

Leptonic and Semileptonic Charm Decays

- Importance of charm leptonic and semileptonic decays in heavy flavor physics
- Recent experimental results from CLEO-c, Babar, Belle, Focus and BES-II
- Comparisons with theory

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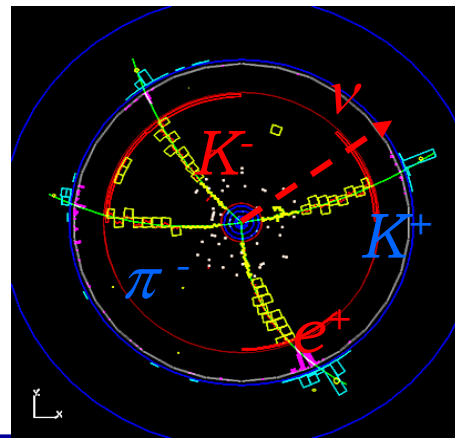
Purdue University (CLEO)

UC, Santa Barbara (CMS)

on behalf of

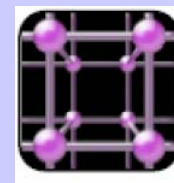
the CLEO collaboration

FPCP-2007, Bled, Slovenia





Introduction: LSL charm decays



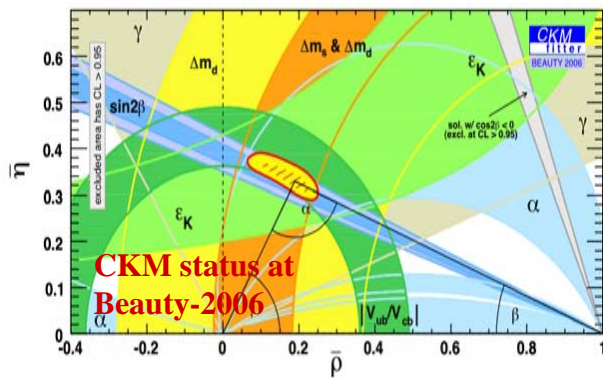
Charm leptonic and semileptonic decays provide stringent tests of theory for decay constants and semileptonic form factors



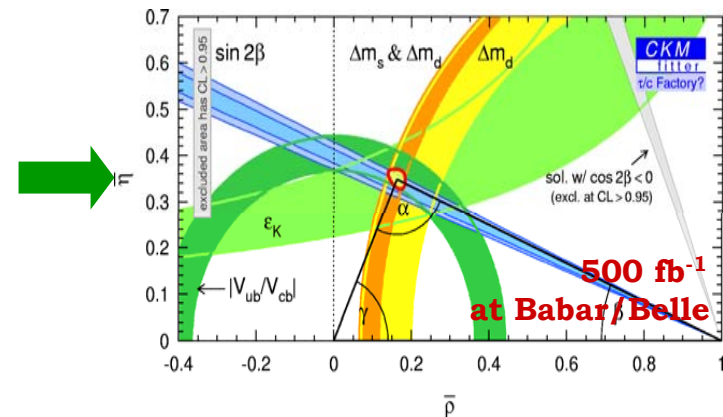
Help heavy flavor physics constrain the CKM matrix now:

- ✓ Precision tests of the Standard Model or
- ✓ Discovery of new physics beyond the SM in b or c quark decays

Difficulty: hadronic uncertainties complicate the interpretation of exp. results:

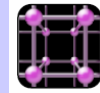


Reduce theory errors on B form factors and B decay constants using tested LQCD

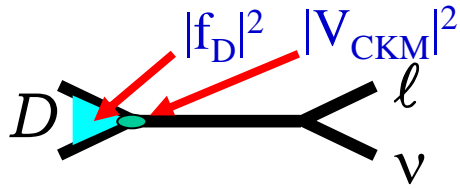




Examples of theory tests and their impact



Leptonic decays ($D^+ \rightarrow \mu\nu$ and $D_s \rightarrow \mu\nu$):



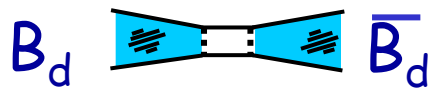
$$\text{Rate} \propto f_{D(s)}^2 |V_{cd(s)}|^2$$

Experiment

LQCD

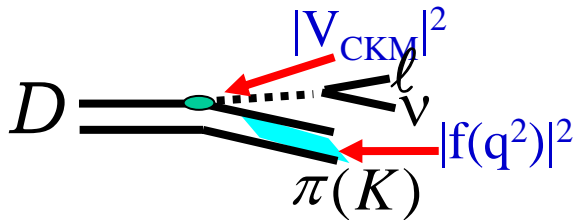
Known to < 1% from the CKM unitarity

Lattice predicts f_B/f_D and f_B/f_{B_s} with small errors \Rightarrow precise f_D gives precise f_B and $|V_{td}|$; f_D/f_{D_s} checks f_B/f_{B_s} and allows precise $|V_{td}|/|V_{ts}|$



$$\text{Rate} \propto f_{B_d}^2 |V_{td} V_{tb}^*|^2$$

Semileptonic decays ($D \rightarrow \pi e\nu$, $D \rightarrow K e\nu$):



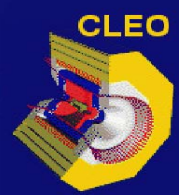
$$\text{Rate} \propto |V_{cd(s)}|^2 |f_+(q^2)|^2, \text{ where } q^2 \equiv M^2(e\nu)$$

Test theory calculations of $f_+(q^2)$ in the D system and apply them to the B system for $|V_{ub}|$ and $|V_{cb}|$

Combination of leptonic and semileptonic decays:

$$\Gamma(D \rightarrow \pi e\nu) / \Gamma(D \rightarrow \mu\nu) \propto f_+^2(q^2) / f_D^2$$

Test theory with no errors from CKM couplings



Experiments

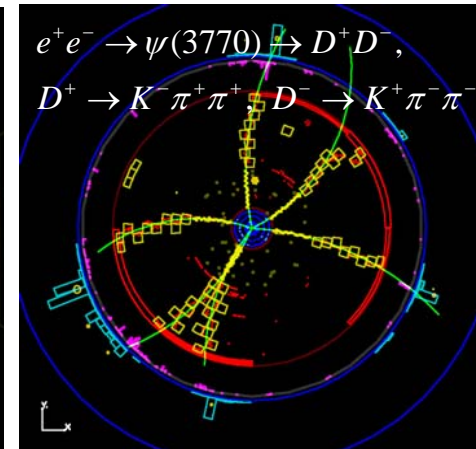
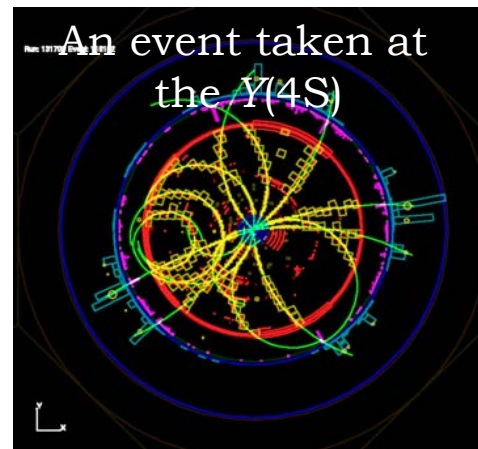


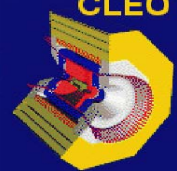
- ❑ CLEO-c: a charm factory at the $\psi(3770)$ and slightly higher E_{CM}
- ❑ Babar and Belle: B-factories at the $Y(4S)$
- ❑ FOCUS (E831): a fixed target experiment
- ❑ BES-II: also a charm factory but smaller lumin. (being upgraded)

The majority of recent precision LSL charm results come from CLEO-c (and from B-factories)

Advantages of running at the $\psi(3770)$ for charm physics:

- ✓ **Pure DD** , no additional particles
- ✓ $\sigma[DD \text{ at } \psi(3770)] = 6.4 \text{ nb}$ [$\sigma(cc)$ at $Y(4S) \sim 1.3 \text{ nb}$]
- ✓ Low multiplicity, **high tagging efficiency** ($>20\%$)





References

very recent references are in red

□ CLEO-c:

- ✓ $D^+ \rightarrow \mu\nu$ with 281 pb^{-1} at the $\psi(3770)$: PRL **95**, 251801 (2005)
- ✓ Exclusive D^+ semileptonic branching fractions with 56 pb^{-1} at the $\psi(3770)$: PRL **95**, 181801 (2005);
- ✓ Exclusive D^0 semileptonic branching fractions with 56 pb^{-1} at the $\psi(3770)$: PRL **95**, 181802 (2005);
- ✓ Inclusive D semileptonic branching fractions with 281 pb^{-1} at the $\psi(3770)$: PRL **97**, 251801 (2006)
- ✓ Form factors in $D^+ \rightarrow K\pi e\nu$ with 281 pb^{-1} at the $\psi(3770)$: PRD **74**, 052001 (2006)
- ✓ $D^+ \rightarrow \tau\nu$ with 281 pb^{-1} at the $\psi(3770)$: PRD **73**, 112005 (2006)
- ✓ Form factors in tagged $D \rightarrow \pi e\nu$ and $D \rightarrow K e\nu$ with 281 pb^{-1} at the $\psi(3770)$: ICHEP-2006
- ✓ Form factors in untagged $D \rightarrow \pi e\nu$ and $D \rightarrow K e\nu$ with 281 pb^{-1} at the $\psi(3770)$: ICHEP-2006
- ✓ Form factors in tagged $D \rightarrow \rho e\nu$ with 281 pb^{-1} at the $\psi(3770)$: ICHEP-2006
- ✓ $D \rightarrow \eta e\nu/\eta' e\nu/\phi e\nu$: ICHEP-2006
- ✓ $D \rightarrow K\pi e\nu$: ICHEP-2006
- ✓ $D_s \rightarrow \mu\nu$ with 314 pb^{-1} at $E_{\text{CM}} \sim 4.17 \text{ GeV}$: arXiv:0704.0437 and arXiv:0704.0629 (submitted to PRL and PRD)

□ Babar:

- ✓ $D \rightarrow K e\nu$ with 75 fb^{-1} at the Y(4S): arXiv:0704.0020 (submitted to PRD)
- ✓ $D_s \rightarrow \mu\nu$ with 230 fb^{-1} at the Y(4S): PRL **98**, 121801 (2007)
- ✓ $D \rightarrow \phi e\nu$ with 79 fb^{-1} at the Y(4S): ICHEP-2006

□ Belle:

- ✓ Form factors in tagged $D \rightarrow \pi e\nu$ and $D \rightarrow K e\nu$ with 282 fb^{-1} at the Y(4S): PRL **97**, 061804 (2006)

□ FOCUS:

- ✓ Form factors in $D^+ \rightarrow K\pi\mu\nu$: PLB **633**, 183 (2006)
- ✓ Form factors $D \rightarrow \pi\mu\nu$ and $D \rightarrow K\mu\nu$

□ BES-II:

- ✓ Branching fractions in $D \rightarrow \pi e\nu$ and $D \rightarrow K e\nu$ PLB **597**, 39 (2004), PLB **608**, 24 (2005).



CLEO-c Data Samples



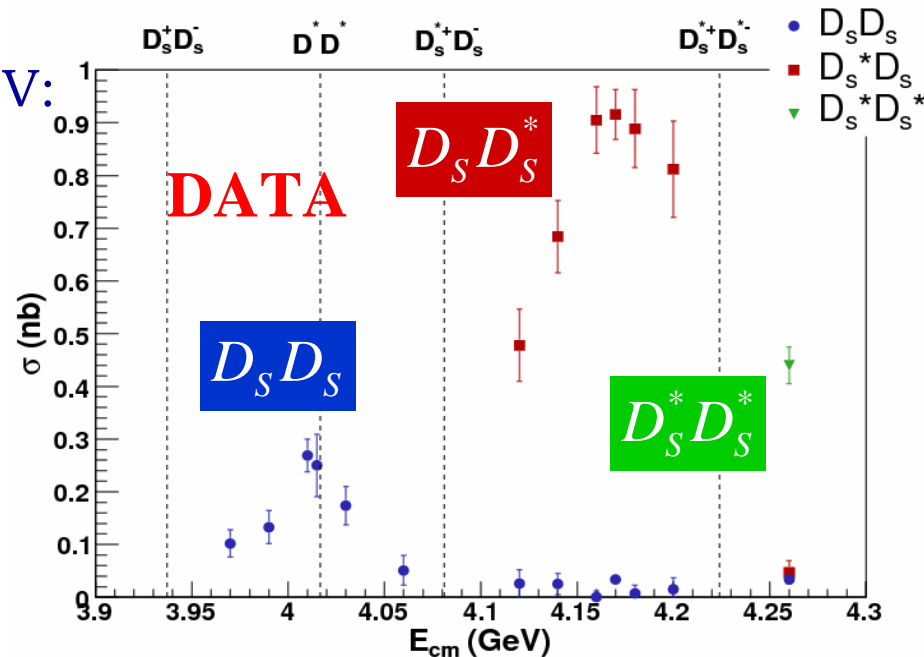
- $\psi(3770)$: total luminosity = $\sim \underline{281 \text{ pb}^{-1}}$
- $E_{\text{CM}} = 4170 \text{ MeV}$: total luminosity = $\sim \underline{314 \text{ pb}^{-1}}$

CLEO scanned $E_{\text{CM}} = 3.97 - 4.26 \text{ GeV}$:

Optimal energy for D_s physics:

$$E_{\text{CM}} = 4.170 \text{ GeV}$$

Dominant production mechanism at this energy:





Tagging technique

Example: the $\psi(3770)$ decays DD pairs ($\vec{P}_D = -\vec{P}_{\bar{D}}$)

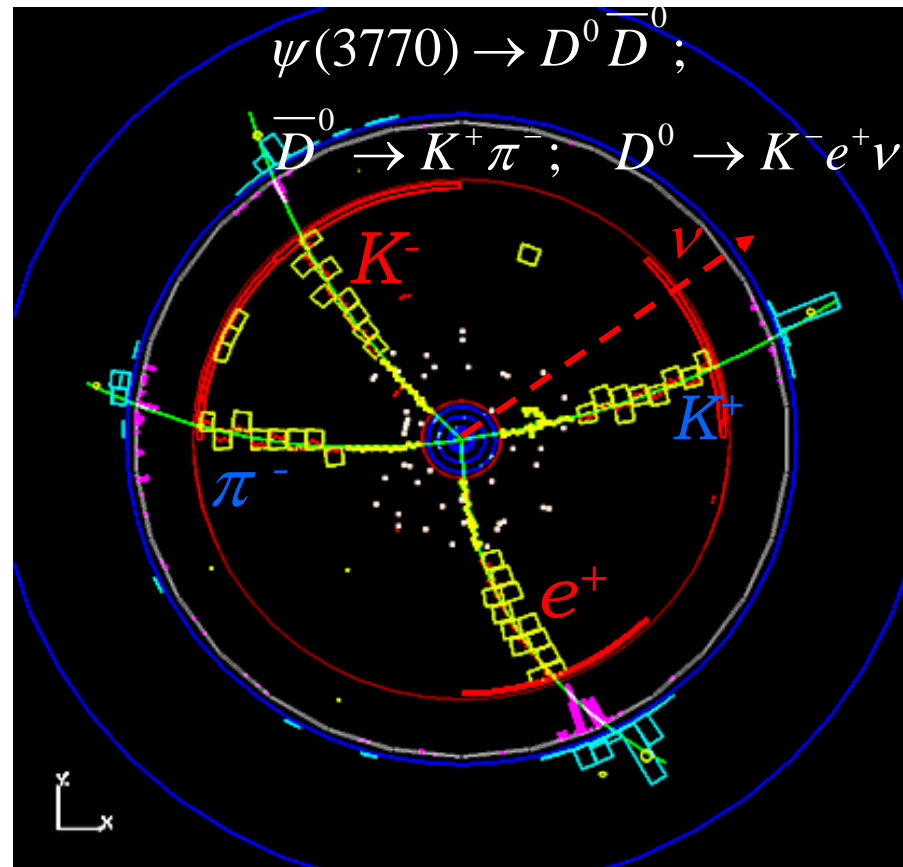
Reconstruct a tag:

Tagging creates a **beam of D mesons** with known momentum

LSL decays are identified using variables U or MM^2 :

$$U \equiv E_{miss} - P_{miss};$$

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



Tags at the $\psi(3770)$

- Variables used in the tag reconstruction:

$$M_{bc} = \sqrt{E_{beam}^2 - P_{candidate}^2}$$

$$\Delta E = E_{candidate} - E_{beam}$$

- Total number of tags:

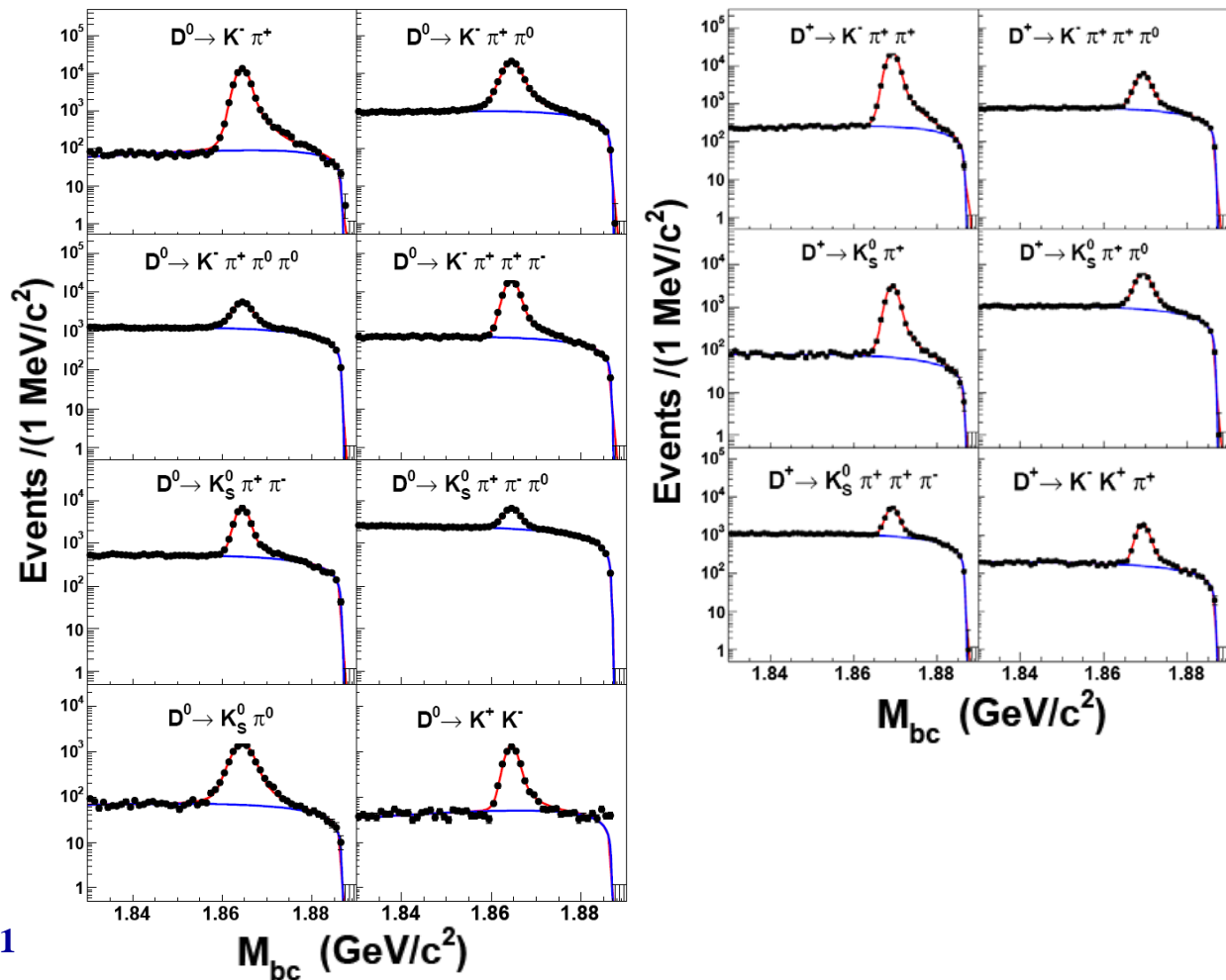
- ✓ D^0 tags: 8 standard tag modes

Total: 3.1×10^5 tags
 $\sim 1.1 \times 10^3$ tags / 1 pb $^{-1}$

- ✓ D^+ tags: 6 standard tag modes

Total: 1.6×10^5 tags
 $\sim 0.6 \times 10^3$ tags / 1 pb $^{-1}$

DATA (281 pb $^{-1}$); NOTE the LOG SCALE





D_S tags at $E_{CM} = 4170$ MeV

□ Recall at $E_{CM} = 4170$ MeV:

$$e^+ e^- \rightarrow D_S D_S^*$$

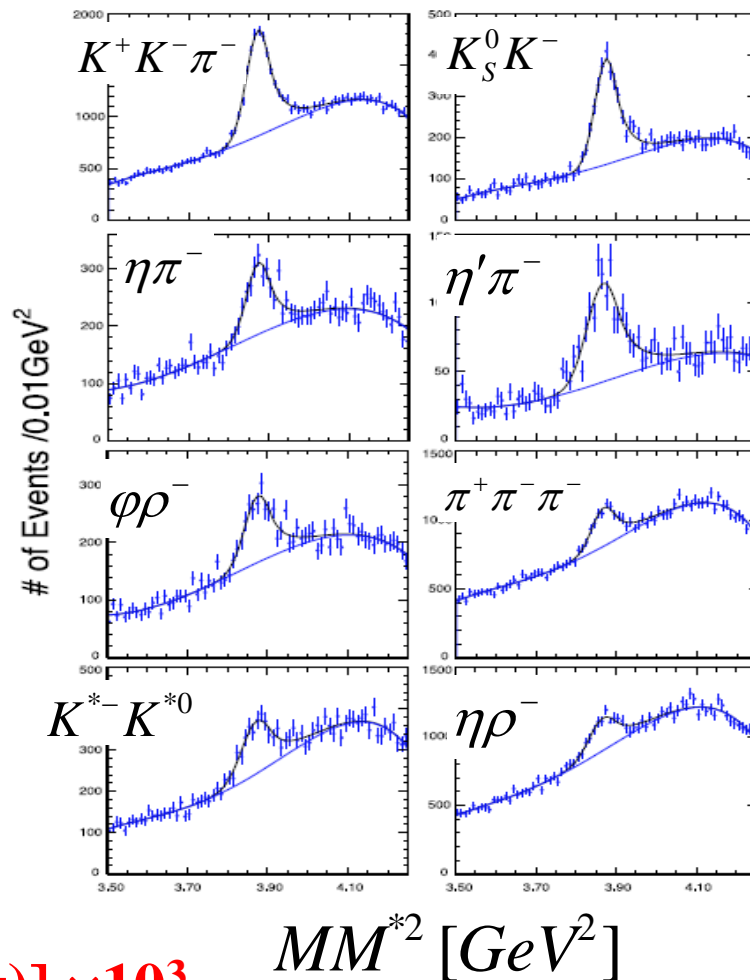
D_S^* decays to D_S via emission of 150 MeV photon 95% of the time \Rightarrow significant smearing of M_{BC}

□ D_S tag yields are determined using:

$$MM_{tag}^{*2} =$$

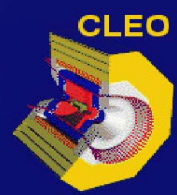
$$(E_{CM} - E_{D_S} - E_\gamma)^2 - (-\vec{p}_{D_S} - \vec{p}_\gamma)^2$$

DATA (314 pb⁻¹)



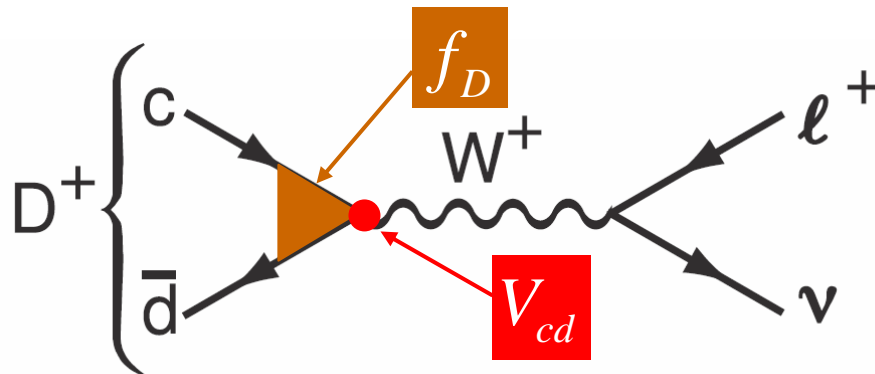
$MM^2 [GeV^2]$

Tag Yield: $[18.6 \pm 0.4$ (stat) ± 0.9 (syst)] $\times 10^3$



Leptonic decays

$D_{(s)}$ Leptonic Decays



$$\Gamma(D^+ \rightarrow l^+ \nu) = \frac{1}{8\pi} G_F^2 \boxed{f_D^2} m_l^2 M_D \left(1 - \frac{m_l^2}{M_D^2}\right)^2 \boxed{|V_{cd}|^2}$$

Standard Model predicts:

- ✓ D decays: $\Gamma(e^+ \nu) : \Gamma(\mu^+ \nu) : \Gamma(\tau^+ \nu) = 2.3 \times 10^{-5} : 1.0 : 2.7$
- ✓ D_s decays: $\Gamma(e^+ \nu) : \Gamma(\mu^+ \nu) : \Gamma(\tau^+ \nu) = 2.5 \times 10^{-5} : 1.0 : 9.7$

Use V_{cd} and V_{cs} from the CKM unitarity constraints to extract f_D and f_{D_s} , and compare them to theory

$D^+ \rightarrow \mu^+ \nu$ with 281 pb^{-1} at the $\psi(3770)$



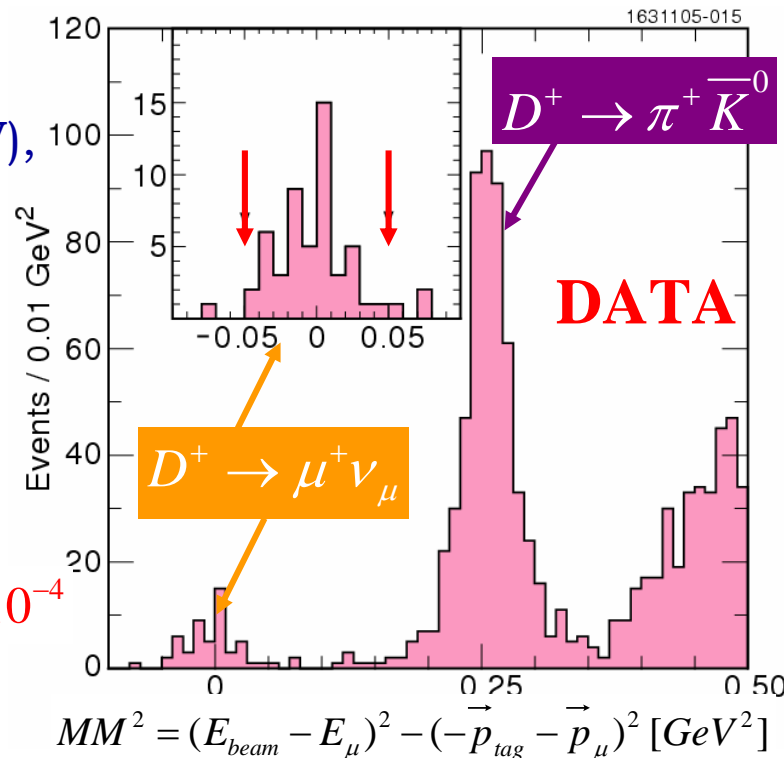
Full event reconstruction:

- ✓ require a tag,
- ✓ require a muon cand. ($E_{\text{CC track}} < 300 \text{ MeV}$),
- ✓ veto events with extra tracks and energy clusters $> 250 \text{ MeV}$.

Results:

- ✓ **50 $D^+ \rightarrow \mu \nu$ candidates**
- ✓ Estimated bckg: 2.8 events
- ✓ $B(D^+ \rightarrow \mu^+ \nu) = [4.4 \pm 0.7(\text{stat}) \pm 0.1(\text{syst})] \times 10^{-4}$

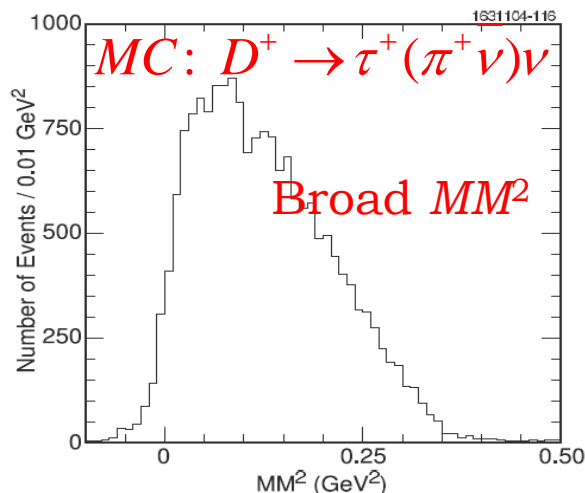
✓ $f_{D^+} = [223 \pm 17(\text{stat}) \pm 3(\text{syst})] \text{ MeV}$



- The same analysis is repeated for $D^+ \rightarrow e^+ \nu$. No signal candidates are seen: $B(D^+ \rightarrow e^+ \nu) < 2.4 \times 10^{-5}$ (at 90% CL)

$D^+ \rightarrow \tau^+ \nu$ with 281 pb^{-1} at the $\psi(3770)$

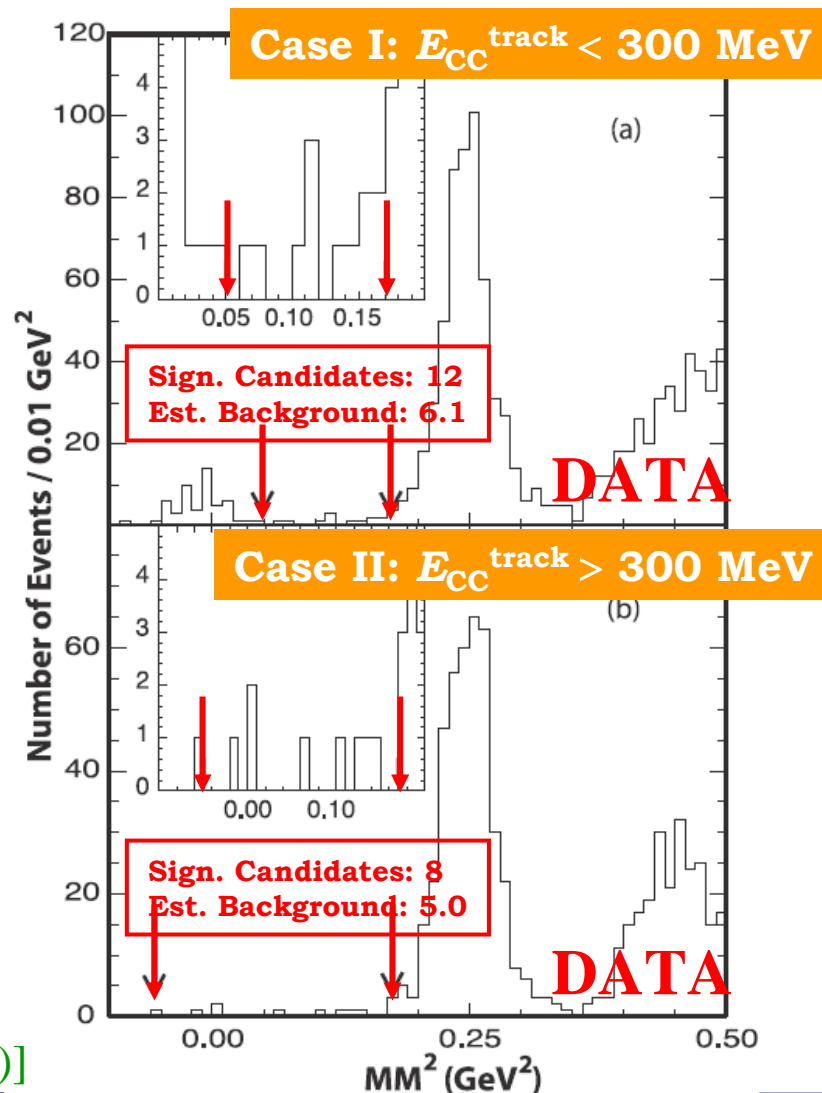
- Reconstruct $D^+ \rightarrow \tau^+ \nu$ with $\tau^+ \rightarrow \pi^+ \nu$ [B($\tau^+ \rightarrow \pi^+ \nu$) $\sim 11\%$]; the same technique but two ν 's complicate the analysis:



- Consider two cases:

- Case I: $E_{\text{CC track}} < 300 \text{ MeV}$ (accept 99% of muons and 60% of pions)
- Case II: $E_{\text{CC track}} > 300 \text{ MeV}$ (accept 1% of muons and 40% of pions)

- No significant signal \Rightarrow
 $B(D^+ \rightarrow \tau^+ \nu) < 2.1 \times 10^{-3}$ (at 90% CL)
 [SM: $B(D^+ \rightarrow \tau^+ \nu) < (1.1 \pm 0.2) \times 10^{-3}$ (at 90% CL)]





$D_S \rightarrow \mu^+ \nu$ and $\tau^+(\pi^+ \nu) \nu$ with 314 pb^{-1} at $E_{CM} = 4170 \text{ MeV}$

Full event reconstruction:

- ✓ Require a tag and a γ from D_S^* ,
- ✓ Require one additional track,
- ✓ Veto events with extra tracks or $E_{CC} > 300 \text{ MeV}$.

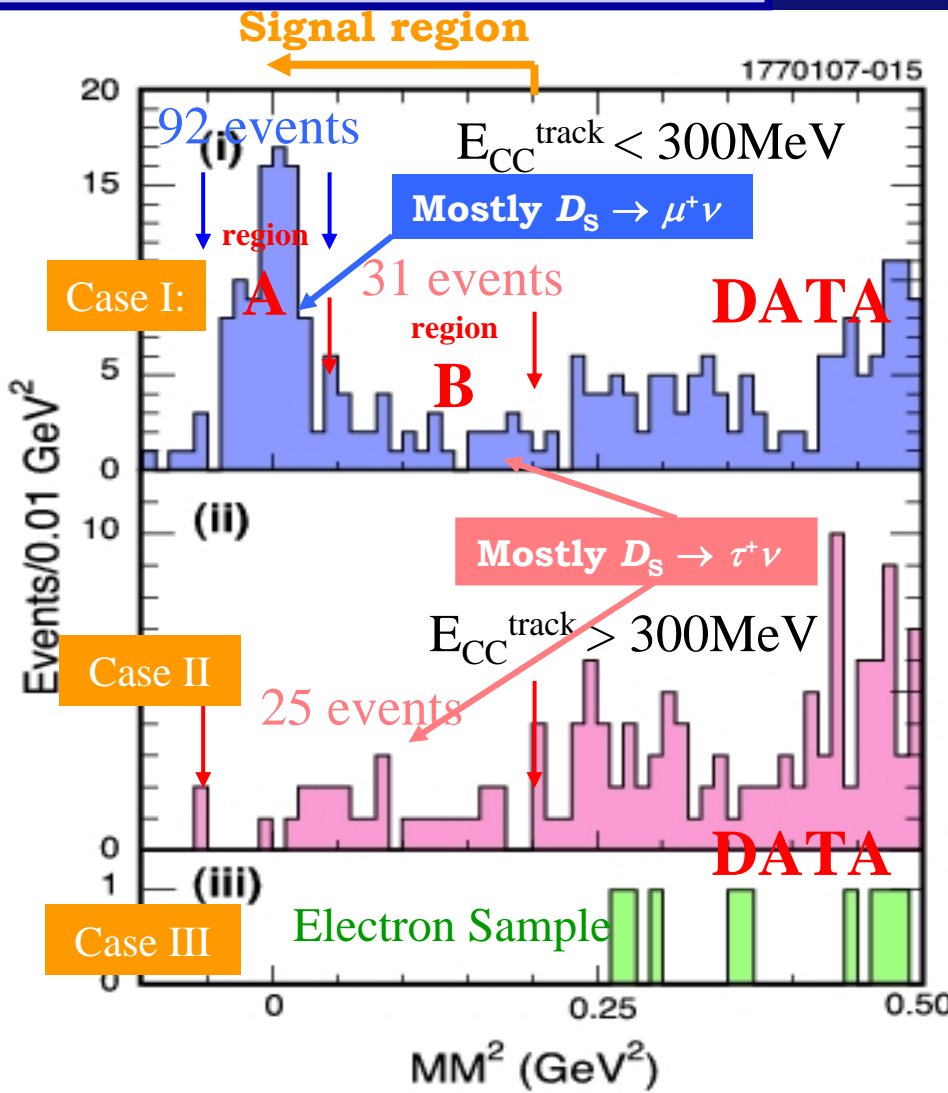
Use MM^2 to separate $\mu^+ \nu$, $\tau^+(\pi^+ \nu) \nu$ and background:

$$MM^2 = (E_{CM} - E_{D_S} - E_\gamma - E_{\mu(\pi)})^2 - (-\vec{p}_{D_S} - \vec{p}_\gamma - \vec{p}_\mu)^2$$

Consider three cases:

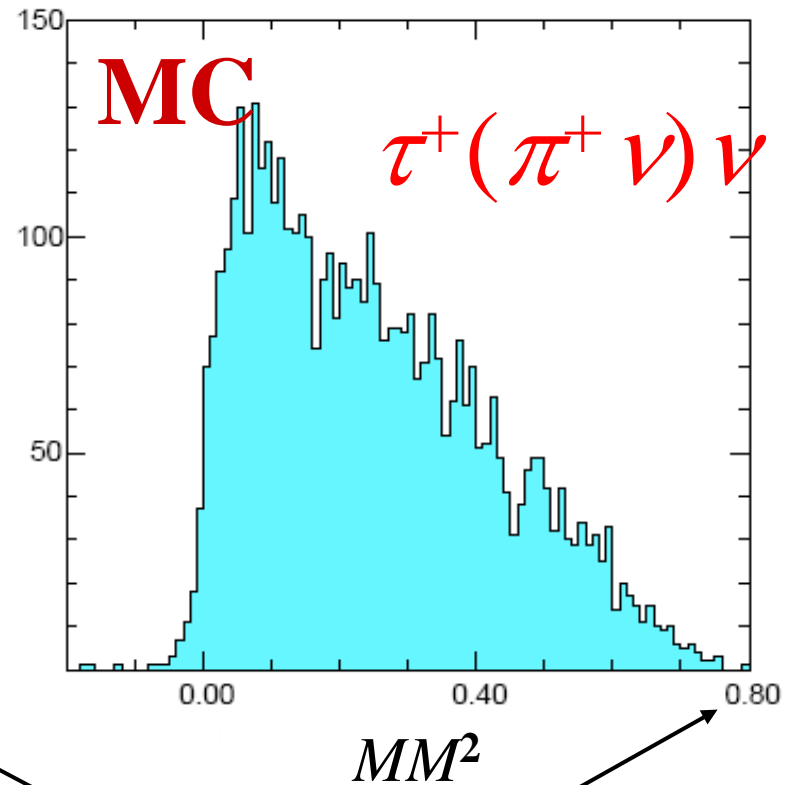
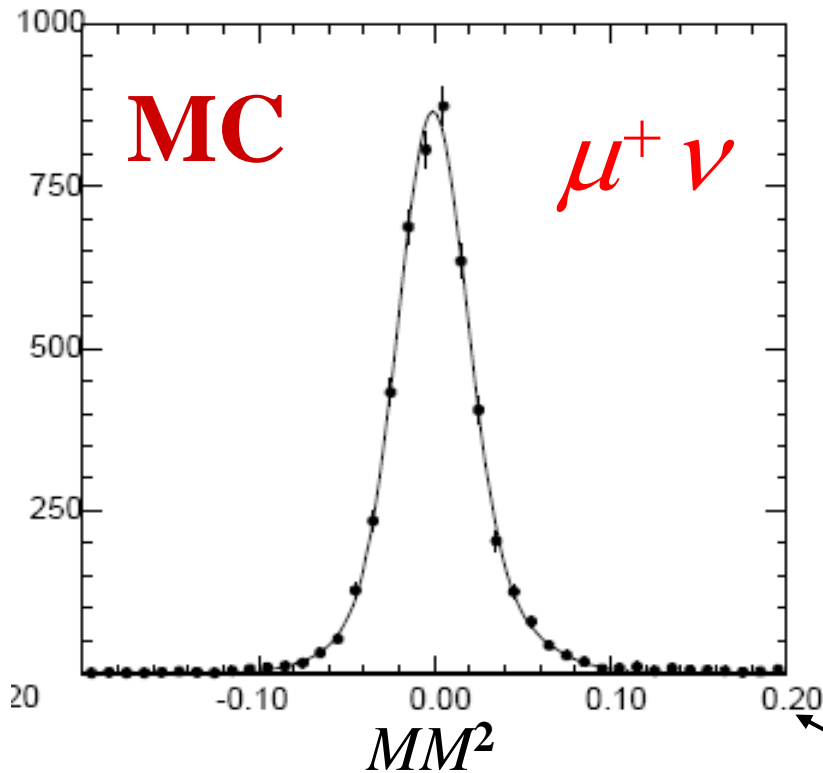
- ✓ **Case I:** $E_{CC \text{ track}} < 300 \text{ MeV}$ (accept 99% of muons and 60% of pions)
- ✓ **Case II:** $E_{CC \text{ track}} > 300 \text{ MeV}$ (accept 1% of muons and 40% of pions)
- ✓ **Case III:** require an electron

[Kinematical constraints are used to improve resolution and remove multiple combinations]





Signal shapes



Note the scale limits: 0.20 and 0.80 GeV^2



$D_S \rightarrow \mu^+ \nu$ and $\tau^+(\pi^+ \nu) \nu$ with 314 pb^{-1} at
 $E_{\text{CM}} = 4170 \text{ MeV}$

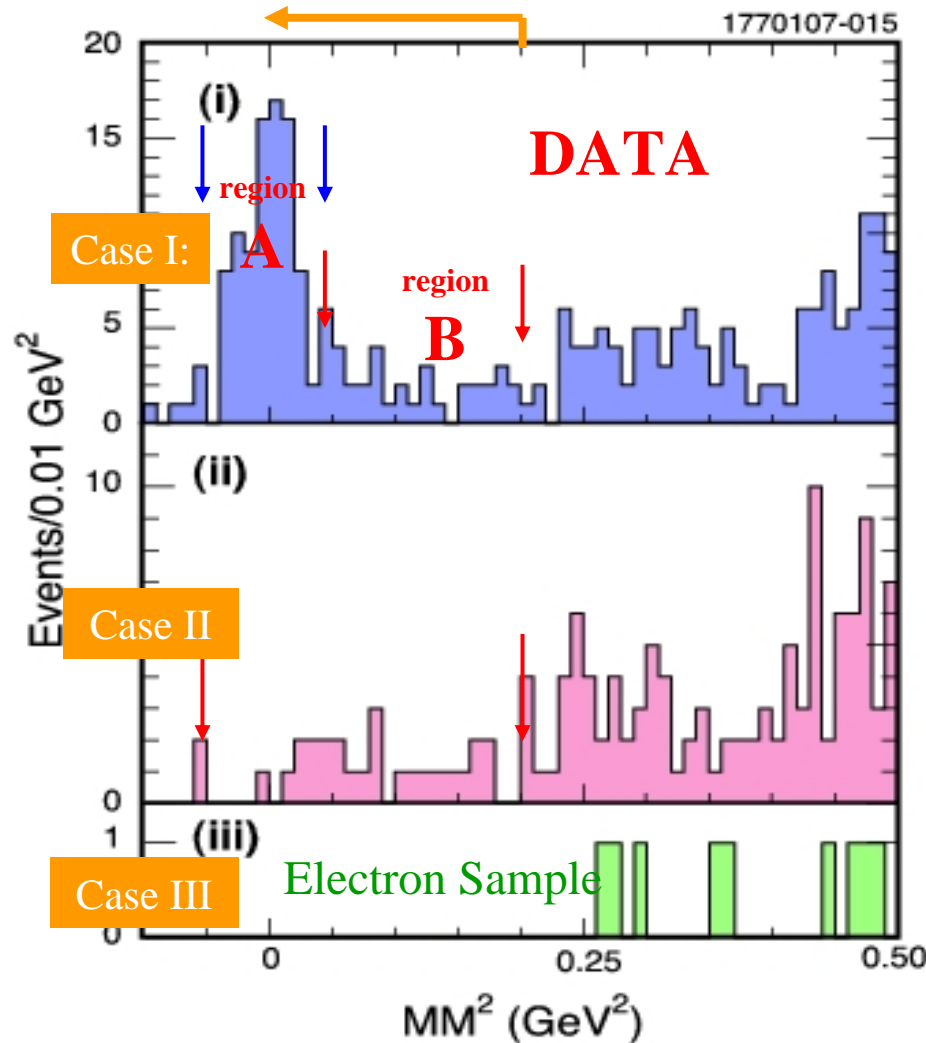
$D_S \rightarrow \mu^+ \nu$ (Case I, Reg.A)
 92 signal candidates, 3.5 bkg events:
 $B(D_S \rightarrow \mu^+ \nu) = [0.59 \pm 0.07(\text{stat}) \pm 0.03(\text{syst})]\%$

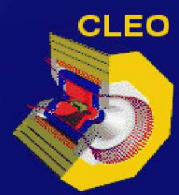
$D_S \rightarrow \tau^+ \nu$ (Case I, Reg.B+Case II)
 56 signal candidates, 7.2 bkg events:
 $B(D_S \rightarrow \tau^+ \nu) = [8.0 \pm 1.3(\text{stat}) \pm 0.4(\text{syst})]\%$
 [PDG-06: $B(D_S \rightarrow \tau^+ \nu) = (6.4 \pm 1.5)\%$]

Using the SM $B(\tau^+ \nu) / B(\mu^+ \nu)$
 the above results are aver'd:
 $B(D_S \rightarrow \mu^+ \nu) = [0.64 \pm 0.06(\text{stat}) \pm 0.03(\text{syst})]\%$
 [PDG-06: $B(D_S \rightarrow \mu^+ \nu) = (0.61 \pm 0.19)\%$]

$f_{D_S} = [270 \pm 13(\text{stat}) \pm 7(\text{syst})] \text{ MeV}$

$D_S \rightarrow e^+ \nu$ (Case III):
 No signal candidates:
 $B(D_S \rightarrow e^+ \nu) < 1.3 \times 10^{-4}$





$$D_S \rightarrow \tau^+(e^+ \nu \nu) \nu \text{ with } 200 \text{ pb}^{-1} \text{ at } E_{CM} = 4170 \text{ MeV}$$

Complimentary analysis:

$$D_S \rightarrow \tau^+ \nu \text{ with } \tau^+ \rightarrow e^+ \nu \nu.$$

$B(D_S \rightarrow \tau^+ \nu) B(\tau^+ \rightarrow e^+ \nu \nu) \sim 1.3\%$ is large [cf. $B(D_S^+ \rightarrow X e^+ \nu) \sim 8\%$]

Analysis Technique:

- ✓ Find e^+ and D_S^- tag (γ from D_S^* is *not* reconstructed, same tag modes)
- ✓ Veto events with extra tracks
- ✓ Extra energy in CC < 400 MeV

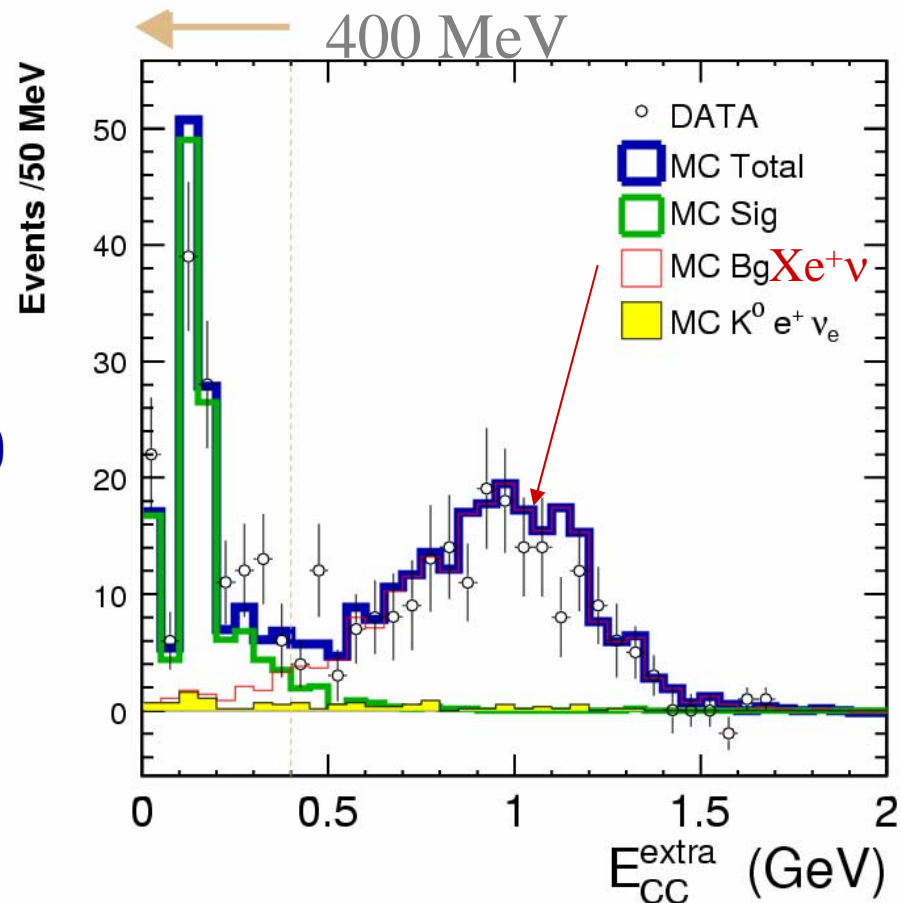
Results:

$$B(D_S \rightarrow \tau^+ \nu) = [6.3 \pm 0.8(stat) \pm 0.5(syst)]\%$$

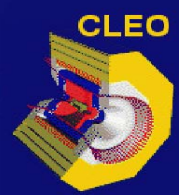
$$[PDG-06: B(D_S \rightarrow \tau^+ \nu) = (6.4 \pm 1.5)\%]$$

$$f_{D_S} = [278 \pm 17(stat) \pm 12(syst)] \text{ MeV}$$

Include yield



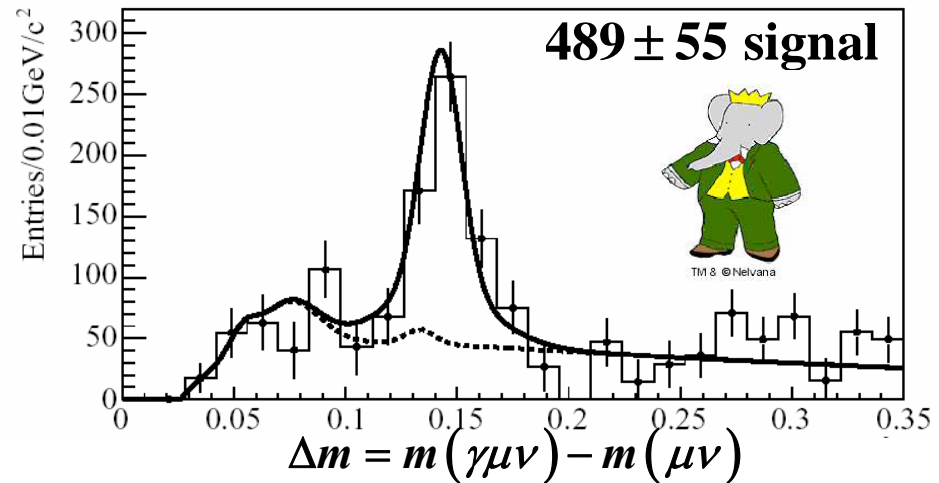
Preliminary



BABAR: $D_S \rightarrow \mu^+ \nu$ with 230 fb^{-1} at the $Y(4S)$

- ❑ Tagged $e^+ e^- \rightarrow D_S^* D_{\text{tag}} X$ events
- ❑ Reconstruct the signal side in $D_S^* \rightarrow D_S \gamma \rightarrow (\mu^+ \nu) \gamma$
- ❑ Fit $\Delta m = m(\mu^+ \nu \gamma) - m(\mu^+ \nu)$
- ❑ Results:

$D_S^* \rightarrow \gamma D_S^+ \rightarrow \gamma(\mu\nu)$ at $Y(4S)$



$\text{BR}(D_S^+ \rightarrow \phi \pi^+) = (4.71 \pm 0.46)\%$ (“BaBar aver.”):

$\text{BR}(D_S^+ \rightarrow \mu^+ \nu) = (6.74 \pm 0.83 \pm 0.26 \pm 0.66) \times 10^{-3}$

$f_{D_S} = (283 \pm 17 \pm 7 \pm 14) \text{ MeV}$

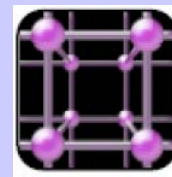
$\text{BR}(D_S^+ \rightarrow \phi \pi^+) = (3.6 \pm 0.9)\%$ (PDG04):

$\text{BR}(D_S^+ \rightarrow \mu^+ \nu) = (5.15 \pm 0.63 \pm 0.20 \pm 1.29) \times 10^{-3}$

$f_{D_S} = (248 \pm 15 \pm 6 \pm 31) \text{ MeV}$

$$\frac{\Gamma(D_S \rightarrow \mu^+ \nu)}{\Gamma(D_S \rightarrow \phi \pi^+)} = 0.143 \pm 0.018 \pm 0.006$$

Comparison with theory



Summary of exper. results:

- $f_{D^+} = [223 \pm 17(stat) \pm 3(syst)] \text{ MeV}$
- $f_{D_s} = [273 \pm 10(stat) \pm 5(syst)] \text{ MeV}$
[Weighted average; syst. errors are mostly uncorrelated]
- $\frac{f_{D_s}}{f_{D^+}} = 1.22 \pm 0.09 \pm 0.03$ **Prelim.**
- Babar: $f_{D_s} = [283 \pm 17(stat) \pm 7(syst) \pm 14(\phi\pi)] \text{ MeV}$

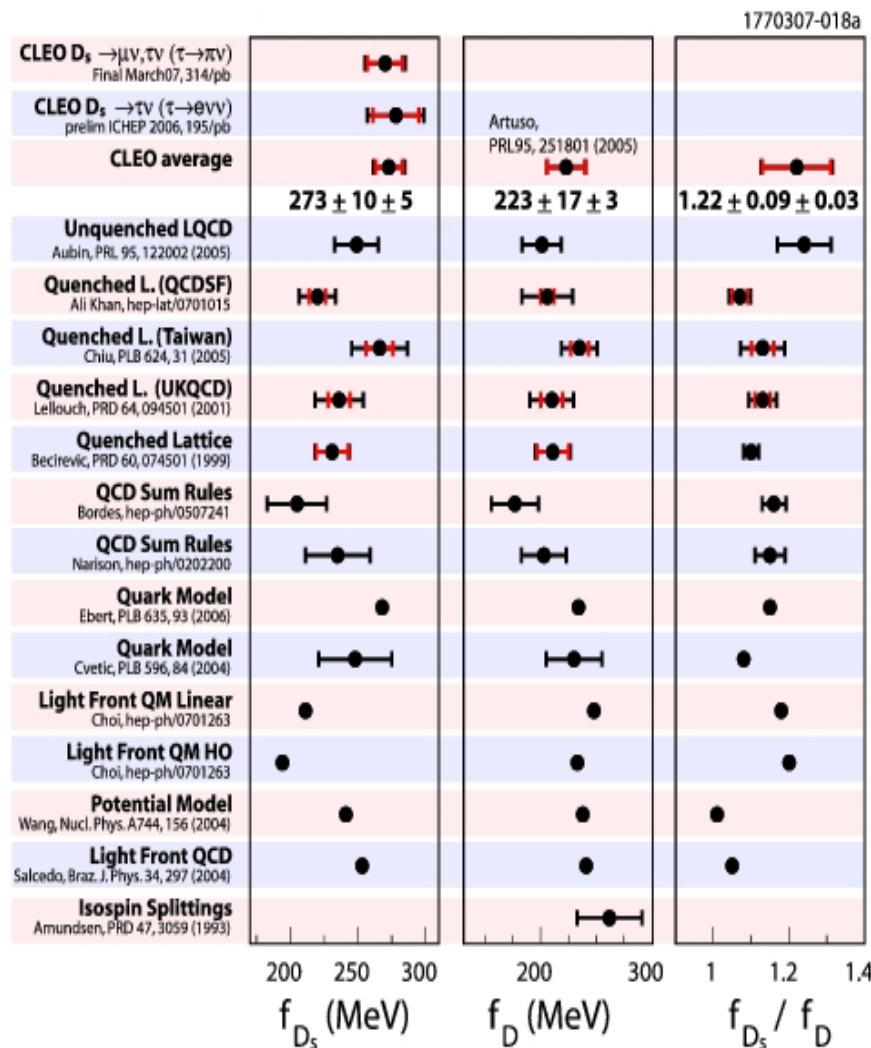
Experiment: statistically limited

An example of theor. predictions:

[Unquenched LQCD [PRL 95, 122002 (2005)]]

- $f_{D^+} = [201 \pm 3(stat) \pm 17(syst)] \text{ MeV}$
- $f_{D_s} = [249 \pm 3(stat) \pm 16(syst)] \text{ MeV}$
- $\frac{f_{D_s}}{f_{D^+}} = 1.24 \pm 0.07$

LQCD: systematically limited





Semileptonic decays

Semileptonic decays

□ The hadronic current can be parameterized by form factors:

✓ For P to P transitions [omitting $f_0(q^2)$]:

$$H^\mu = f_+(q^2)(p_i + p_f)^\mu$$

Gold-plated for both theory and experiment

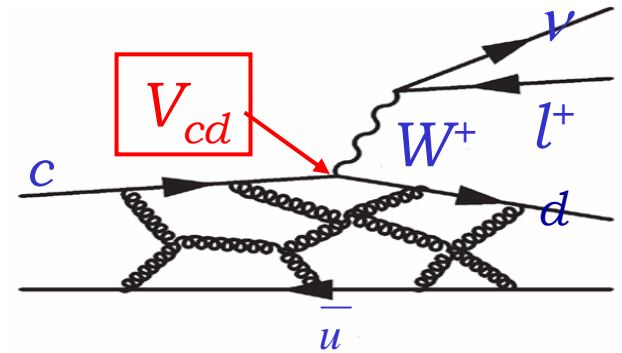
✓ For P to V transitions three form factors are needed [omitting $A_0(q^2)$ and $A_3(q^2)$]:

$$H^\mu = \frac{2ie^{\mu\nu\alpha\beta}}{M_D + m_V} e_\nu^* p_{f\alpha} p_{i\beta} V(q^2) - (M_D + m_V) e^{\mu\nu} A_1(q^2) + \frac{e \cdot q}{M + m_V} (p_i + p_f)^\mu A_2(q^2)$$

More complicated; unquenched LQCD calculations do not exist

□ Use V_{cs} and V_{cd} from the CKM unitarity constraints to measure absolute semileptonic form factors and compare them to theory

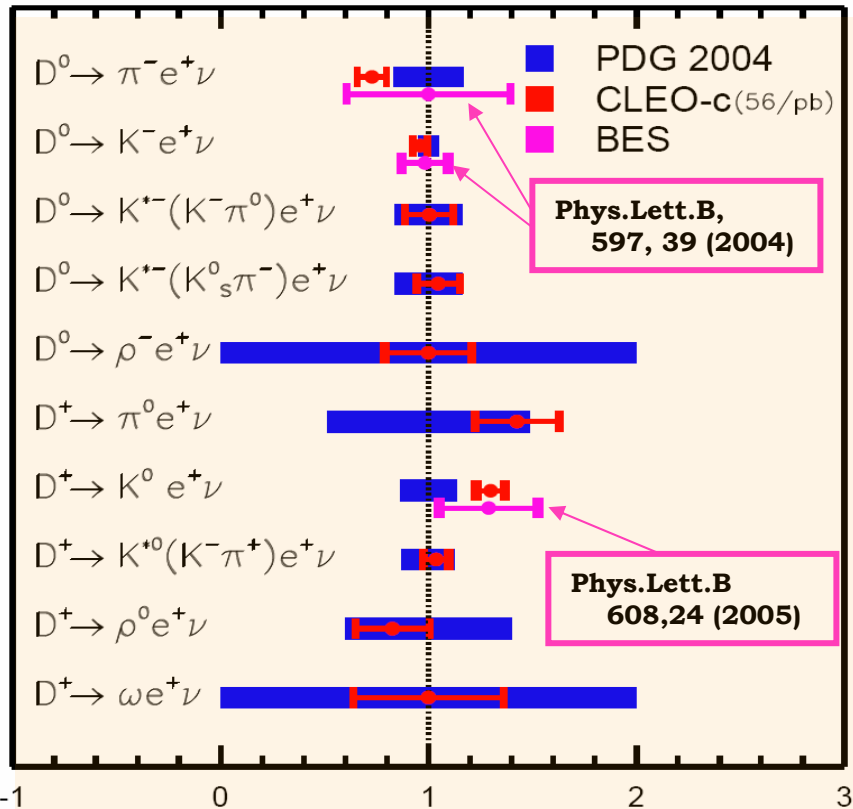
$$M(D^0 \rightarrow \pi^- l^+ \nu) = -i \frac{G_{\text{Fermi}}}{\sqrt{2}} V_{cd} L_\mu H^\mu$$





SL at CLEO-c: $56 \text{ pb}^{-1} \rightarrow 281 \text{ pb}^{-1}$ at the $\psi(3770)$

Status as of 2005 (56 pb^{-1})



**Most precise BFs for ALL modes;
Two first observations.**

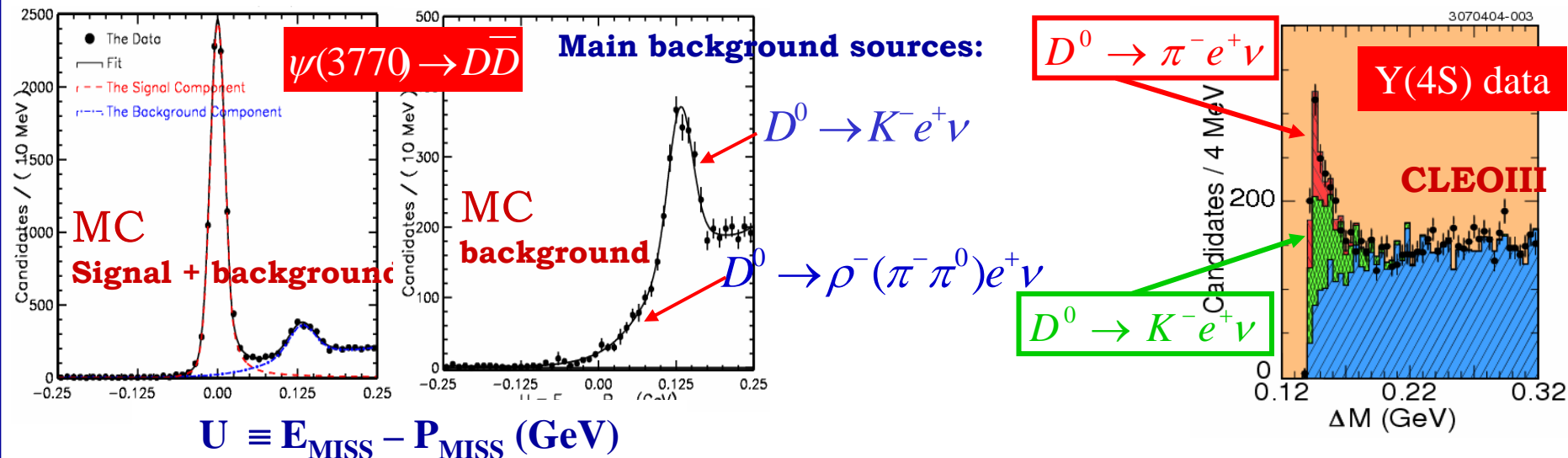
Form Factor Studies with 281 pb^{-1} :

- ✓ Cabibbo-favored $P \rightarrow P$ semileptonic transitions
 - $D^0 \rightarrow K^- e^+ \nu$ $N \sim 7000$
 - $D^+ \rightarrow \bar{K}^0 e^+ \nu$ $N \sim 2900$
- ✓ Cabibbo-suppressed $P \rightarrow P$ semileptonic transitions
 - $D^0 \rightarrow \pi^- e^+ \nu$ $N \sim 700$
 - $D^+ \rightarrow \pi^0 e^+ \nu$ $N \sim 290$
- ✓ Cabibbo favored $P \rightarrow V$ semileptonic transitions
 - $D^+ \rightarrow K^{*0} e^+ \nu$ $N \sim 2800$
- ✓ Cabibbo suppressed $P \rightarrow V$ semileptonic transitions
 - $D^0 \rightarrow \rho^- e^+ \nu$ $N \sim 130$
 - $D^+ \rightarrow \rho^0 e^+ \nu$ $N \sim 170$

Rare SL Decays with 281 pb^{-1} :

- ✓ $D^+ \rightarrow \eta / \eta' / \phi e^+ \nu$
- ✓ $D^0 \rightarrow K^- \pi^+ \pi^- e^+ \nu$

Example for $D^0 \rightarrow \pi^- e^+ \nu$



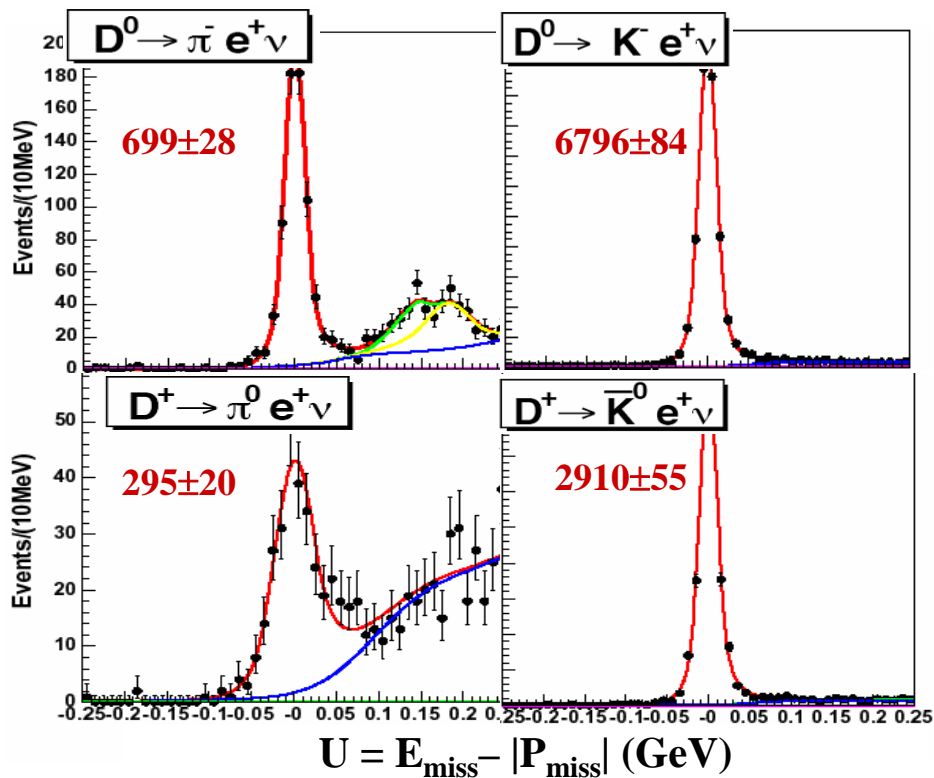
- Background is small and peaks outside the signal region (kinematic separation)
- Most background comes from cross-feed among D SL decays

- When the momentum of the parent D is unmeasured, the separation between signal and background is poorer
- Example (CLEO, PRL **94**, 011802 (2005)) the $D^0 \rightarrow \pi^- e^+ \nu$ signal mode is combined with π_{slow} : $D^{*-} \rightarrow D^0 \pi_{\text{slow}}$
- Fits are made to $\Delta M \equiv M(D^{*-}) - M(D^0)$ in bins of q^2

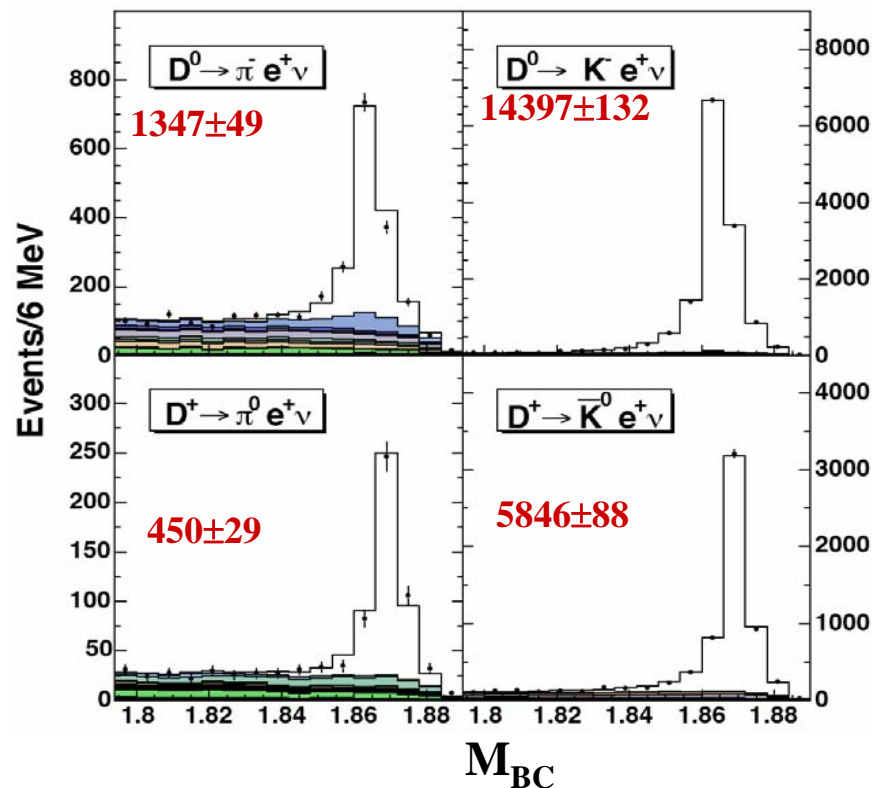
$D \rightarrow K/\pi e^+ \nu$ with 281 pb^{-1} at the $\psi(3770)$



1) Tagged CLEO-c analysis:



2) Untagged CLEO-c analysis: [analogous to neutrino reconstruction at the Y(4S)]



The untagged analysis has larger signal yields but larger systematic uncertainties



$D \rightarrow K/\pi e^+ \nu$ at the Y(4S)

Tagged $e^+ e^- \rightarrow D^{(*)}_{\text{tag}} D^{*-} X$ events (about 56×10^3 tags in total)

Similar to the CLEO-c tagged analysis

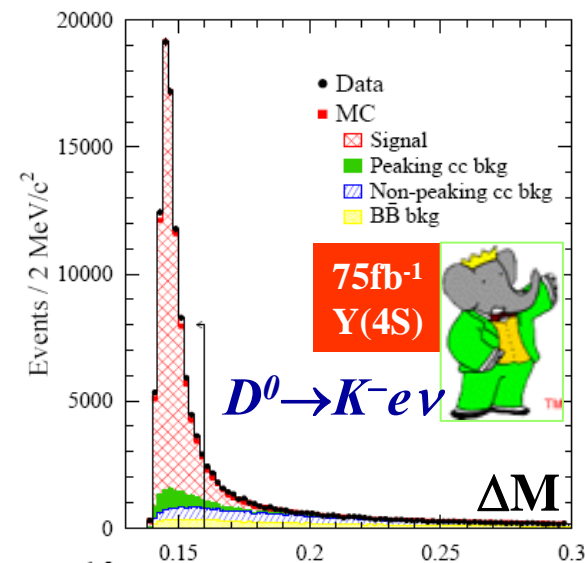
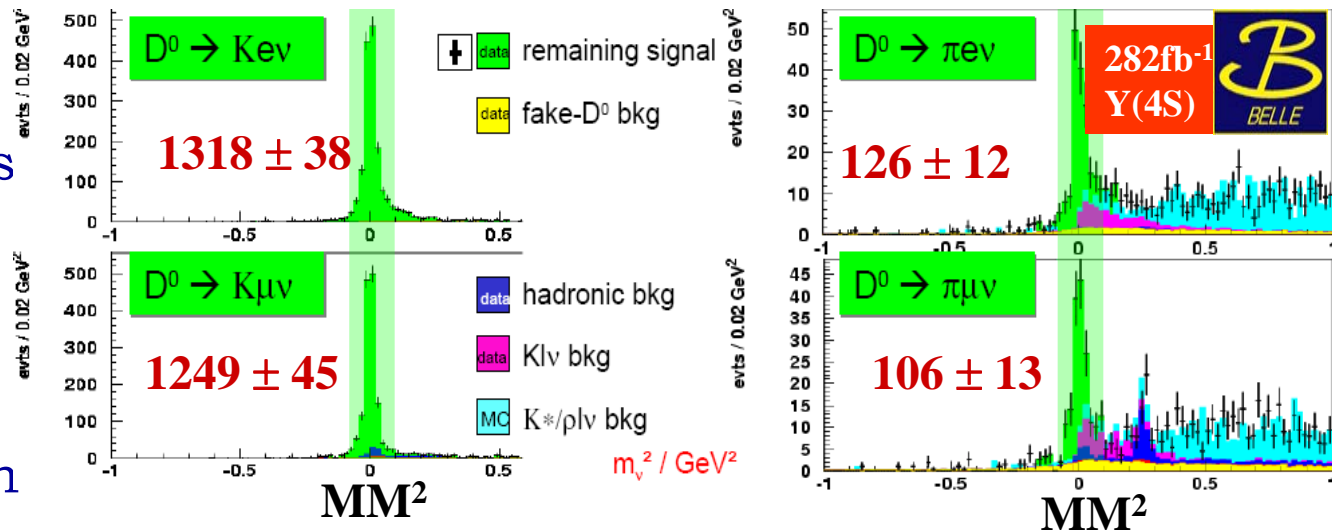
Excellent q^2 resol'n

Similar to the CLEO III untagged $D \rightarrow K/\pi e^+ \nu$

The neutrino momentum is estimated using all other particles in the event (no tag required)

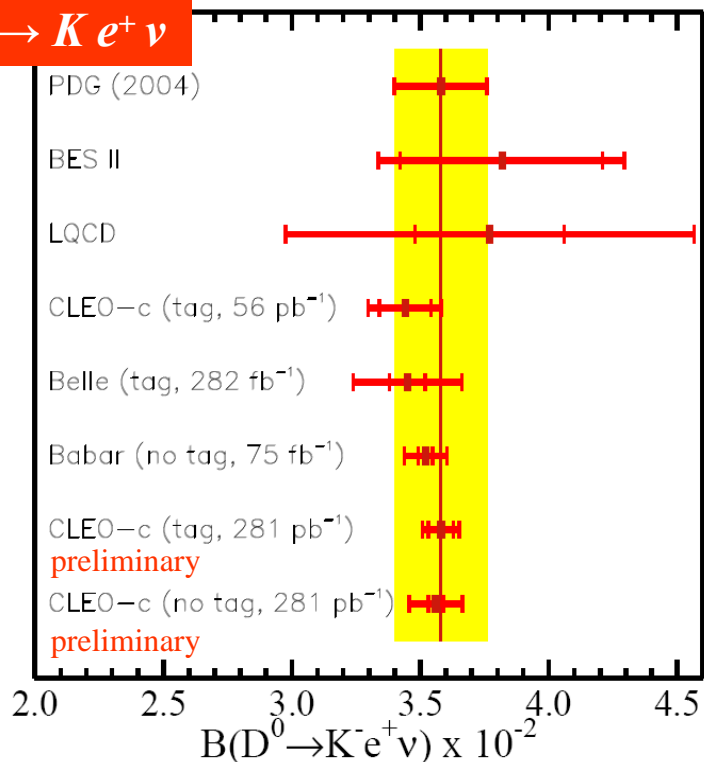
The $D^0 \rightarrow K^- e^+ \nu$ signal mode is combined with $\pi_{\text{slow}} : D^{*-} \rightarrow D^0 \pi_{\text{slow}}$

Plot on the right: $\Delta M \equiv M(D^{*-}) - M(D^0)$ with about 74×10^3 signal events

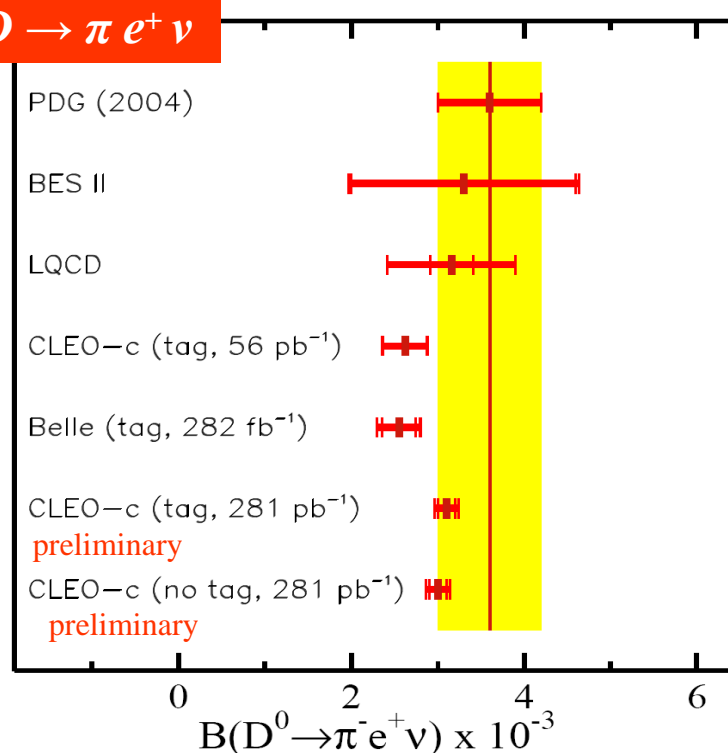


$D \rightarrow K/\pi e^+ \nu$: branching fractions

$D \rightarrow K e^+ \nu$



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



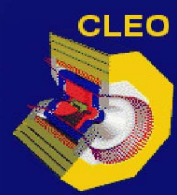
Babar measures:

$$\frac{B(D^0 \rightarrow K^- e \nu)}{B(D^0 \rightarrow K \pi)} = 0.927 \pm 0.007 \pm 0.012;$$

$$PDG-06: B(D^0 \rightarrow K \pi) = (3.80 \pm 0.07) \% \Rightarrow$$

$$B(D^0 \rightarrow K^- e \nu) = (3.522 \pm 0.027 \pm 0.045 \pm 0.065) \%$$

Good consistency between measurements
LQCD precision lags experiment



Form Factor Models

- The Simple Pole Model:

$$f_+(q^2) = \frac{f(0)}{\left(1 - q^2 / M_{pole}^2\right)};$$

- The Modified Pole Model [Phys.Lett.B 52, 478,417(2000)]:

$$f_+(q^2) = \left(\frac{f(0)}{1 - q^2 / M_{D^*(s)}^2}\right) \left(\frac{1}{1 - \alpha q^2 / M_{D^*(s)}^2}\right);$$

- The ISGW2 Model [Phys.Rev. D 52,2783,(1985)]:

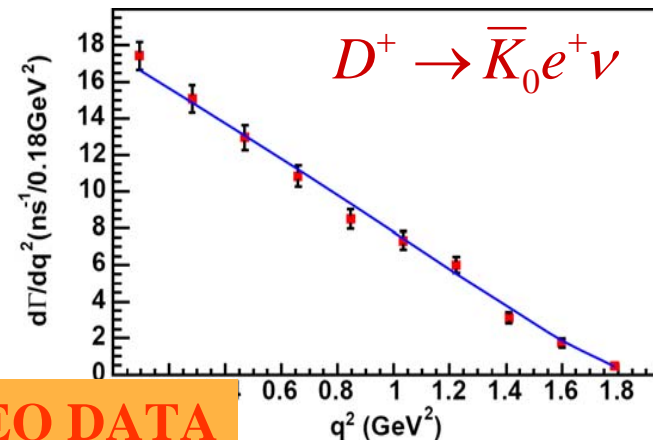
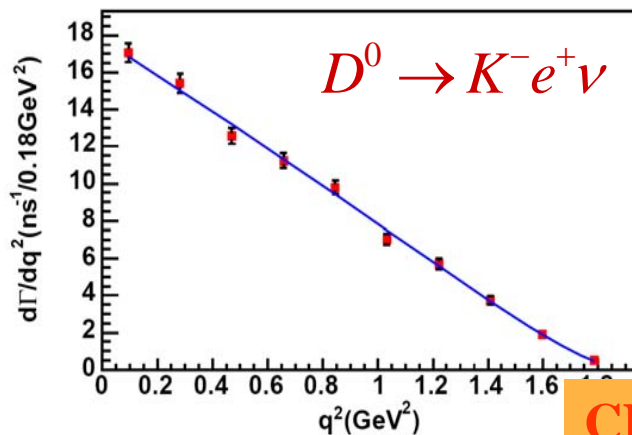
$$f(q^2) = \left(1 + \frac{r^2}{12} (q_{max}^2 - q^2)\right)^{-2}$$

- The Series Parameterization [T. Becher and R. Hill, hep-ph/0509090]

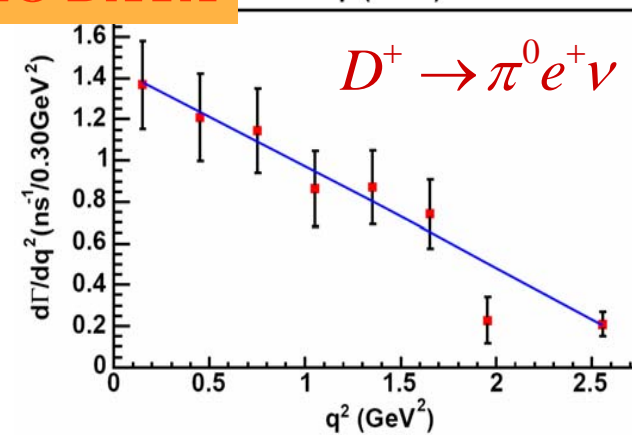
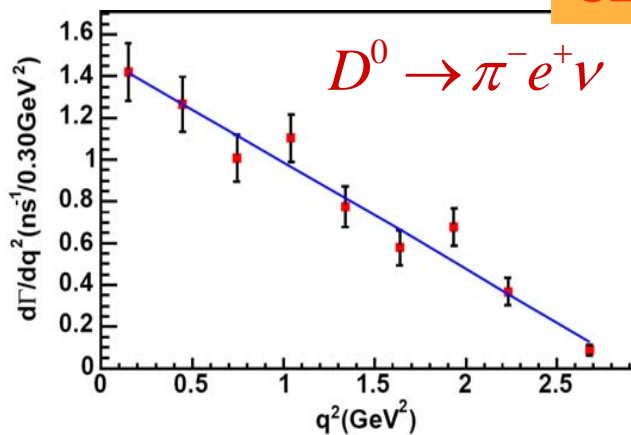
$D \rightarrow K/\pi e^+ \nu$: CLEO-c fits (tagged analysis)

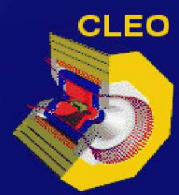
$$\frac{d\Gamma(D \rightarrow K(\pi)e\nu)}{dq^2} = \frac{G_F^2 |V_{cs(cd)}|^2 P_{K(\pi)}^3}{24\pi^2} |f_+(q^2)|^2$$

Simultaneous fits to isospin conjugate pairs for the simple pole model:

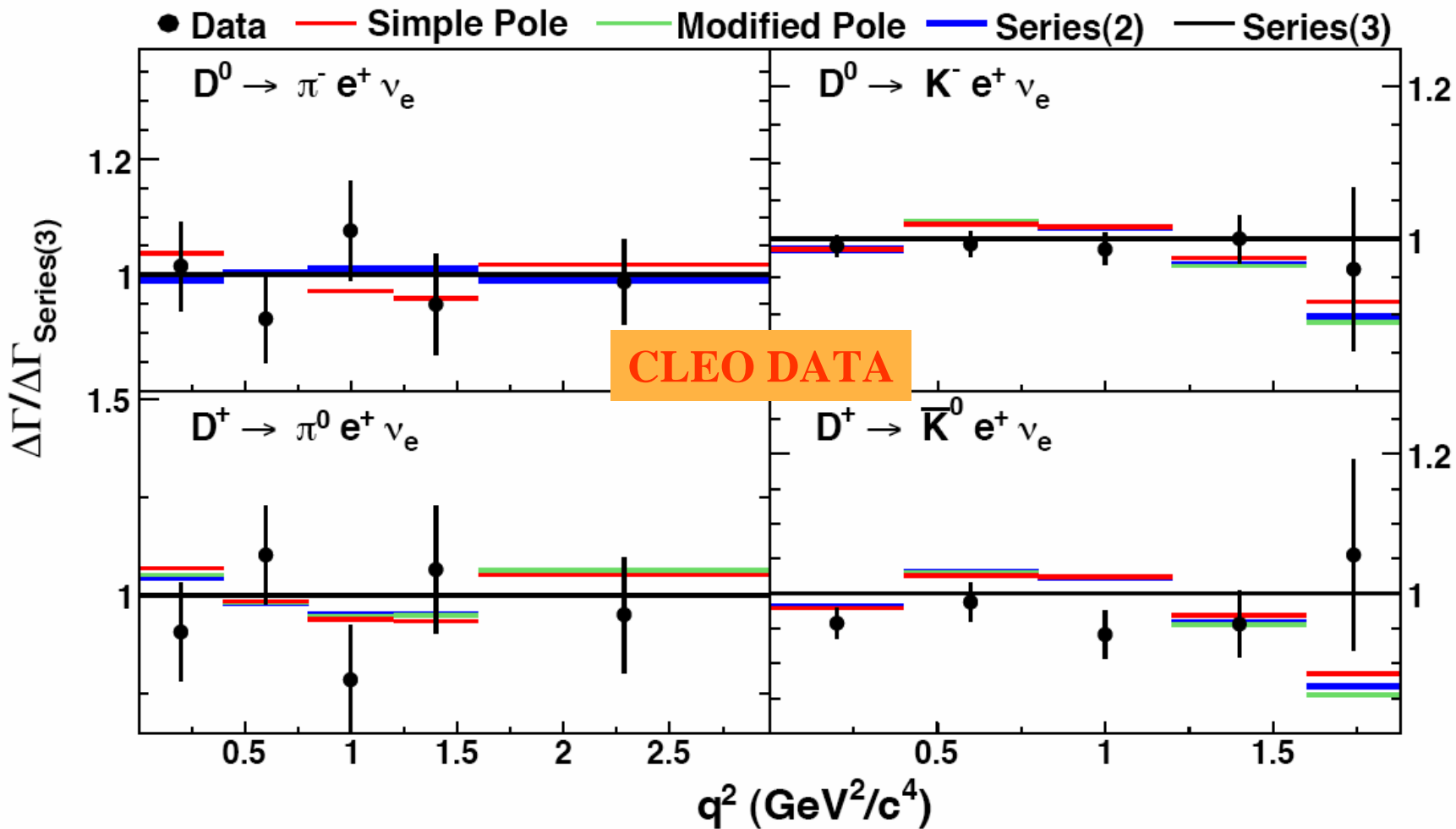


CLEO DATA

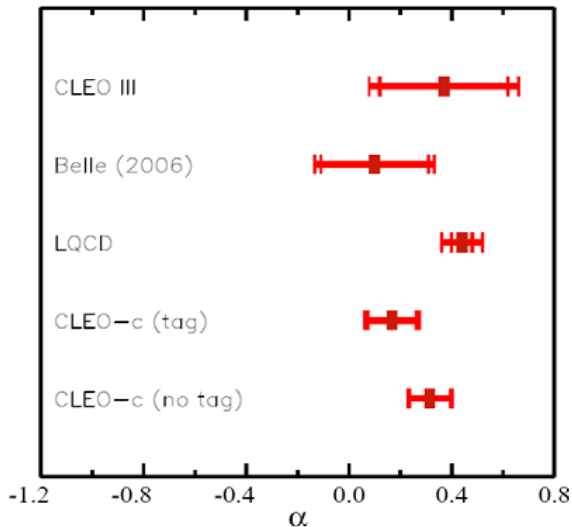
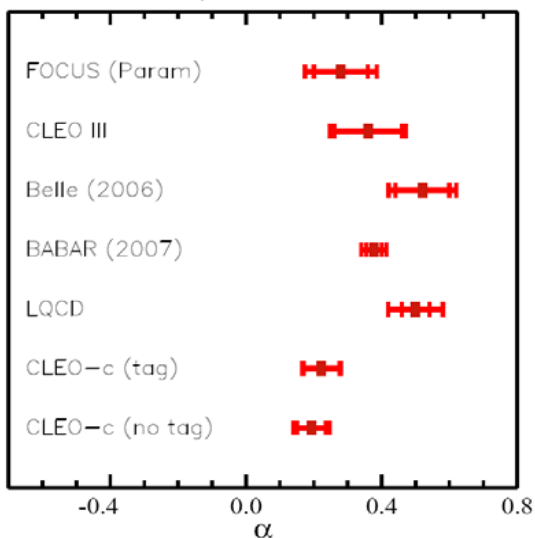
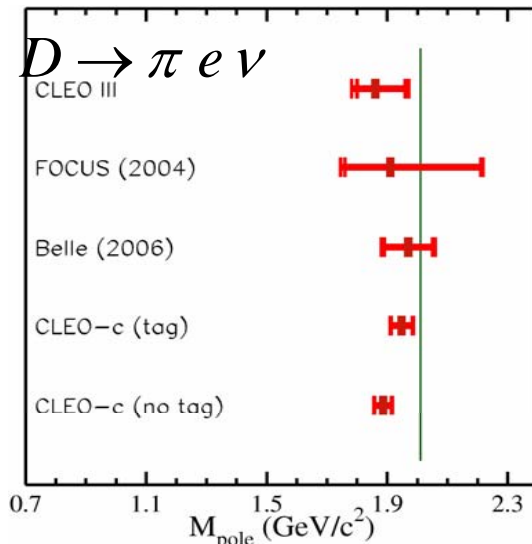
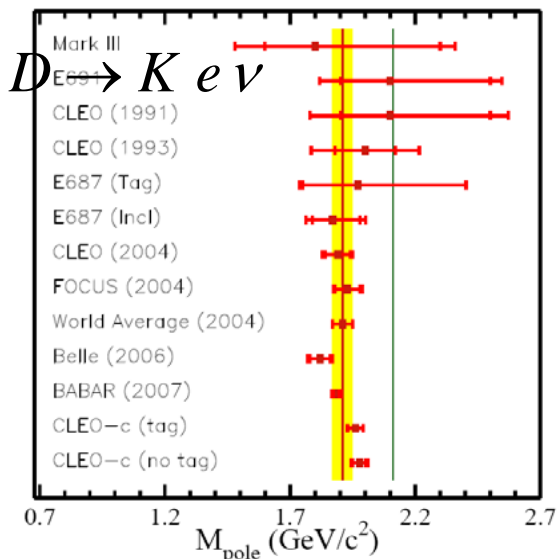




$D \rightarrow K/\pi e^+ \nu$: CLEO-c fits (untagged analysis)



$D \rightarrow K/\pi e^+ \nu$: form factor shape results



CLEO is most precise for $\pi e \nu$,
Babar is most precise for $K e \nu$

Some tension between CLEO-c
and Babar/Belle meas'nts;
LQCD precision is comparable
to experiment

$$D \rightarrow K / \pi e^+ \nu: f_+(q^2)$$


- Plotted LQCD results (blue) are recent results of FNAL+MILC unquenched three flavor LQCD [C. Aubin *et al.*, PRL **94** 011601 (2005)]

✓ Lattice systematic uncertainties dominate:

✓ $LQCD(D \rightarrow K e \nu)$:

$$f_+(0) = 0.73 \pm 0.03 \pm 0.07;$$

$$\alpha = 0.50 \pm 0.04 \pm 0.07.$$

✓ $LQCD(D \rightarrow \pi e \nu)$:

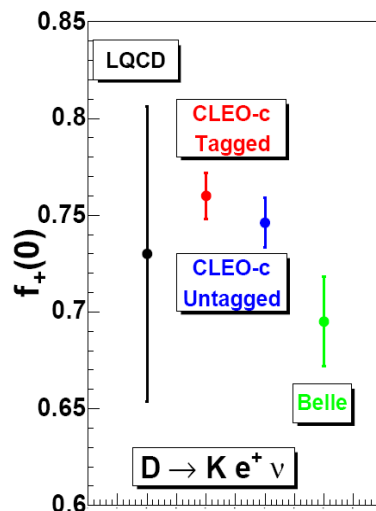
$$f_+(0) = 0.64 \pm 0.03 \pm 0.06;$$

$$\alpha = 0.44 \pm 0.04 \pm 0.07.$$

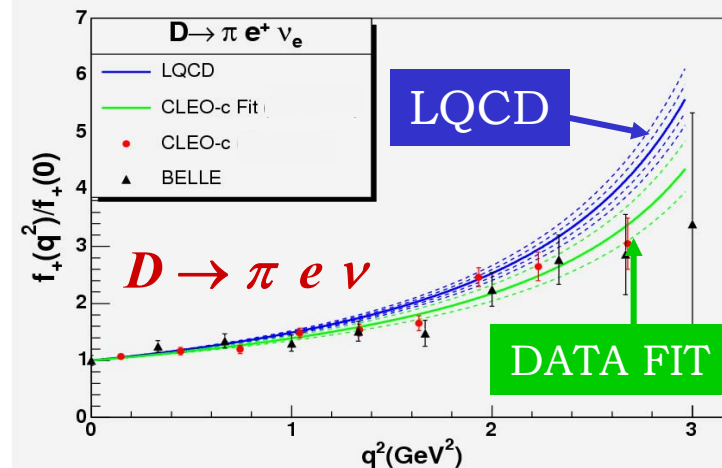
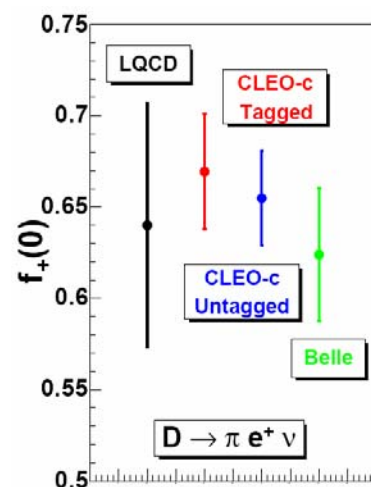
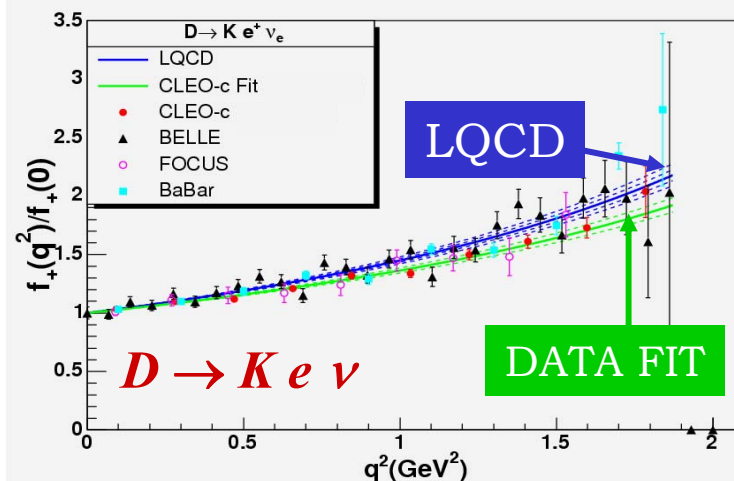
- The green lines are untagged CLEO-c fits

- Babar result for $f_+(0)$:

$$f_+(0) = 0.727 \pm 0.007 \pm 0.005 \pm 0.007$$



CLEO-c, Babar, Belle, FOCUS



$D \rightarrow V e^+ \nu$

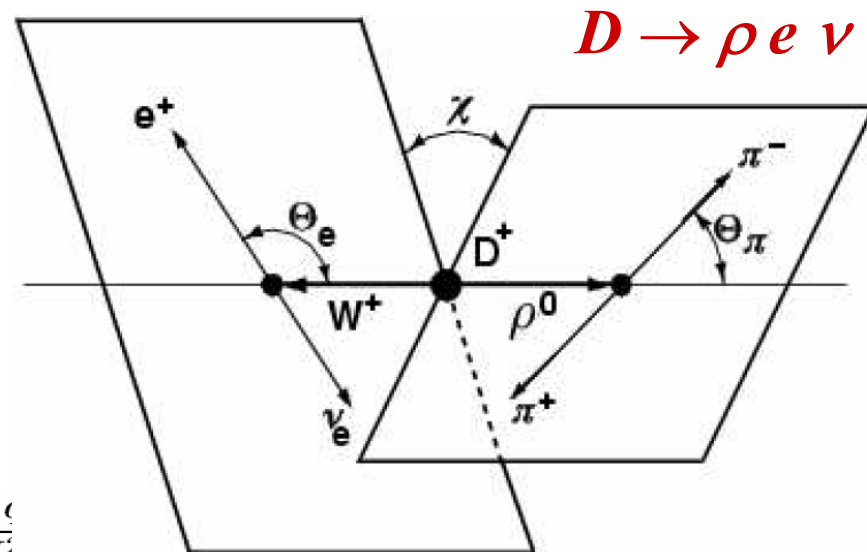
- Five kinematic variables describe the decay rate (plot):

$$q^2, \cos \theta_e, \cos \theta_\pi, \chi, m(\pi\pi)$$

- The decay rate we make a fit to:

$$\frac{d\Gamma}{dq^2 d \cos \theta_\pi d \cos \theta_e d\chi} = \mathcal{B}(\rho^0 \rightarrow \pi\pi) \frac{3G_F^2}{8(4\pi)^4} |V_{cs}|^2 \frac{p_{\rho^0} \epsilon}{M_D^2} \left\{ \begin{aligned} & (1 + \cos \theta_e)^2 \sin^2 \theta_\pi |H_+(q^2)|^2 \\ & + (1 - \cos \theta_e)^2 \sin^2 \theta_\pi |H_-(q^2)|^2 \\ & + 4 \sin^2 \theta_e \cos^2 \theta_\pi |H_0(q^2)|^2 \\ & + 4 \sin \theta_e (1 + \cos \theta_e) \sin \theta_\pi \cos \theta_\pi \cos \chi |H_+(q^2) H_0(q^2)| \\ & - 4 \sin \theta_e (1 - \cos \theta_e) \sin \theta_\pi \cos \theta_\pi \cos \chi |H_-(q^2) H_0(q^2)| \\ & - 2 \sin^2 \theta_e \sin^2 \theta_\pi \cos 2\chi |H_+(q^2) H_-(q^2)| \end{aligned} \right\}$$

- Dependence on the form factors enters through H_+ , H_- and H_0 .



Form Factor Ratios R_V and R_2

- The helicity amplitudes are given by

$$H_{\pm}(q^2, m_{\pi\pi}) = (M_D + m_{\pi\pi}) A_1(q^2) \mp 2 \frac{M_D P_{\pi\pi}}{M_D + m_{\pi\pi}} V(q^2);$$

$$H_0(q^2, m_{\pi\pi}) = \frac{1}{2m_{\pi\pi} \sqrt{q^2}} \left[(M_D^2 - m_{\pi\pi}^2 - q^2)(M_D + m_{\pi\pi}) A_1(q^2) - 4 \frac{M_D^2 P_{\pi\pi}^2}{M_D + m_{\pi\pi}} A_2(q^2) \right]$$

- Form factors are parameterized using the simple pole model (*i.e.*, vector dominance):

$$A_{1(2)}(q^2) = \frac{A_{1(2)}(0)}{1 - q^2 / M_A^2}; \quad V(q^2) = \frac{V(0)}{1 - q^2 / M_V^2}$$

- 4D fits to the decay rate for form factor ratios R_V and R_2 are made:

$$R_V \equiv \frac{V(0)}{A_1(0)}; \quad R_2 \equiv \frac{A_2(0)}{A_1(0)}$$

- The fitting technique is described in D.M.Schmidt, R.J.Morrison and M.S.Witherell in *Nucl. Instr. and Meth.* **A328**, 547 (1993): a multidimensional fit to variables modified by experimental acceptance and resolution taking into account correlations among them.

$D \rightarrow \rho e^+ \nu$ with 281 pb^{-1} at the $\psi(3770)$



- Two isospin conjugate modes $D^+ \rightarrow \rho^0 e^+ \nu$ and $D^0 \rightarrow \rho^- e^+ \nu$ (~ 300 events) are fit **simultaneously**:

$$R_V = 1.40 \pm 0.25 \text{ (stat)} \pm 0.03 \text{ (syst)}$$

$$R_2 = 0.57 \pm 0.18 \text{ (stat)} \pm 0.06 \text{ (syst)}$$

This is the first multidimensional fit for form factors in Cabibbo-suppressed $P \rightarrow V l \nu$ transitions

$$\mathbf{B}(D^0 \rightarrow \rho^- e^+ \nu) = (1.56 \pm 0.16 \pm 0.09) \times 10^{-3}$$

$$\mathbf{B}(D^+ \rightarrow \rho^0 e^+ \nu) = (2.32 \pm 0.20 \pm 0.12) \times 10^{-3}$$

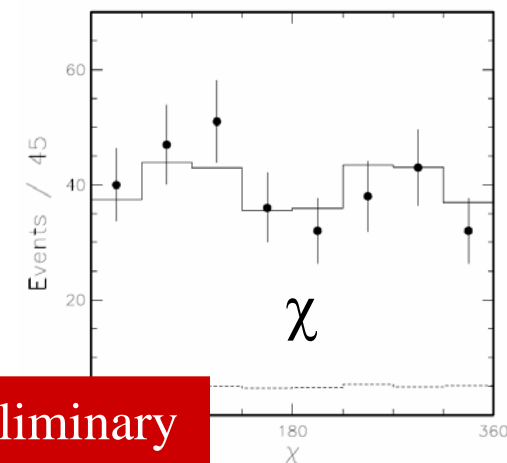
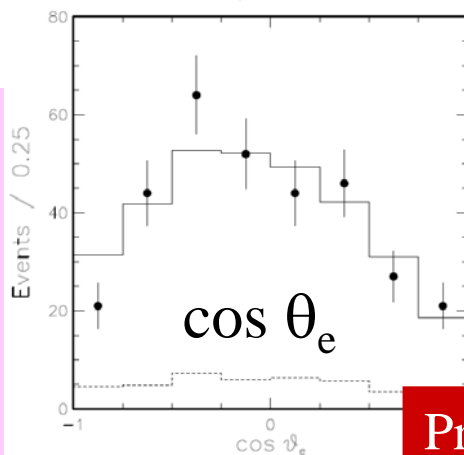
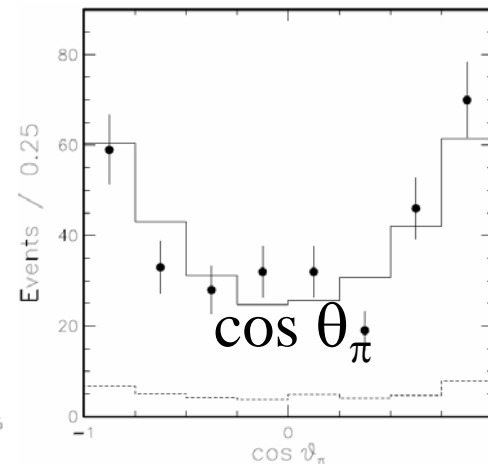
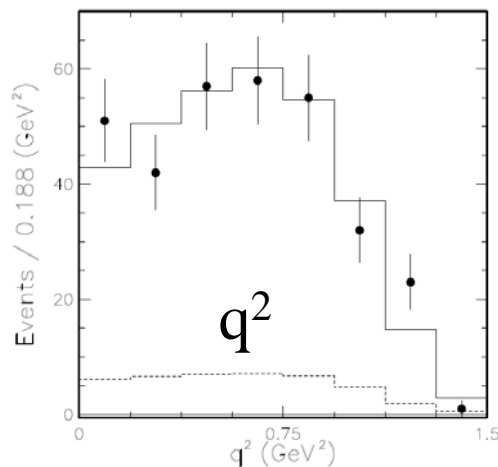
Isospin average:

$$\Gamma(D^0 \rightarrow \rho^- e^+ \nu) = (0.41 \pm 0.03 \pm 0.02) \times 10^{-2} \text{ ps}^{-1}$$

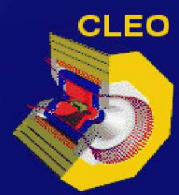
this analysis

$$\Gamma(D^0 \rightarrow \rho^- e^+ \nu) = (0.44 \pm 0.06 \pm 0.02) \times 10^{-2} \text{ ps}^{-1}$$

FOCUS PLB 637,32 (2006)



Preliminary



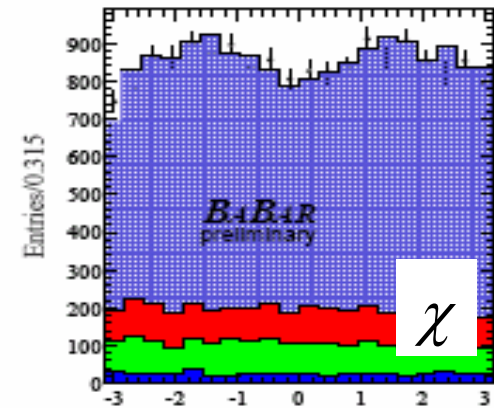
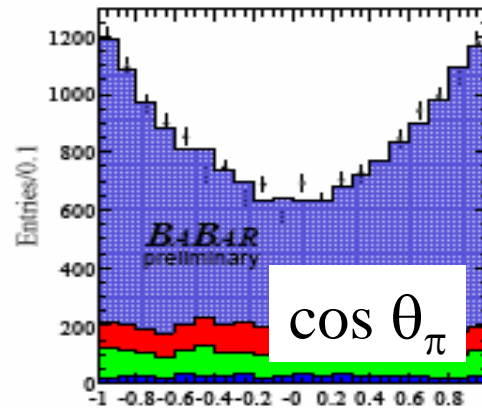
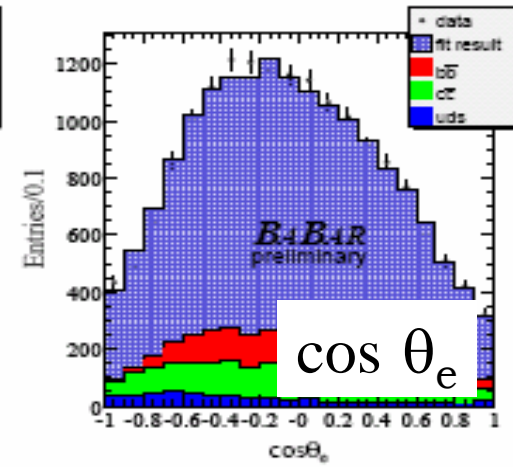
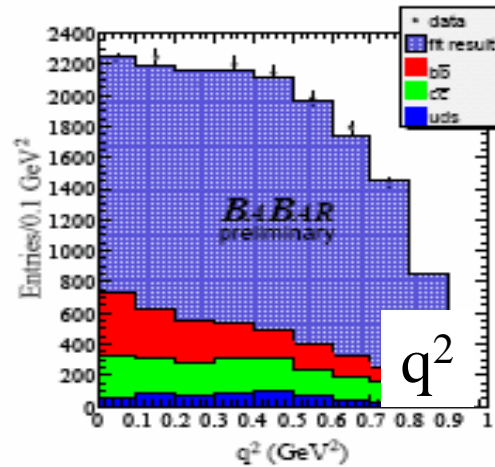
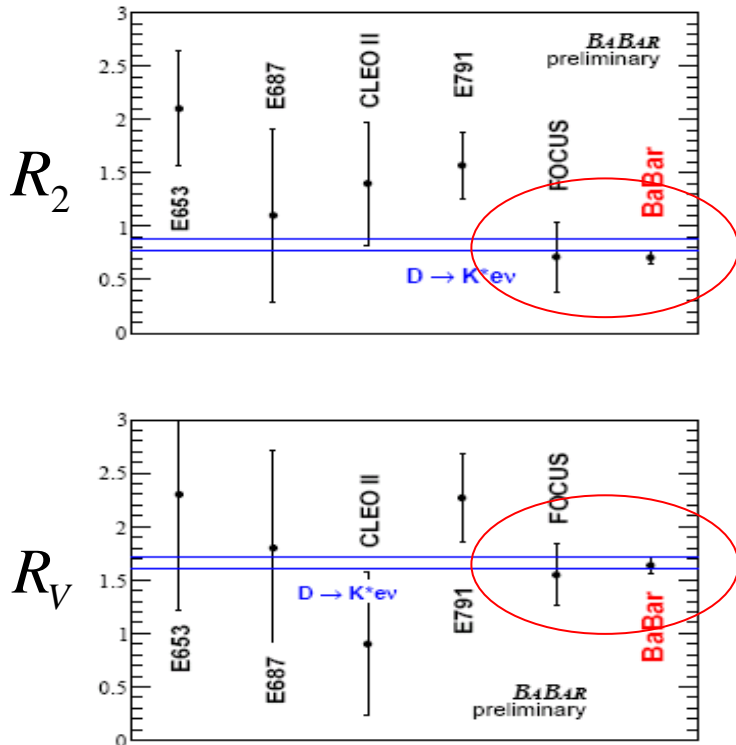
$D_S \rightarrow \phi e^+ \nu$ with 79 fb^{-1} at the Y(4S)



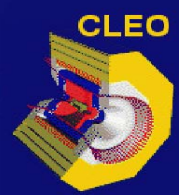
A fit to about reconstructed 13,000 signal events:

$$R_V = 1.64 \pm 0.07 \text{ (stat)} \pm 0.04 \text{ (syst)}$$

$$R_2 = 0.71 \pm 0.06 \text{ (stat)} \pm 0.03 \text{ (syst)}$$



Preliminary



$D \rightarrow X e^+ \nu$: with 281 pb^{-1} at the $\psi(3770)$

Results:

$$B(D_{incl\ semil}^0) = (6.46 \pm 0.17 \pm 0.13)\%$$

$$B(D_{incl\ semil}^+) = (16.13 \pm 0.20 \pm 0.33)\%$$

Consistent with the isospin symmetry:

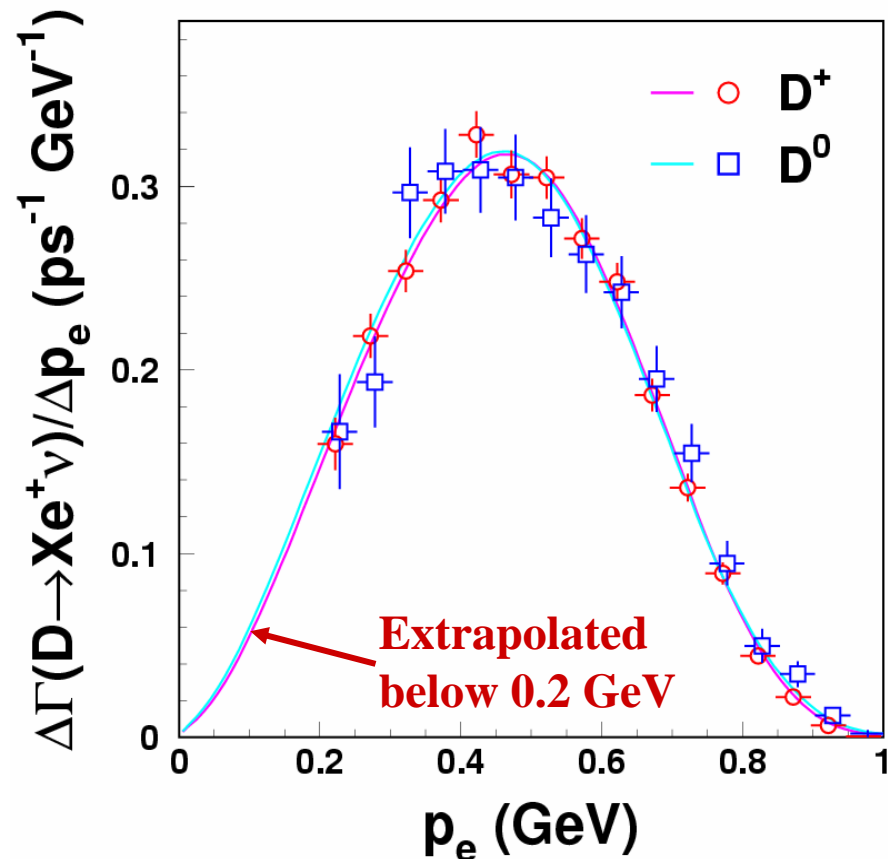
$$\frac{\Gamma_{D^+}^{SL}}{\Gamma_{D^0}^{SL}} = \frac{B_{D^+}^{SL}}{B_{D^0}^{SL}} \times \frac{\tau_{D^0}}{\tau_{D^+}} = 0.985 \pm 0.028 \pm 0.015$$

Consistent with the sum of exclusive SL modes (56/pb)

$$\sum B(D_{excl\ semil}^0) = (6.1 \pm 0.2 \pm 0.2)\%$$

$$\sum B(D_{excl\ semil}^+) = (15.1 \pm 0.5 \pm 0.5)\%$$

which excludes the possibility of new D SL modes with large branching fractions

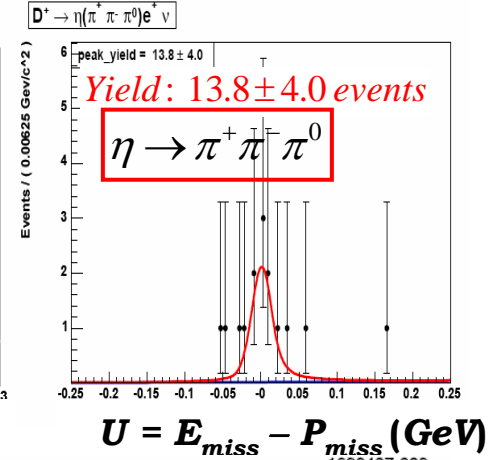
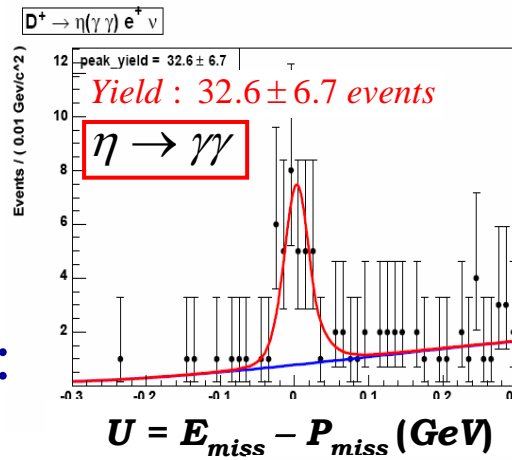




Observation of $D^+ \rightarrow \eta e^+ \nu$ Evidence for $D^+ \rightarrow K^- \pi^+ \pi^- e^+ \nu$



- Search for $D^+ \rightarrow \eta e^+ \nu$, $\eta' e^+ \nu$ and $\phi e^+ \nu$ (allows to study η - η' and ω - ϕ mixing):
- Search for $D^0 \rightarrow K^- \pi^+ \pi^- e^+ \nu$.
10 candidates; ~ 1.8 bkg events (about 4.0σ significance)



Results:

Preliminary

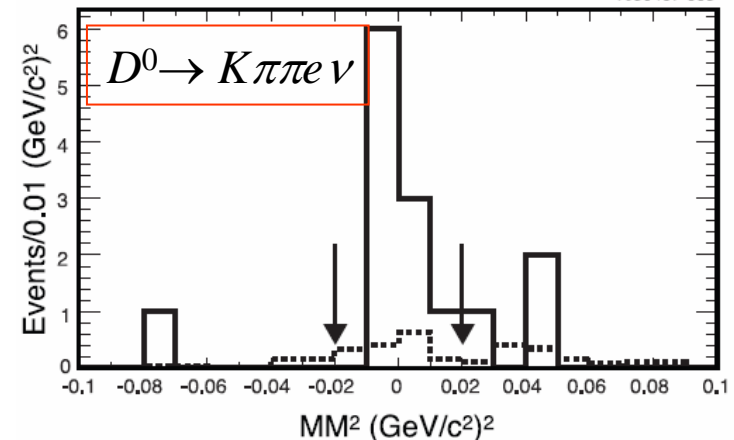
$$B(D^+ \rightarrow \eta e^+ \nu) = (1.29 \pm 0.19 \pm 0.07) \times 10^{-3}$$

$$B(D^+ \rightarrow \eta' e^+ \nu) < 2.0 \times 10^{-4} \text{ (90\% C.L.)}$$

$$B(D^+ \rightarrow \phi e^+ \nu) < 1.6 \times 10^{-4} \text{ (90\% C.L.)}$$

$$B(D^0 \rightarrow K^- \pi^+ \pi^- e^+ \nu) = (2.8_{-1.1}^{+1.4} \pm 0.3) \times 10^{-4}$$

$$B(D^0 \rightarrow K_1^- (1270) e^+ \nu) = (7.6_{-3.0}^{+4.1} \pm 0.6 \pm 0.7) \times 10^{-4}$$



Two orders of magnitude more restrictive limits

All consistent with ISGW2 within large uncertainties
Do not cover the gap between incl and excl measurements



Other analyses



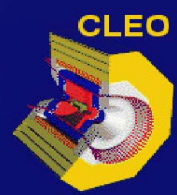
- Model independent form factors in $D^+ \rightarrow K^- \pi^+ e^+ \nu$:
FOCUS: PLB 633, 183 (2006); CLEO-c: PRD 74, 052001 (2006)
- Results on D_S semileptonic decays from $E_{\text{CM}} = 4.170$ GeV are to appear soon



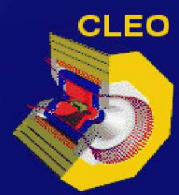
Conclusions and Outlook



- ❑ Charm leptonic and semileptonic decays provide stringent tests of theory.
- ❑ Current precision of leptonic experimental and LQCD results is comparable. Experimental results are statistically limited; LQCD results are limited by systematic uncertainties.
- ❑ Experimental precision exceeds the current LQCD precision for semileptonic branching fractions and absolute form factors.
- ❑ Charm LSL results from $Y(4S)$ analyses are competitive in some cases; very large $Y(4S)$ data samples make possible new techniques.
- ❑ Expect a 2 - 3 fold increase in the size of CLEO-c data sample and a complete suite of leptonic and semileptonic measurements in the next few years.
- ❑ On a longer time scale, BES III (China) should be able to achieve higher precision and further constrain theory.



Additional Slides



CESR and CLEO



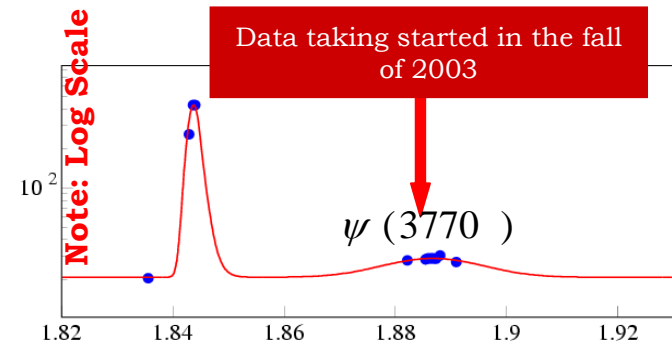
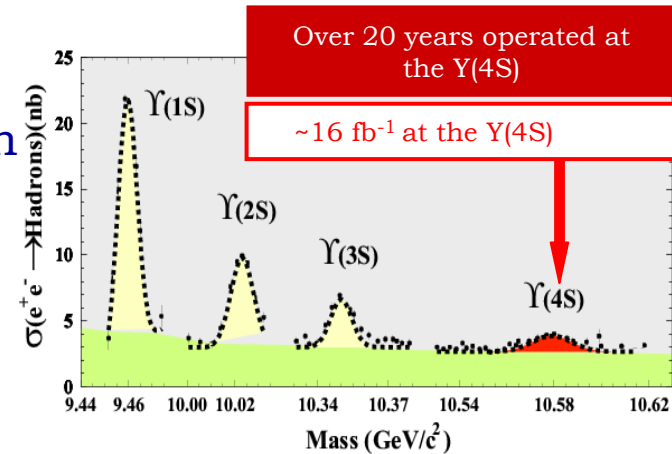
□ The **CLEO** experiment is located at the **Cornell Electron Storage Ring (CESR)**, a symmetric e^+e^- collider that operated in the region of the Upsilon resonances for over 20 years:

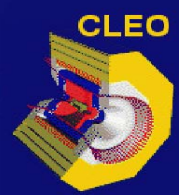
- ✓ Max inst luminosity achieved: $1.3 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- ✓ Total integrated luminosity at the Y(4S): 16 fb^{-1}
- ✓ Lots of important discoveries, e.g., $Y(nS)$, $b \rightarrow s\gamma$, $b \rightarrow uW$.

□ In 2003, CLEO started running at the $\psi(3770)$, $\sim 40 \text{ MeV}$ above DD production threshold, and slightly higher energies for D_s studies.

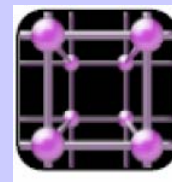
□ Transition from CESR to CESR-c:

- ✓ 12 wigglers are installed to increase synchrotron radiation/beam cooling
- ✓ Max luminosity achieved: $\sim 7 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$





Why a Charm Factory?



The main task of the CLEO-c open charm program:

Calibrate and Validate Lattice QCD

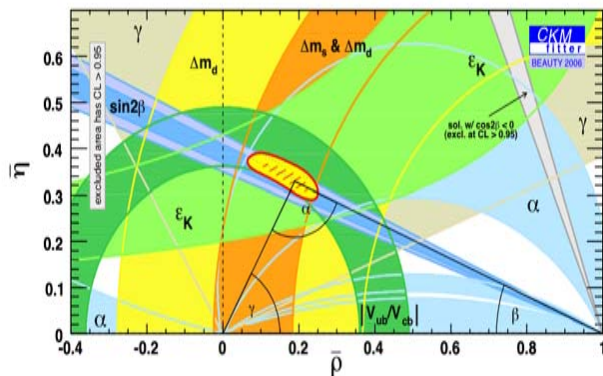


Help heavy flavor physics constrain the CKM matrix now:

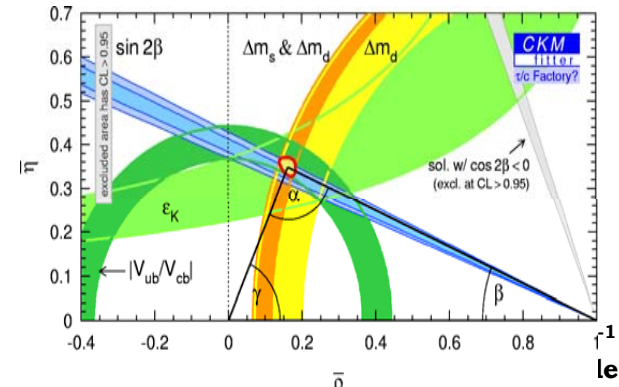
- ✓ Precision tests of the Standard Model or
- ✓ Discovery of new physics beyond the SM in b or c quark decays

Difficulty: hadronic uncertainties complicate interpretation of exp. results

A realistic example using recent CKM status:



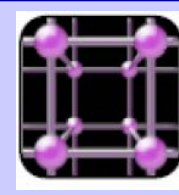
Reduce theory error on B form factors and B decay constants using tested LQCD



Help LHC search for and interpret new physics (future)



Why now?



□ C. Davies at EPS-2005:

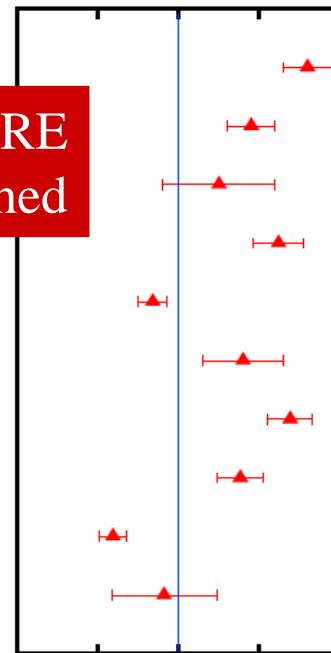
“There has been a revolution in LQCD...”

LQCD demonstrated that it can reproduce a wide range of mass differences and decay constants in unquenched calculations. These were postdictions.

Testable predictions are now being made for:
Decay constants f_D and f_B ;
 D and B Semileptonic form factors

CLEO-c can test f_D and D semileptonic form factors

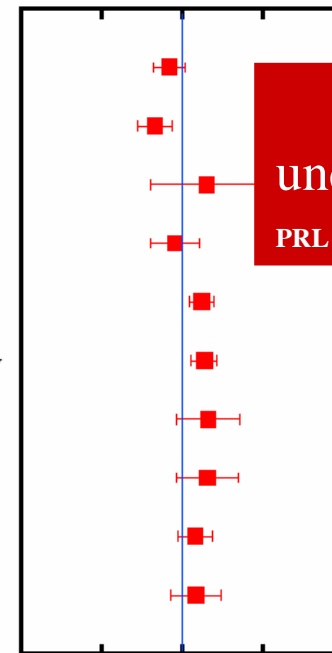
BEFORE
quenched



LQCD
exp .

NOW
unquenched
PRL 92, 022001 (2004)

f_π
 f_K
 $3m_\Xi - m_N$
 m_Ω
 $\psi(1P-1S)$
 $2m_{B_{s,av}} - m_Y$
 $Y(3S-1S)$
 $Y(2P-1S)$
 $Y(1P-1S)$
 $Y(1D-1S)$



LQCD
exp .