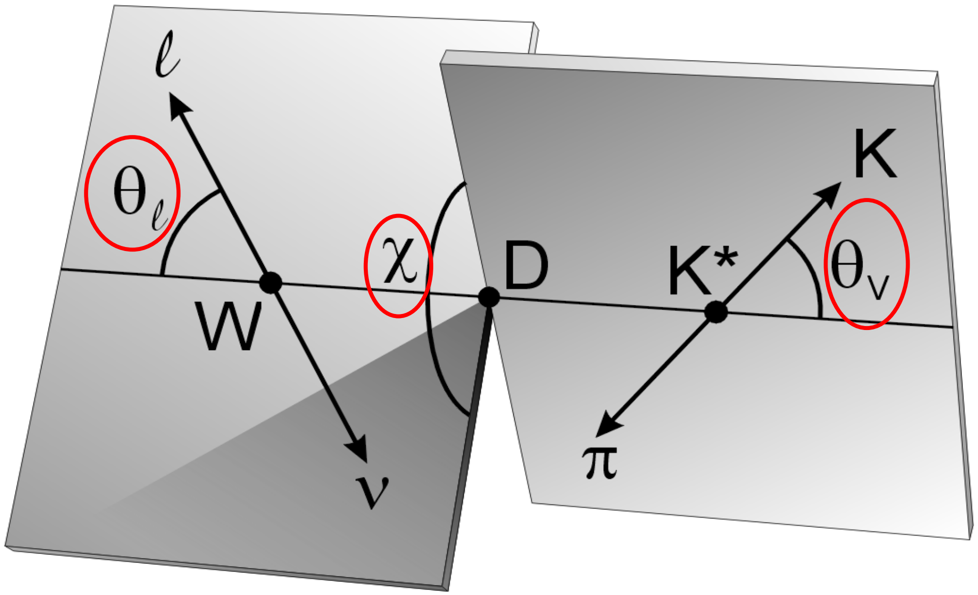


q^2 Dependence in $D \to \pi e \nu$ (750 pb^{-1})



Aubin *et al*., PRL 94, 011601 (2005) + syst. err.

$D\to$"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.

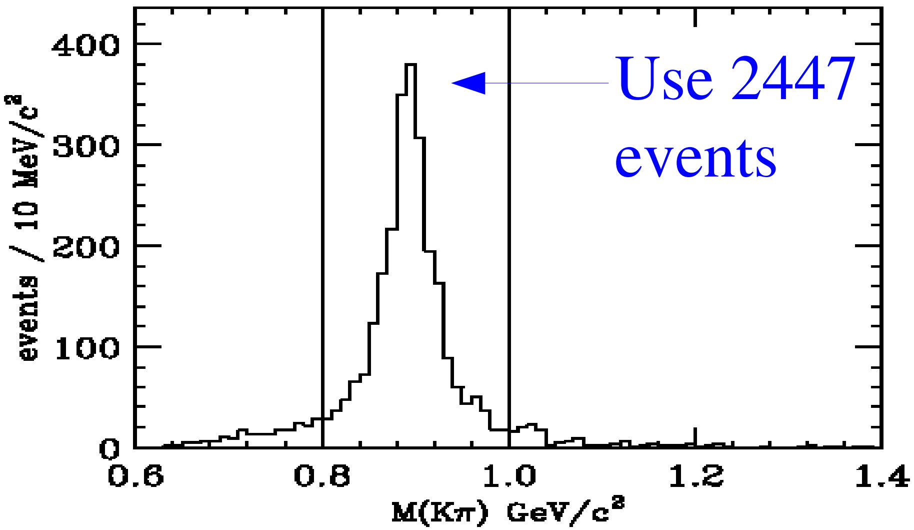
$$|A|^2 = \frac{q^2}{8}\left|\begin{array}{l} (1+\cos\theta_l)\sin\theta_V e^{i\chi}\ \mathrm{BW}\, H_+(q^2) \\ -(1-\cos\theta_l)\sin\theta_V e^{-i\chi}\ \mathrm{BW}\, H_-(q^2) \\ -2\sin\theta_l\left(\cos\theta_V\ \mathrm{BW}\, H_0(q^2) + \mathrm{A}e^{i\delta} h_0(q^2)\right) \end{array}\right|^2$$

Focus found A 7% of BW peak if they assumed

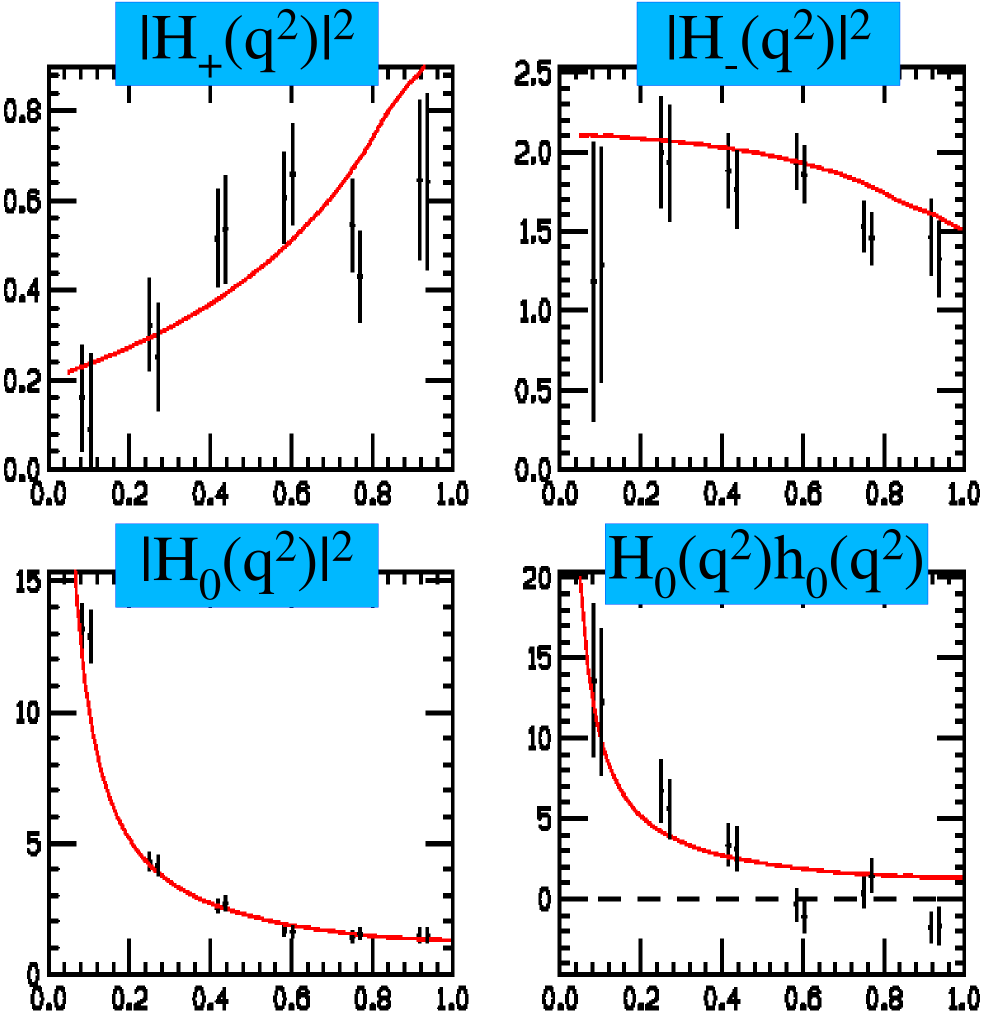
$$h_0(q^2) = H_0(q^2)$$

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

Preliminary



Use 2447 events

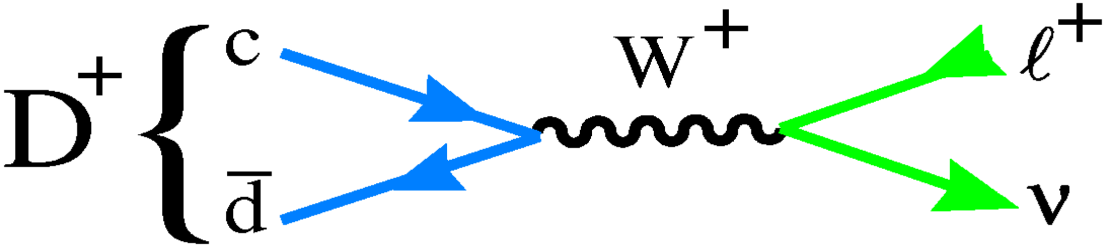


- Non-parametric fit
- Clear evidence for S-wave

Summary of Semileptonic Decays

- CLEO-c measurements are now the best for all semileptonic branching fractions of *D* mesons
- Form factor studies are now underway
  - Will provide stringent tests of Lattice calculations
- Can measure the form factor normalization – or equivalently the CKM matrix elements.
- In addition to the analyses presented here based on *D*-tagging, there are neutrino reconstruction style analysis is progress as well.

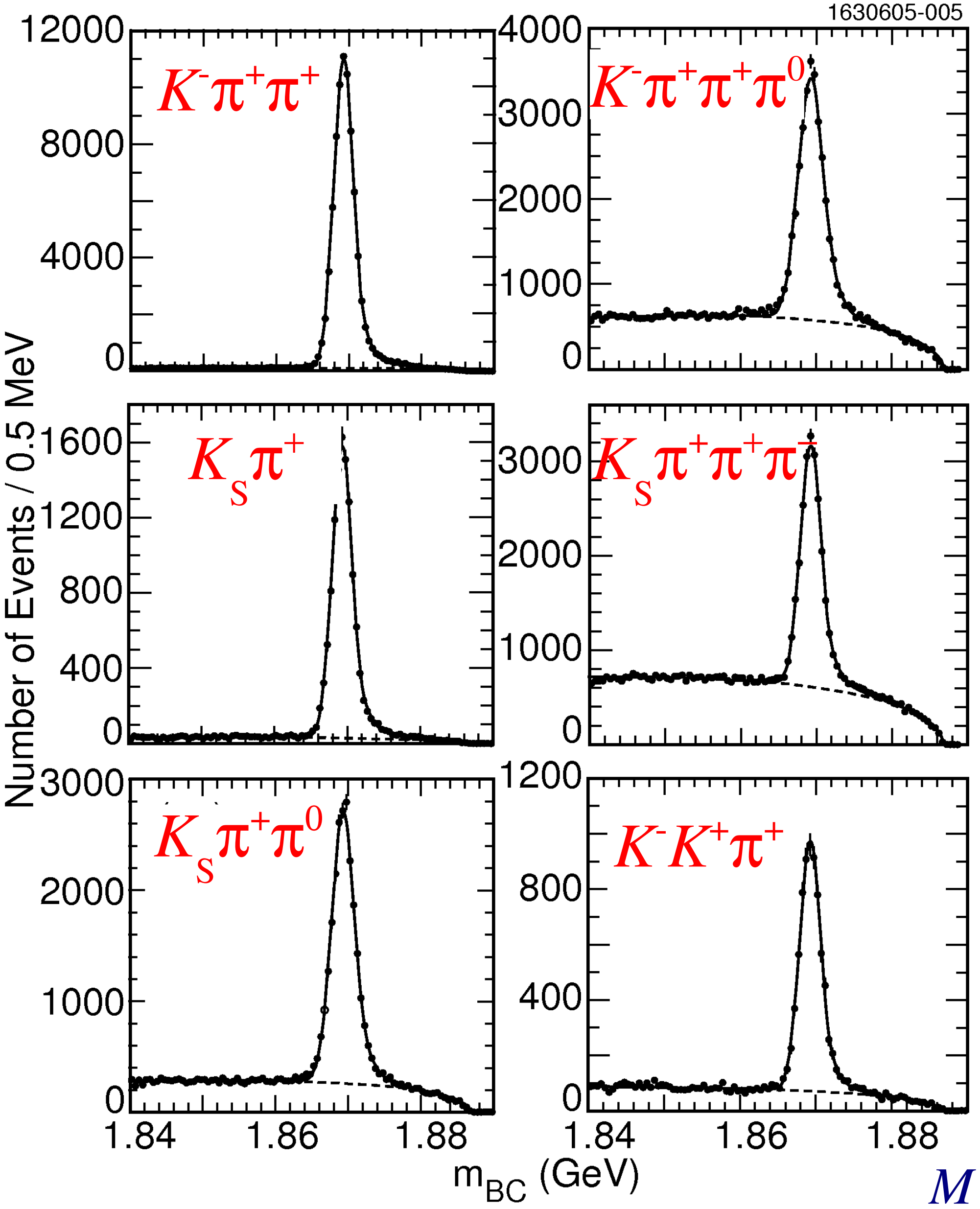
$D^+ \to \mu^+ \nu_\mu$ and f_{D^+}



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

- 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.

Charged *D*-tag Reconstruction



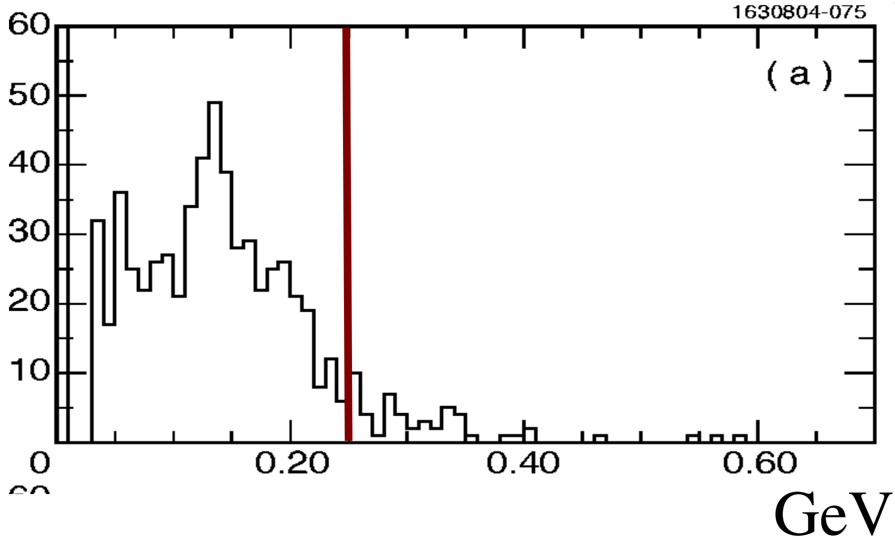
Mode	Signal	Background
$K^+\pi^-\pi^-$	77387 ± 281	1868
$K^+\pi^-\pi^-\pi^0$	24850 ± 214	12825
$K_S\pi^-$	11162 ± 136	514
$K_S\pi^-\pi^-\pi^+$	18176 ± 255	8976
$K_S\pi^-\pi^0$	20244 ± 170	5223
$K^+K^-\pi^-$	6535 ± 95	1271
Sum	158354 ± 496	30677

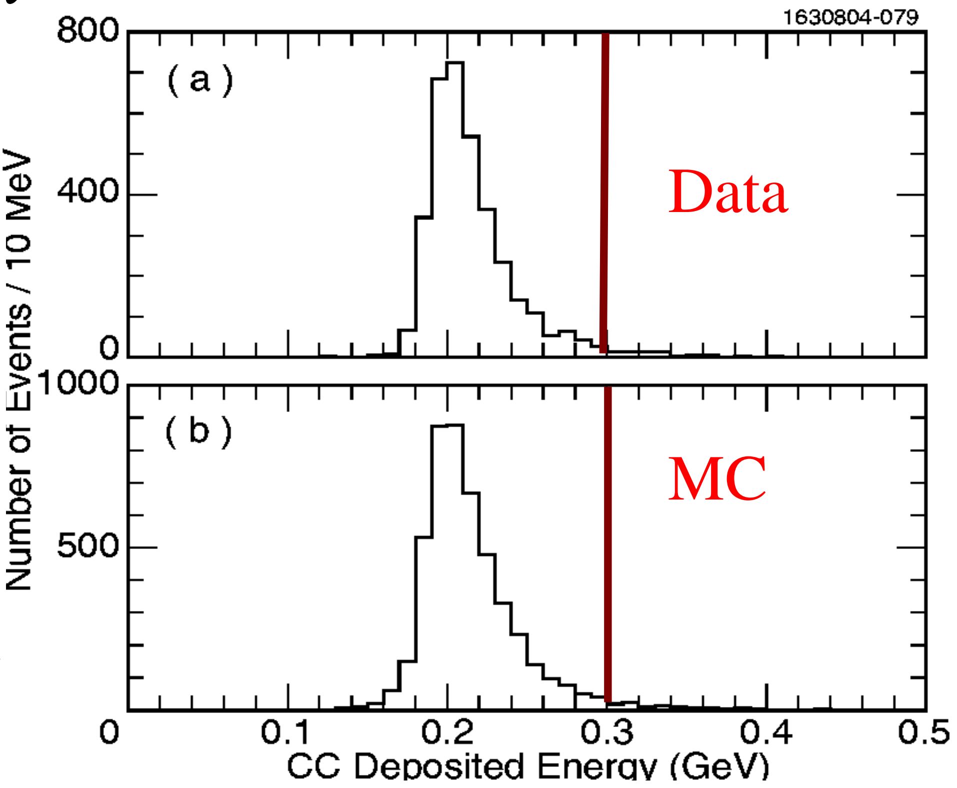
$$M_{BC}=\sqrt{E_{\text{beam}}^2-|p(D)|^2}$$

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
- Require no unmatched showers over 250 MeV
  - Veto background from $D^+ \to \pi^+ \pi^0$

Highest energy unmatched cluster





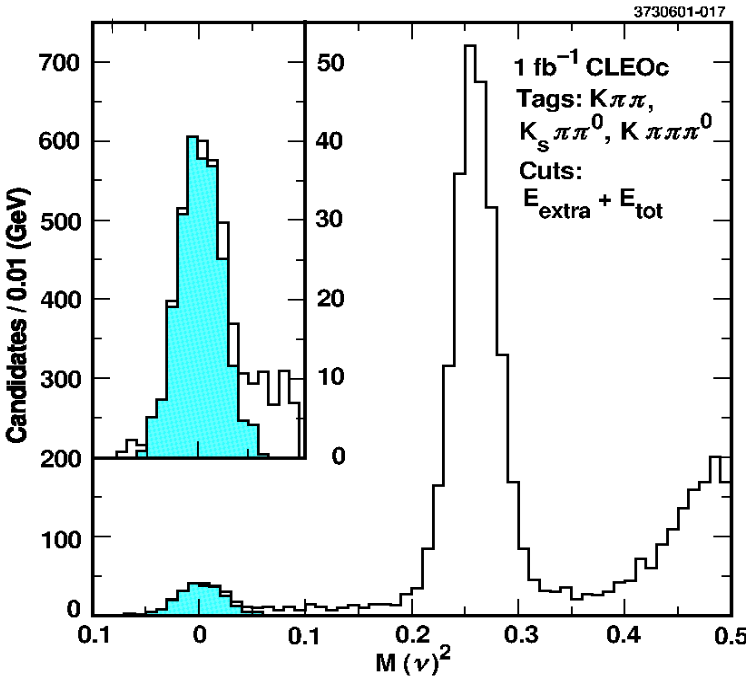
Signal Extraction

- For events with μ candidate form

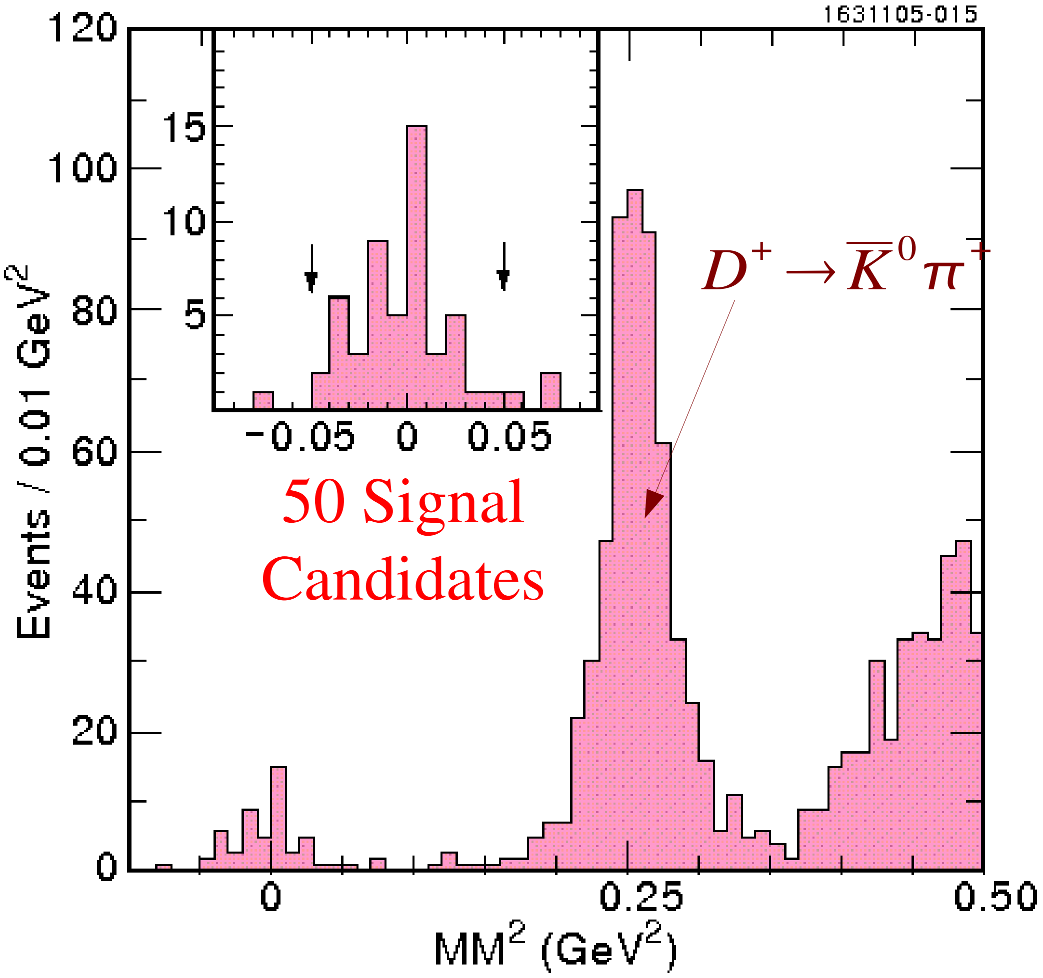
$$MM^2=(E_{beam}-E_\mu)^2-(-\vec{p}_{D^-}-\vec{p}_\mu)^2$$

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

"Yellow book" MC Study



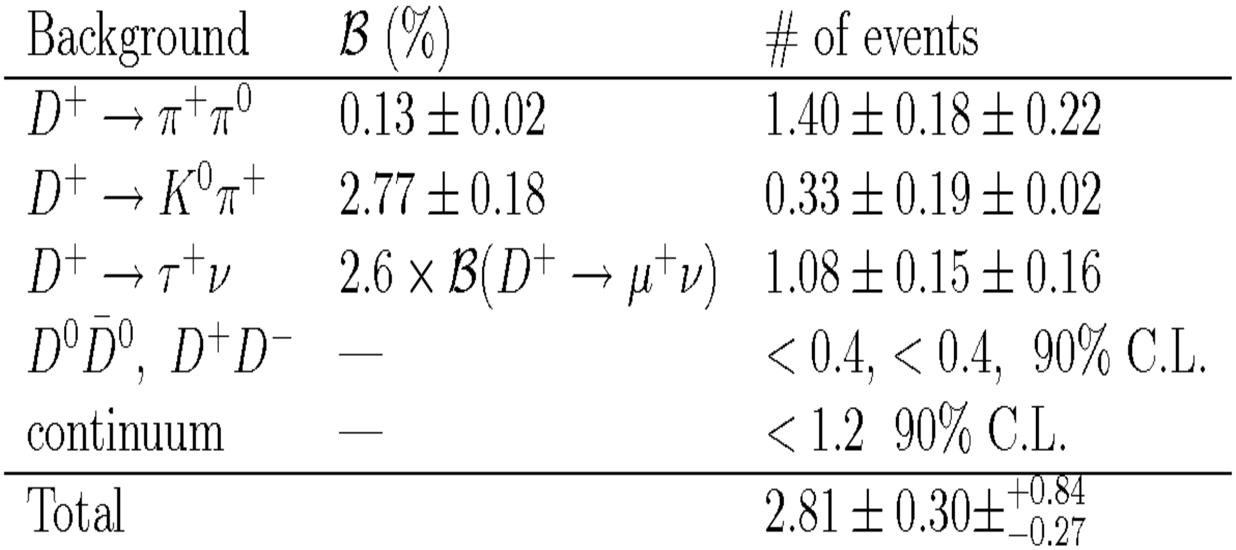
Data 281 pb^{-1}



50 Signal Candidates

$D^+ \to \mu^+ \nu_\mu$ 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		$2.81 \pm 0.30 \pm^{+0.84}_{-0.27}$

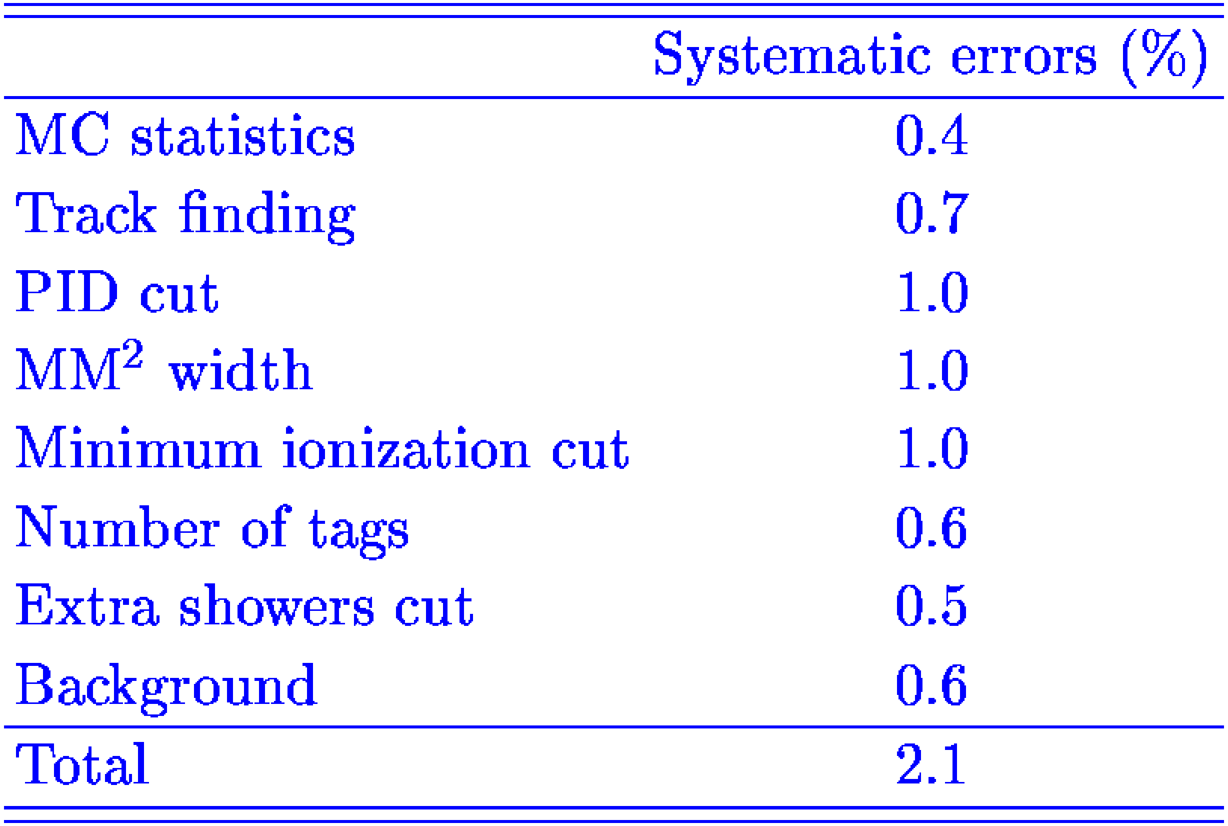
- With 158,354 D^+ tags and an efficiency of 67.7% for signal events to satisfy the selection criteria given a D^+ tag we obtain:

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

(Accepted by PRL)

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

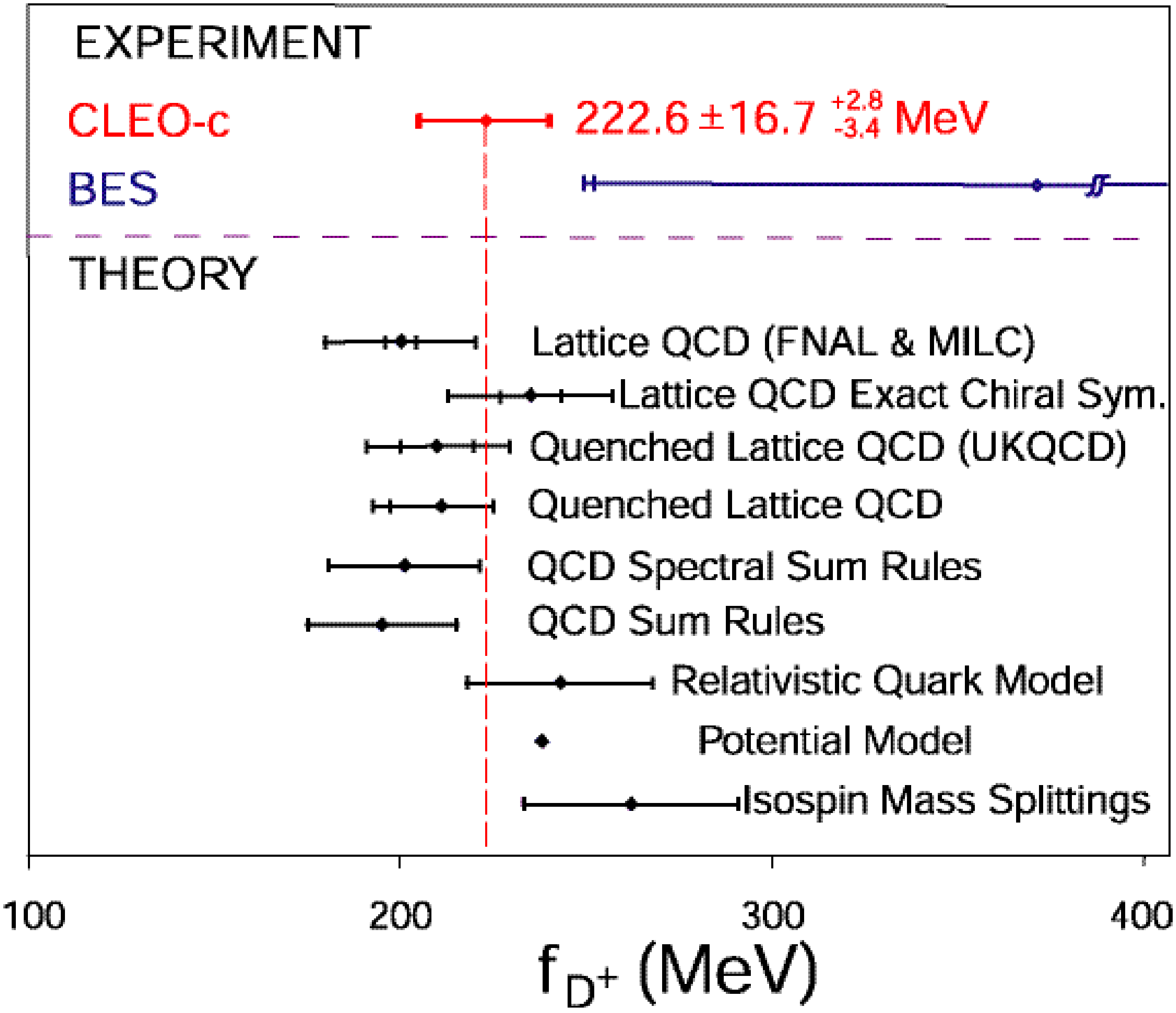
Systematics $\mathcal{B}(D^+\to\mu^+\nu_\mu)$



	Systematic errors (%)
MC statistics	0.4
Track finding	0.7
PID cut	1.0
MM^2 width	1.0
Minimum ionization cut	1.0
Number of tags	0.6
Extra showers cut	0.5
Background	0.6
Total	2.1

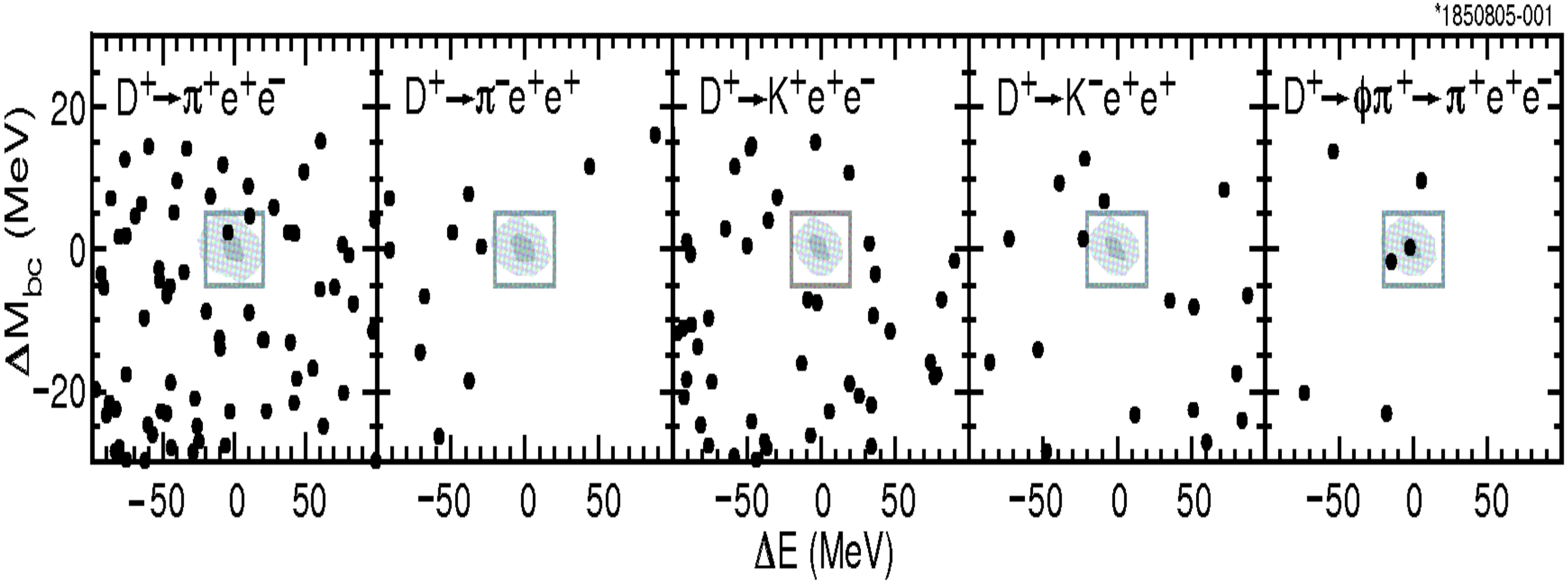
- Systematics much smaller than statistical error (~15%)
- At 750 pb^{-1} statistical error 9% on $\mathcal{B}(D^+\to\mu^+\nu_\mu)$
  - or 4.5% on f_{D+}

Comparing with Theory



Rare *D*-decays

- CLEO-c has searched for the rare decays $D \to (K,\pi)e^+e^-$.
  - No significant signal observed, limits a factor of 10 better than PDG.



- Searches also underway for $D \to \phi\gamma$ and $D \to K^*\gamma$
  - These rare decays are likely to be long distance dominated, but one should still look for them.

Conclusions

- CLEO-c has accumulated ~281 pb^{-1} of data at the $\psi(3770)$
- The detector is now well understood and we are producing very precise results based on our current data sample
- We have about 10% D^+ and 17% D^0 tagging efficiency
- CLEO-c has a good start to measure practically all decays that are in the PDG
- Absolute hadronic branching fractions results from 56 pb^{-1} are being updated for 281 pb^{-1}. Statistical precision of ~1%.
  - Many other hadronic final states are studied
- Semileptonic and leptonic decays are providing detailed tests of calculations of strong interactions:
  - Form factors for $D\to(K,\pi)e\nu$
  - Decay constant, f_D, from $D^+\to\mu^+\nu_\mu$
- CLEO-c with 750 pb^{-1}will provide detailed tests of strong interactions

Backup Slides

Comparison to Yellow Book

- Luminosity – lower than we had assumed, discussed earlier.
- Cross-section – we observe ~6.4 nb, compare to 10nb assumed.
- Tagging efficiency
  - D^0 Yellow Book had 14% we can use 17%
  - D^+ Yellow Book had 7.5% we can use 10.5%
- Some tags have a higher level of background, but are usable.

Tracking Efficiencies

- For example, we want to measure $B(D \rightarrow K\pi)$ to better than 1%
- We need to measure the tracking efficiency to ~0.3% in order achieve this goal.
- Luckily, we have data samples that allow crosschecks at this level.
- A very clean sample is the $\psi' \rightarrow J/\psi\ \pi^+\pi^-$, with $J/\psi \rightarrow e^+e^-$ or $\mu^+\mu^-$.
  - To measure the, *e.g.*, the efficiency for finding a π^+ we reconstruct the J/ψ and the π^-. Then we check if the J/ψ and π^- are consistent with a missing π^+.
  - This allows us to count the number of events of the type $\psi' \rightarrow J/\psi\ \pi^+\pi^-$ without actually finding the π^+.
  - Now we can simply measuring the efficiency be seeing how often we actually find the π^+ in the event.

Pion Tracking Efficiency