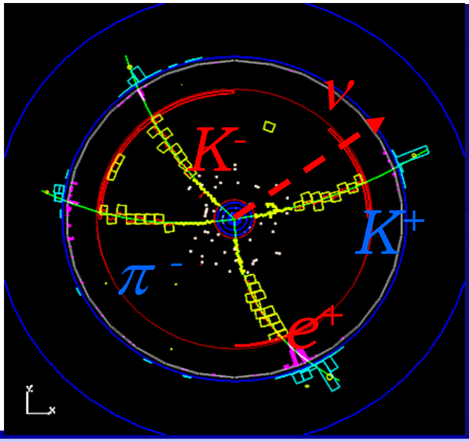
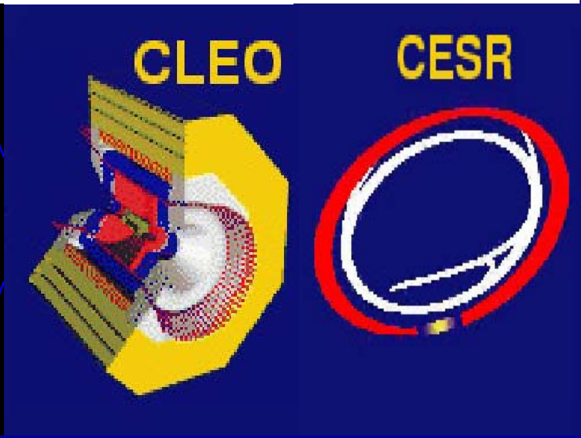
Leptonic and Semileptonic Charm Decays

- 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

Victor Pavlunin
Purdue University (CLEO)
UC, Santa Barbara (CMS)
on behalf of
the CLEO collaboration

FPCP-2007, Bled, Slovenia



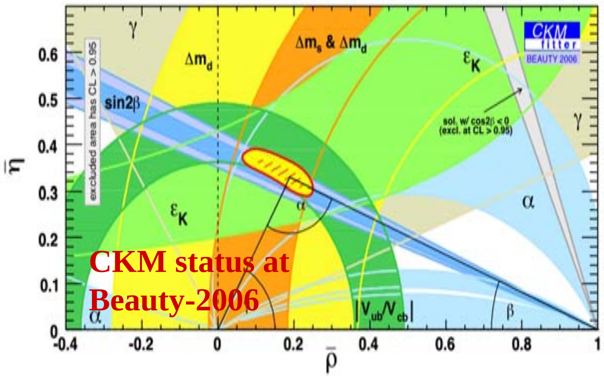


Introduction: LSL charm decays

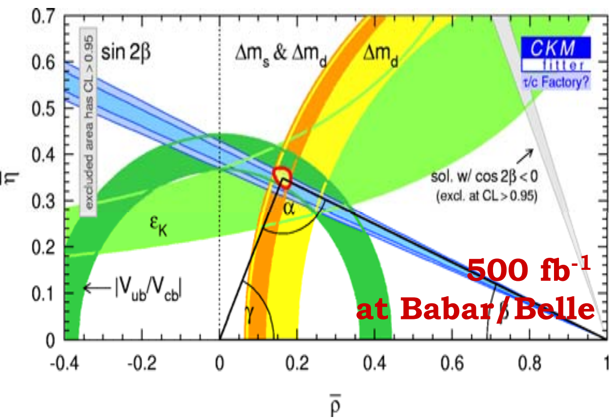
Charm leptonic and semileptonic decays provide stringent tests of theory for <u>decay constants</u> and <u>semileptonic form factors</u>

- 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

<u>Difficulty</u>: hadronic uncertainties complicate the interpretation of exp. results:

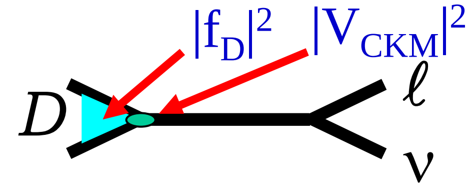


Reduce theory errors on B form factors and B decay constants using <u>tested</u> LQCD



Examples of theory tests and their impact

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

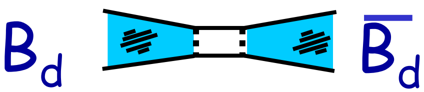


$$Rate \propto f_{D_{(s)}}^2 \, |V_{cd(s)}|^2$$

Experiment

LQCD

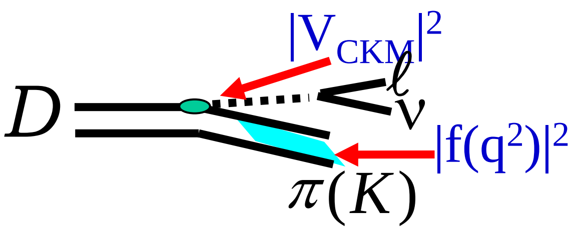
Known to < 1% from the CKM unitarity



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

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

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



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

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:

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

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)

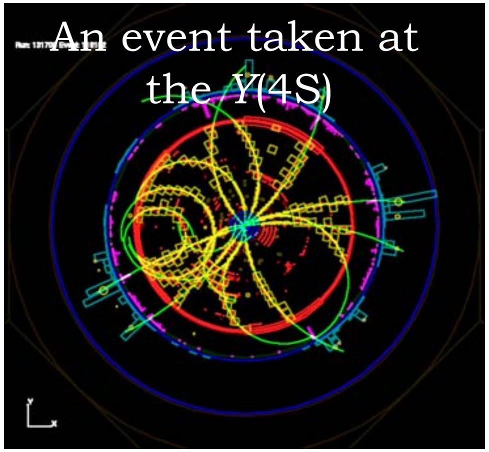
The majority of recent precision LSL charm results come from CLEO-c (and from B-factories)

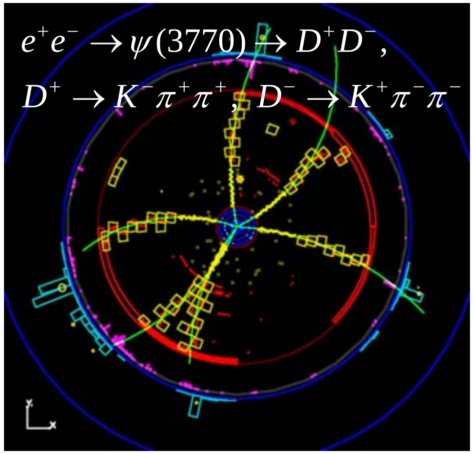
Advantages of running at the $\psi(3770)$ for charm physics:

✓ Pure DD, no additional particles

✓ $\sigma[DD$ at $\psi(3770)] = 6.4$ nb [$\sigma(cc)$ at Y(4S) ~1.3 nb]

✓ Low mulitplicity, high tagging efficiency (>20%)





References

very recent references are in red

CLEO-c:

- ✓ $D^+ \to \mu\nu$ 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 $D^+ \to K\pi e\nu$ with 281 pb^{-1} at the $\psi(3770)$: PRD **74**, 052001 (2006)
- ✓ $D^+ \to \tau\nu$ with 281 pb^{-1} at the $\psi(3770)$: PRD **73**, 112005 (2006)
- ✓ Form factors in tagged $D \to \pi e\nu$ and $D \to K e\nu$ with 281 pb^{-1} at the $\psi(3770)$: ICHEP-2006
- ✓ Form factors in untagged $D \to \pi e\nu$ and $D \to K e\nu$ with 281 pb^{-1} at the $\psi(3770)$: ICHEP-2006
- ✓ Form factors in tagged $D \to \rho e\nu$ with 281 pb^{-1} at the $\psi(3770)$: ICHEP-2006
- ✓ $D \to \eta e\nu / \eta' e\nu / \phi e\nu$: ICHEP-2006
- ✓ $D \to K\pi\pi e\nu$: ICHEP-2006
- ✓ $D_S \to \mu\nu$ with 314 pb^{-1} at $E_{CM} \sim 4.17$ GeV: arXiv:0704.0437 and arXiv:0704.0629 (submitted to PRL and PRD)

Babar:

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

Belle:

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

FOCUS:

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

BES-II:

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

CLEO-c Data Samples

- $\psi(3770)$: total luminosity = ~ <u>281 pb $^{-1}$</u>
- E_{CM} = 4170 MeV: total luminosity = ~ <u>314 pb^{-1}</u>

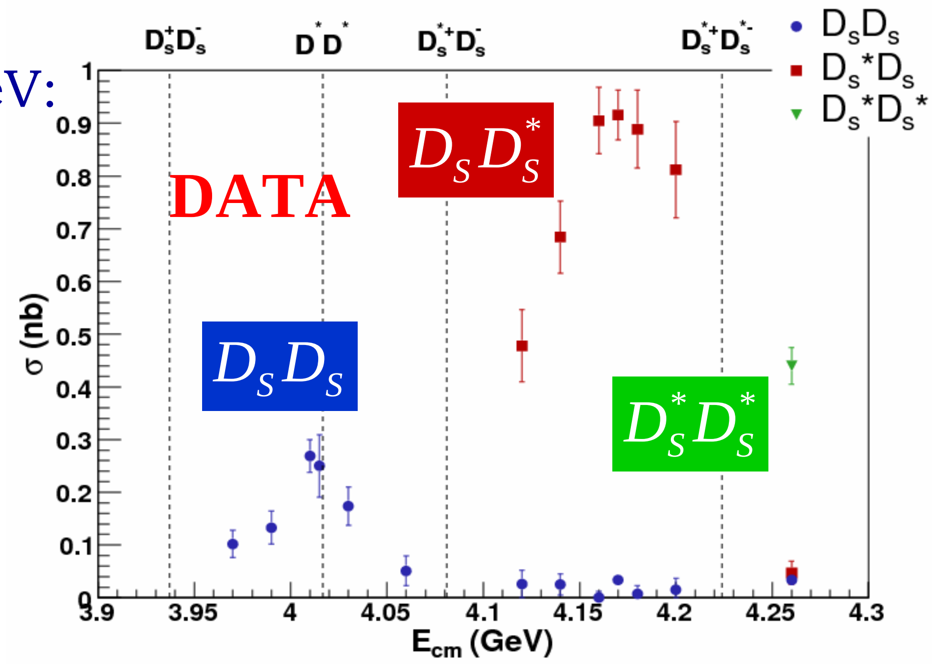
CLEO scanned E_{CM} = 3.97 – 4.26 GeV:

Optimal energy for D_s physics:

E_{CM} = 4.170 GeV

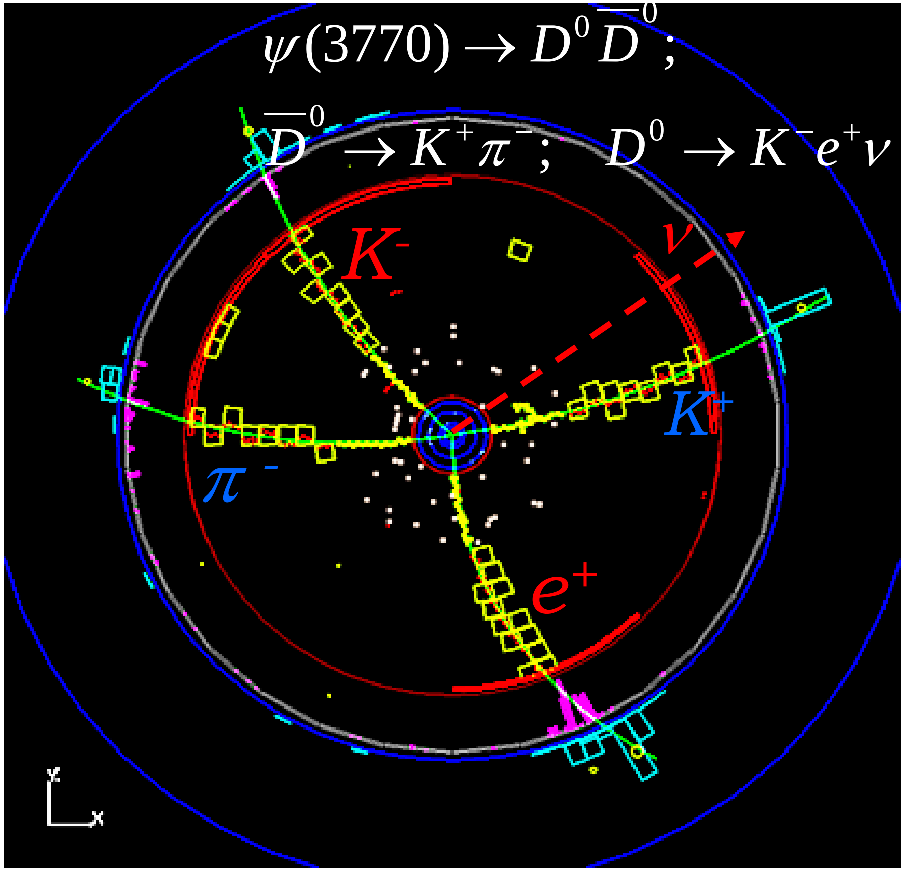
Dominant production mechanism at this energy:

$$e^+e^- \to D_S D_S^* \to D_S D_S \gamma$$



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

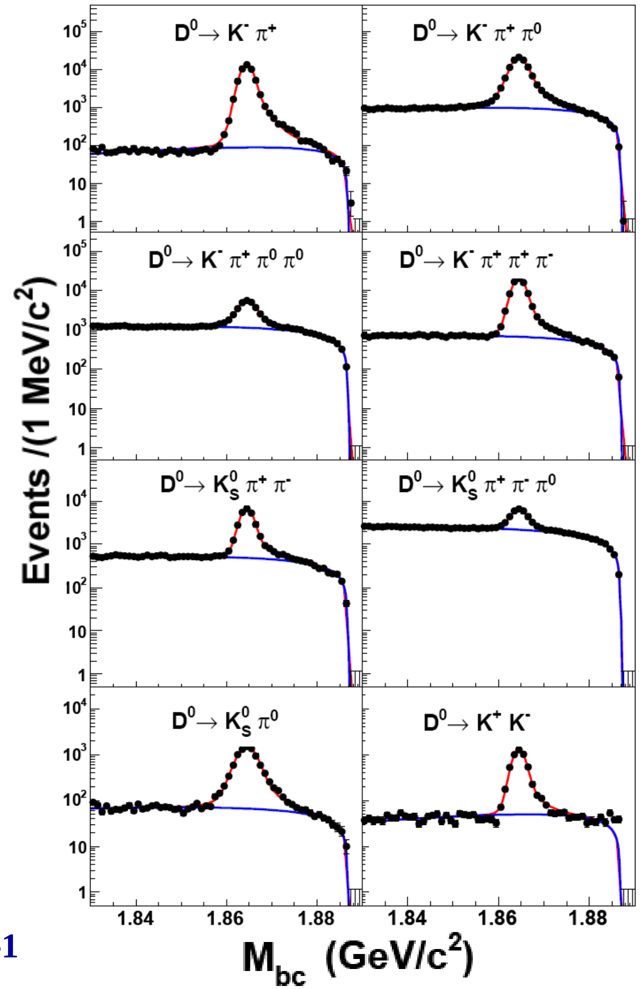
    Total: 3.1×10^5 tags

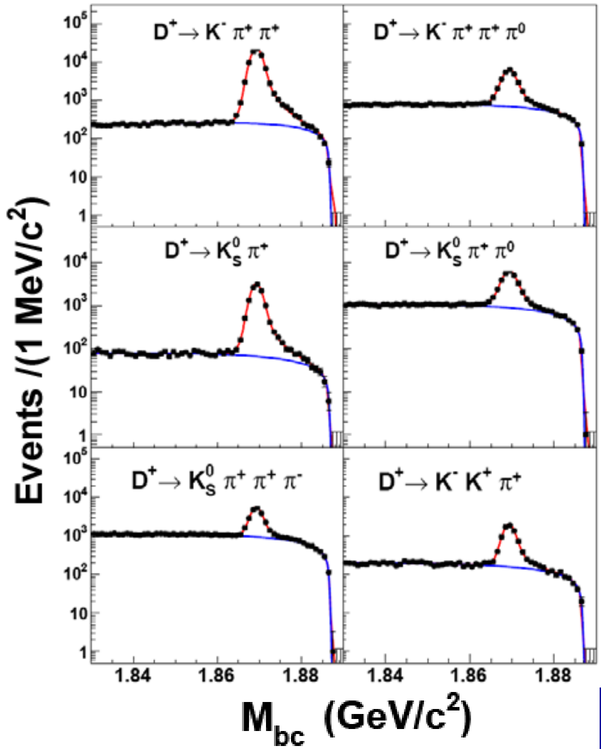
    ~ 1.1×10^3 tags / 1 pb^{-1}
  - ✓ D^+ tags: 6 standard tag modes

    Total: 1.6×10^5 tags

    ~ 0.6×10^3 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:

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

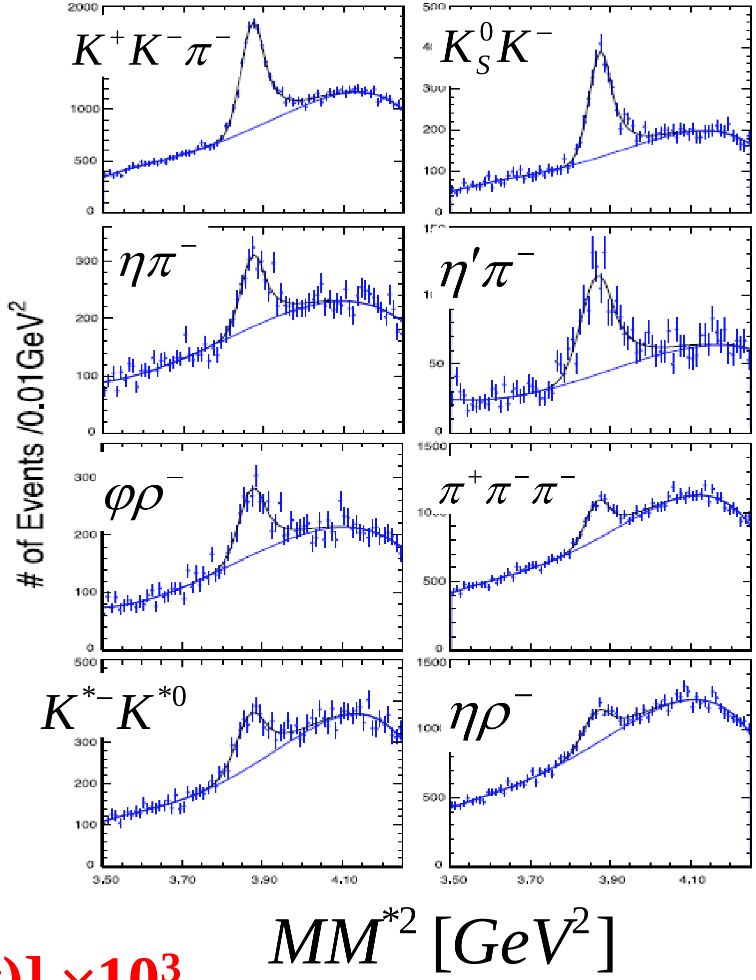
D_S^* decays to D_S via emission of 150 MeV photon 95% of the time $\Rightarrow$ significant smearing of M_{BC}

- D_S tag yields are determined using:

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

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

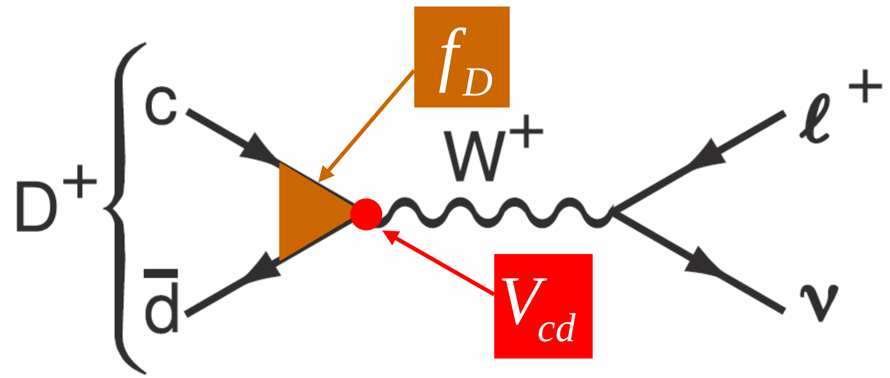
DATA (314 pb^{-1})



Tag Yield: [18.6 ± 0.4 (stat) ± 0.9 (syst)] ×10^3

Leptonic decays

$D_{(s)}$ Leptonic Decays

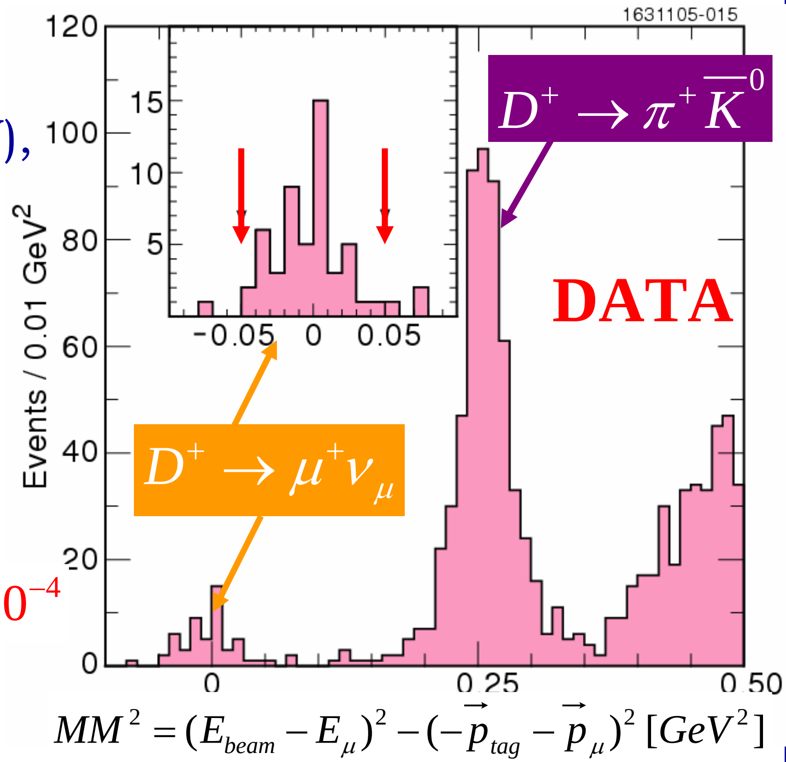


$$\Gamma(D^+ \to l^+\nu) = \frac{1}{8\pi} G_F^2 f_D^2 m_l^2 M_D \left(1 - \frac{m_l^2}{M_D^2}\right)^2 |V_{cd}|^2$$

- Standard Model predicts:
  - ✓ D decays: $\Gamma(e^+\nu):\Gamma(\mu^+\nu):\Gamma(\tau^+\nu) = 2.3\times10^{-5}:1.0:2.7$
  - ✓ D_s decays: $\Gamma(e^+\nu):\Gamma(\mu^+\nu):\Gamma(\tau^+\nu) = 2.5\times10^{-5}:1.0:9.7$
- Use V_{cd} and V_{cs} from the CKM unitarity constraints to extract f_D and f_{Ds}, and compare them to theory

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

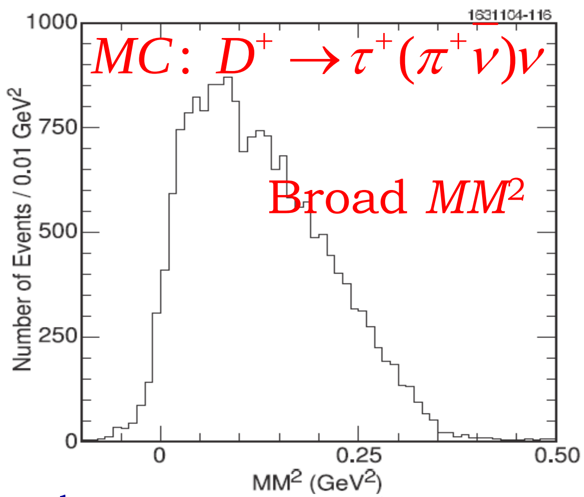
- **Full event reconstruction:**
  - ✓ require a tag,
  - ✓ require a muon cand. ($E_{CC}^{track} < 300$ MeV),
  - ✓ veto events with extra tracks and energy clusters > 250 MeV.
- **Results:**
  - ✓ 50 $D^+ \to \mu\nu$ candidates
  - ✓ Estimated bckg: 2.8 events
  - ✓ $B(D^+ \to \mu^+\nu) = [4.4 \pm 0.7(stat) \pm 0.1(syst)] \times 10^{-4}$
  - ✓ $f_{D^+} = [223 \pm 17(stat) \pm 3(syst)]\ MeV$



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

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

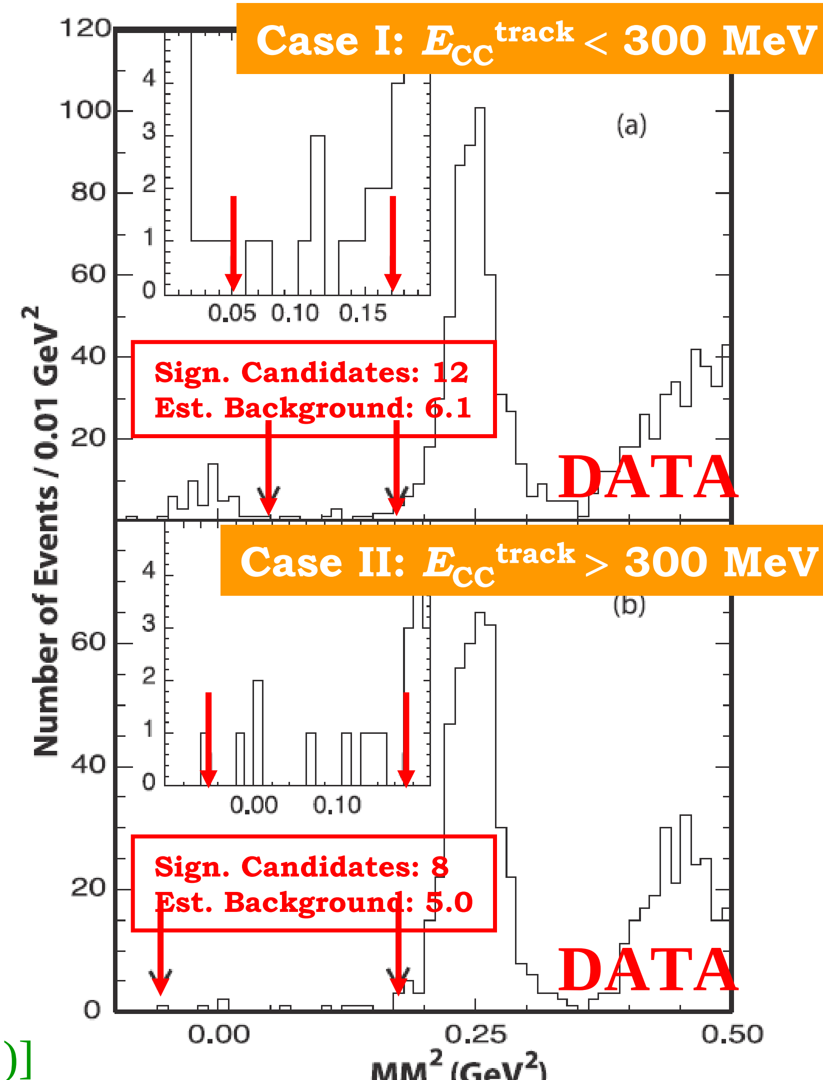
- Reconstruct $D^+ \to \tau^+ \nu$ with $\tau^+ \to \pi^+ \nu$ [B($\tau^+ \to \pi^+ \nu$) ~11%]; the same technique but two ν's complicate the analysis:



- Consider two cases:
  - ✓ Case I: E_{CC}^{track} < 300 MeV (accept 99% of muons and 60% of pions)
  - ✓ Case II: E_{CC}^{track} > 300 MeV (accept 1% of muons and 40% of pions)
- *No* significant signal ⇒

$$B(D^+ \to \tau^+\nu) < 2.1\times10^{-3} \; (at \;\; 90\% \;\; CL)$$

$$[SM: \; B(D^+ \to \tau^+\nu) < (1.1 \pm 0.2)\times10^{-3} \; (at \;\; 90\% \;\; CL)]$$



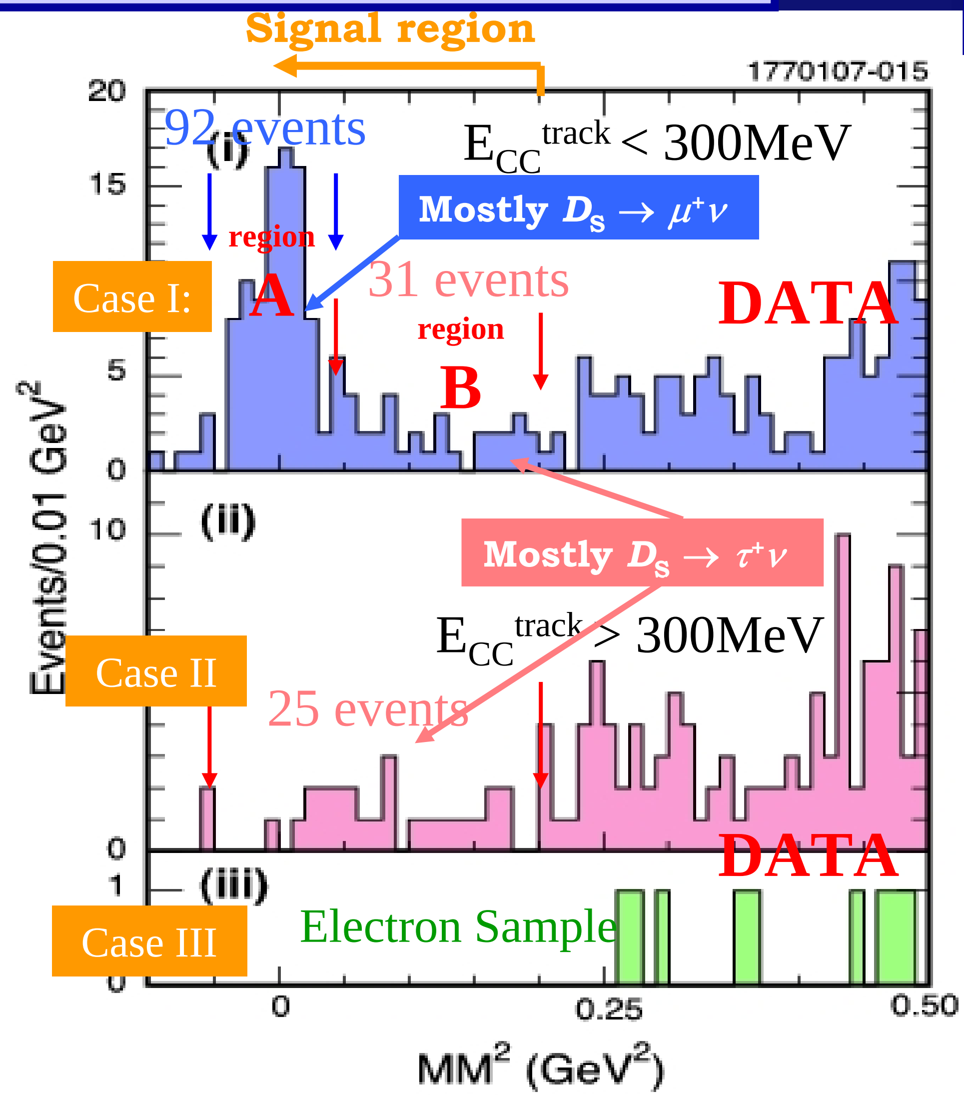
$D_S \to \mu^+\nu$ and $\tau^+(\pi^+\nu)\nu$ with 314 pb^{-1} at E_{CM} = 4170 MeV

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

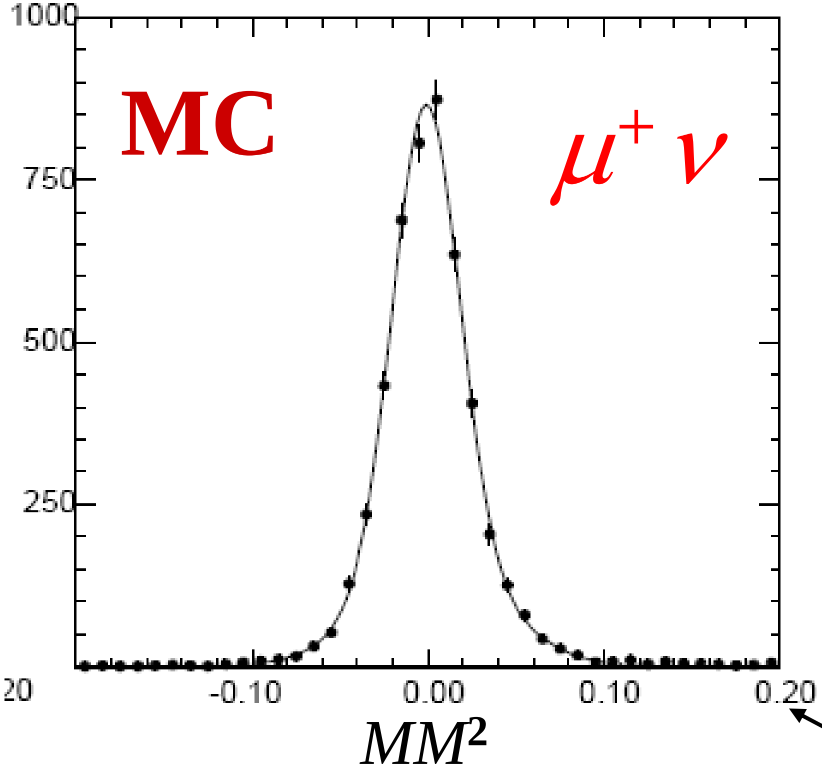
$$MM^2 = (E_{CM} - E_{D_S} - E_\gamma - E_{\mu(\pi)})^2 - (-\vec{p}_{D_S} - \vec{p}_\gamma - \vec{p}_\mu)^2$$

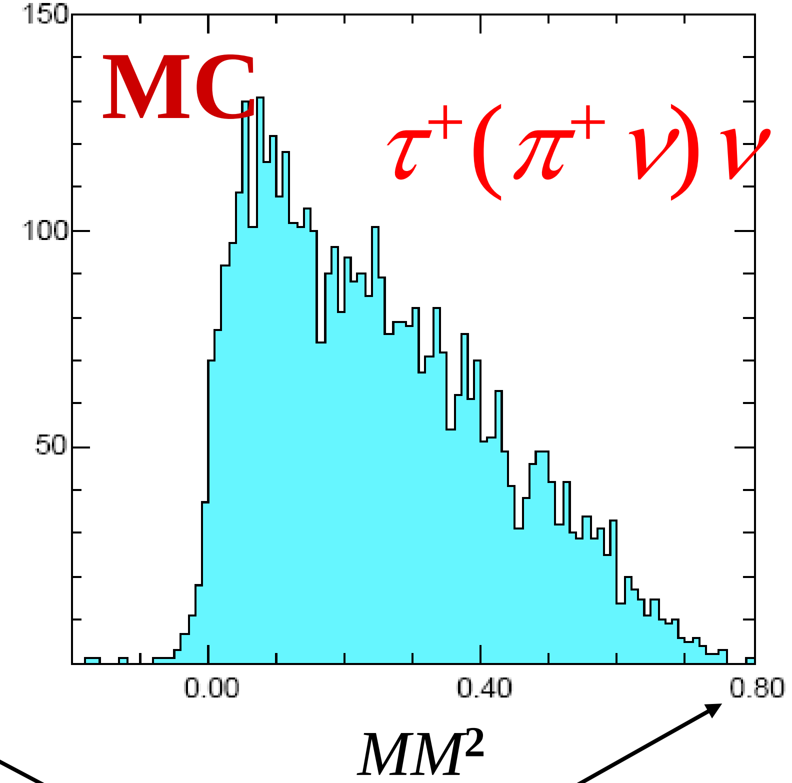
- Consider three cases:
  - ✓ Case I: E_{CC}^{track} < 300 MeV (accept 99% of muons and 60% of pions)
  - ✓ Case II: E_{CC}^{track} > 300 MeV (accept 1% of muons and 40% of pions)
  - ✓ Case III: require an electron

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



Signal shapes





Note the scale limits: 0.20 and 0.80 GeV^2

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

- $D_S \to \mu^+ \nu$ (Case I, Reg.A)

  92 signal candidates, 3.5 bkg events:

  $B(D_s \to \mu^+\nu) = [0.59 \pm 0.07(stat) \pm 0.03(syst)]\%$

- $D_S \to \tau^+ \nu$ (Case I,Reg.B+Case II)

  56 signal candidates, 7.2 bkg events:

  $B(D_s \to \tau^+\nu) = [8.0 \pm 1.3(stat) \pm 0.4(syst)]\%$

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

- Using the SM $B(\tau^+\nu)/B(\mu^+\nu)$ the above results are aver'd:

  $B(D_s \to \mu^+\nu) = [0.64 \pm 0.06(stat) \pm 0.03(syst)]\%$

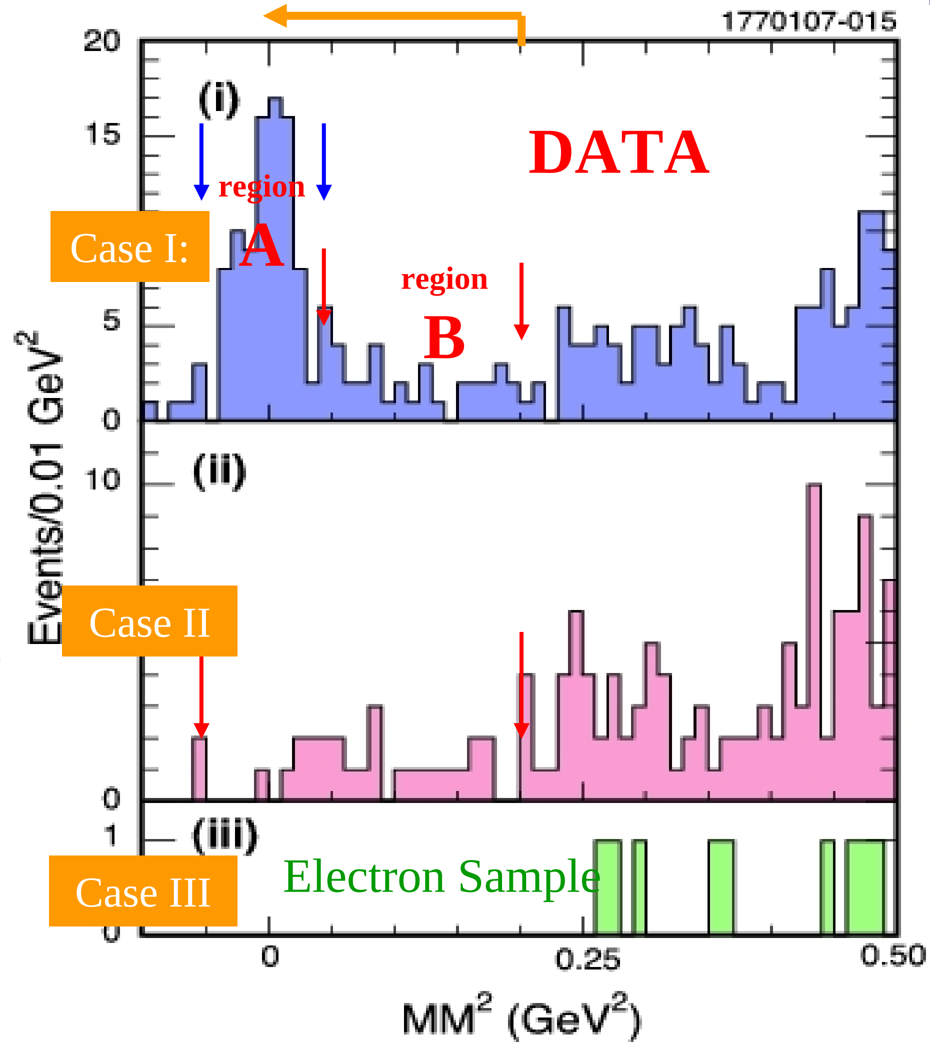
  $[PDG-06:\ B(D_s \to \mu^+\nu) = (0.61 \pm 0.19)\%]$

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

- $D_S \to e^+ \nu$ (Case III):

  No signal candidates:

  $B(D_s \to e^+\nu) < 1.3 \times 10^{-4}$



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

- Complimentary analysis:

  $D_S \to \tau^+\nu$ with $\tau^+ \to e^+\nu\,\nu$.

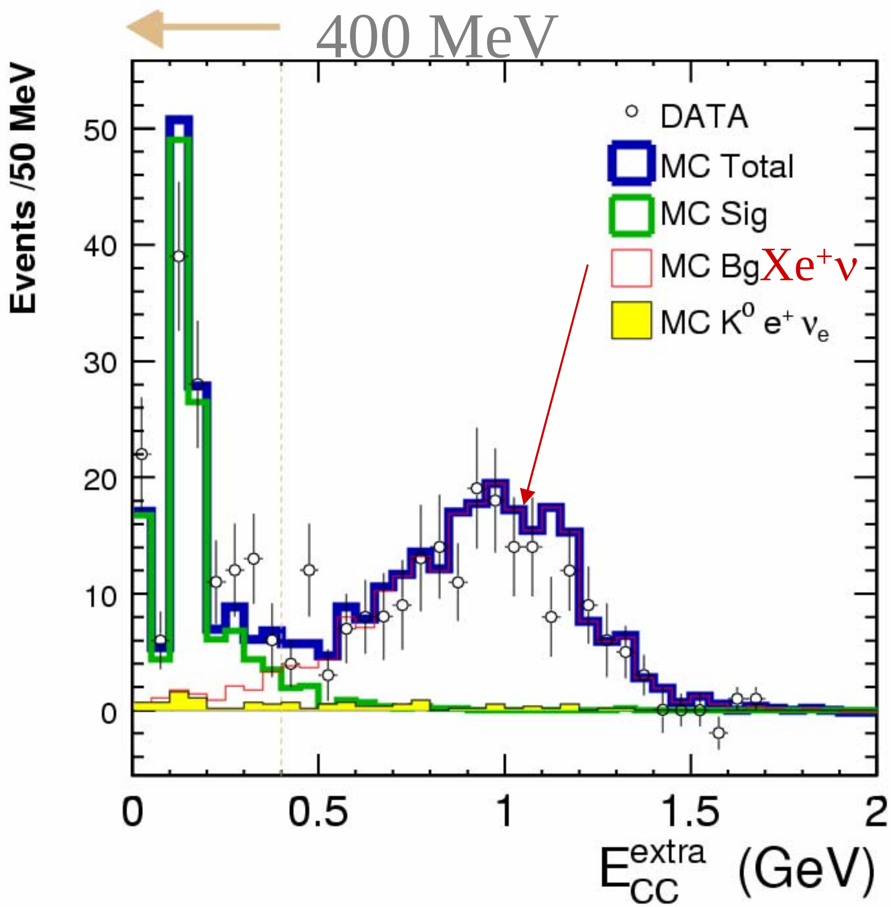
- $B(D_S \to \tau^+\nu)B(\tau^+ \to e^+\nu\nu) \sim 1.3\%$ is large [cf. $B(D_S^+ \to Xe^+\nu) \sim 8\%$]
- Analysis Technique:
  - ✓ Find e^+ and D_S^- tag (γ from D_S^* is *not* reconstructed, same tag modes)
  - ✓ Veto events with extra tracks
  - ✓ Extra energy in CC < 400 MeV
- Results:

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

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

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

Include yield

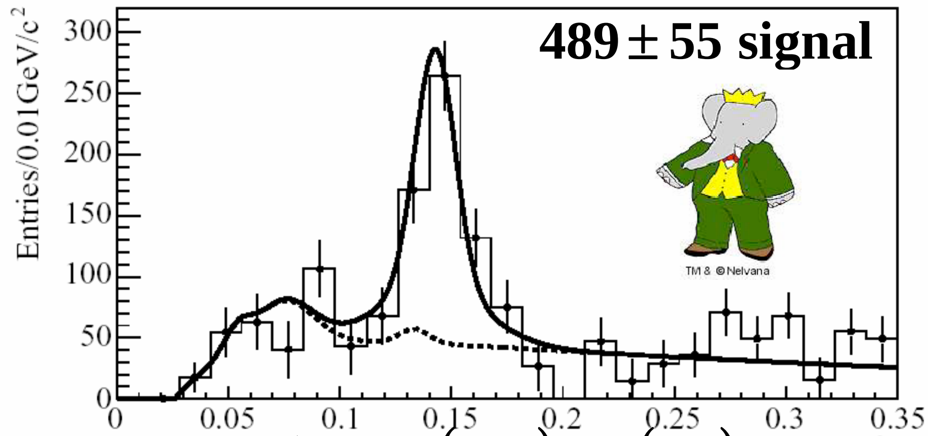


Preliminary

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

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

$D_S^* \to \gamma D_s^+ \to \gamma(\mu\nu)$ **at $\Upsilon(4S)$**



$\Delta m = m(\gamma\mu\nu) - m(\mu\nu)$

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

$BR(D_s^+ \to \phi\pi^+)$ = $(4.71 \pm 0.46)\%$ ("BaBar aver."):

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

f_{Ds} = (283 ± 17 ± 7 ± 14) MeV

$BR(D_s^+ \to \phi\pi^+)$ = $(3.6 \pm 0.9)\%$ (PDG04):

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

f_{Ds} = (248 ± 15 ± 6 ± 31) MeV

Comparison with theory

Summary of exper. results:

- $f_{D^+} = [223 \pm 17(stat) \pm 3(syst)]\ MeV$
- $f_{D_S} = [273 \pm 10(stat) \pm 5(syst)]\ MeV$

[Weighted average; syst. errors are mostly uncorrelated]

- $\frac{f_{D_S}}{f_{D^+}} = 1.22 \pm 0.09 \pm 0.03$ **Prelim.**
- Babar: $f_{Ds} =$

$[283 \pm 17(stat) \pm 7(syst) \pm 14(\varphi\pi)]\ MeV$

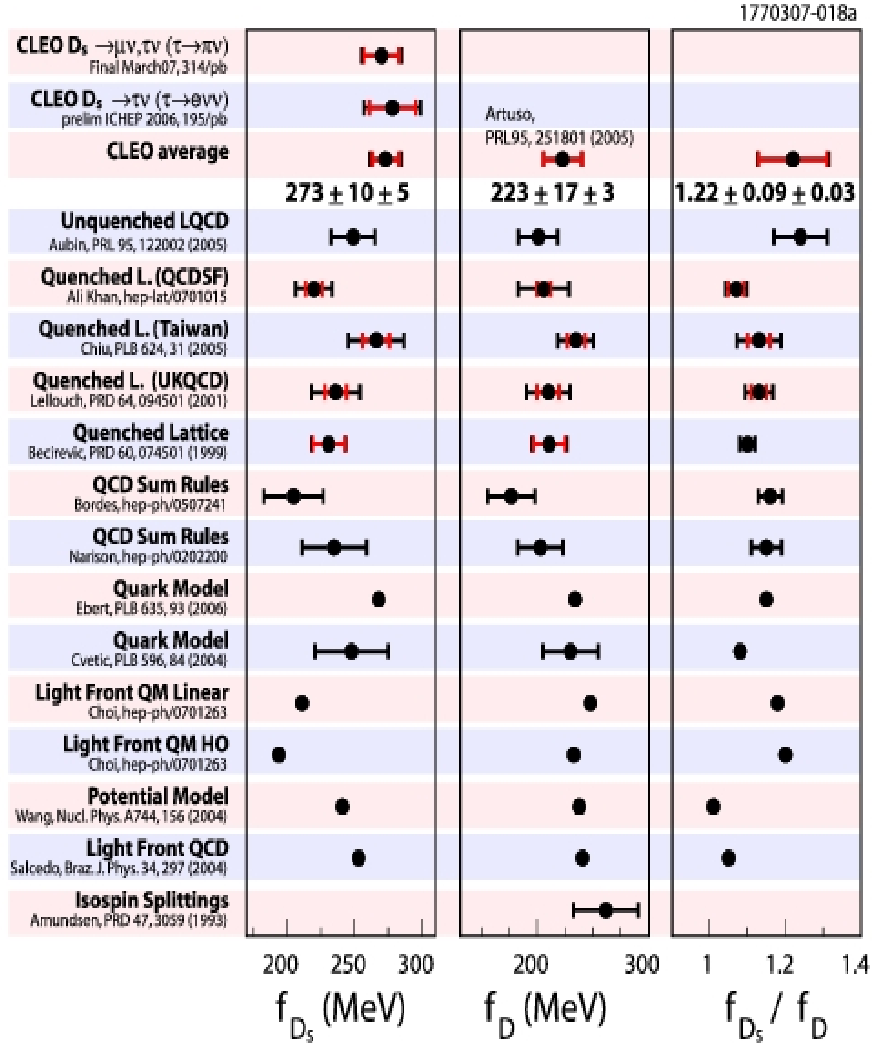
Experiment: statistically limited

An example of theor. preditions:

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

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

LQCD: systematically limited



Semileptonic decays

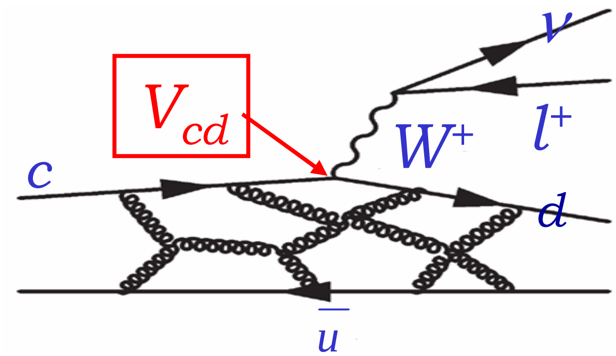
Semileptonic decays

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

- 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 $A_3(q^2)$] :

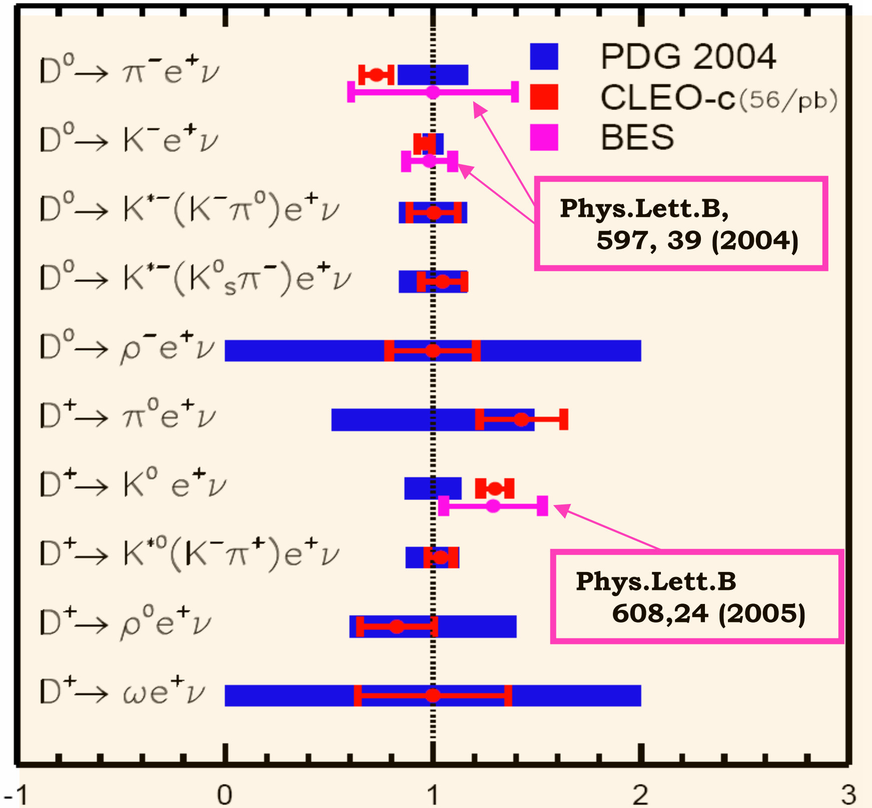
$$H^\mu = \frac{2i\epsilon^{\mu\nu\alpha\beta}}{M_D + m_V} e^*_\nu p_{f\alpha} p_{i\beta} V(q^2) - (M_D + m_V) e^{*\mu} A_1(q^2) + \frac{e^* \cdot q}{M + m_V} (p_i + p_f)^\mu A_2(q^2)$$

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

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

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



Most precise BFs for ALL modes; Two first observations.

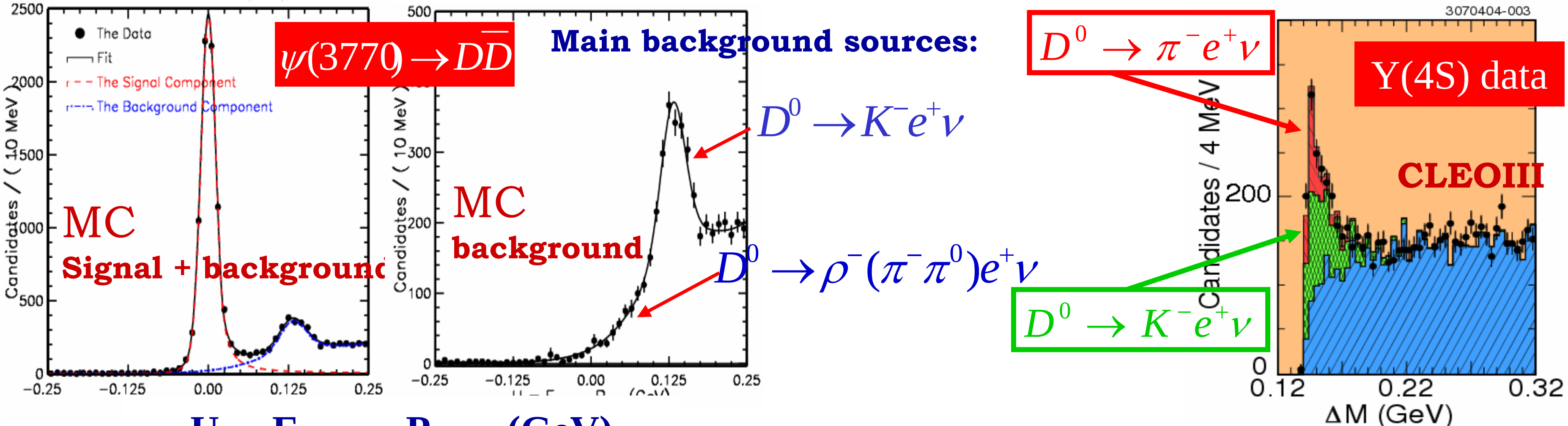
Form Factor Studies with 281 pb^{-1} :

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



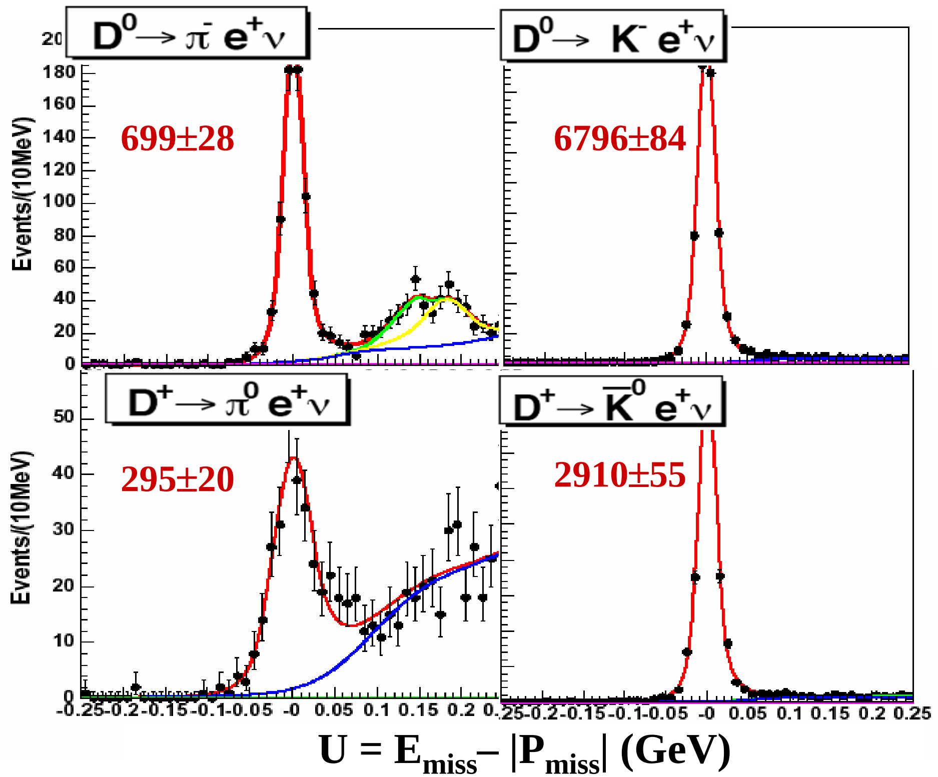
$U \equiv E_{MISS} - P_{MISS}$ (GeV)

- 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 $D^0 \to \pi^- e^+ \nu$ signal mode is combined with π_{slow} : $D^{*-} \to D^0 \pi_{slow}$
- Fits are made to $\Delta M \equiv M(D^{*-}) - M(D^0)$ in bins of q^2

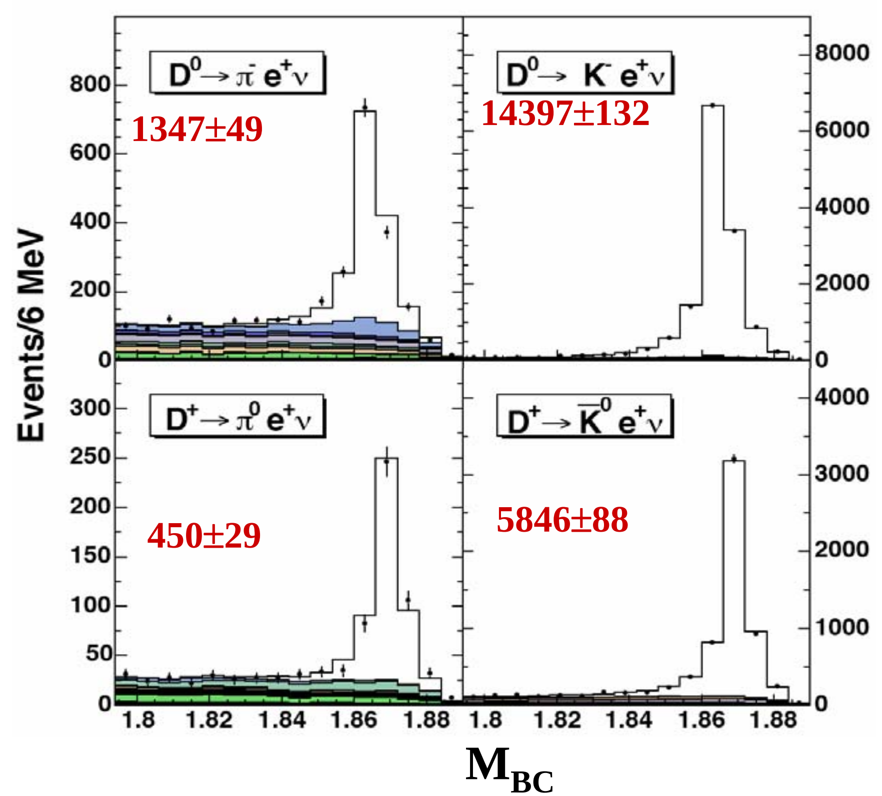
$D \to K/\pi\, e^+ \nu$ with 281 pb^{-1} at the $\psi(3770)$

1) Tagged CLEO-c analysis:



2) Untagged CLEO-c analysis:

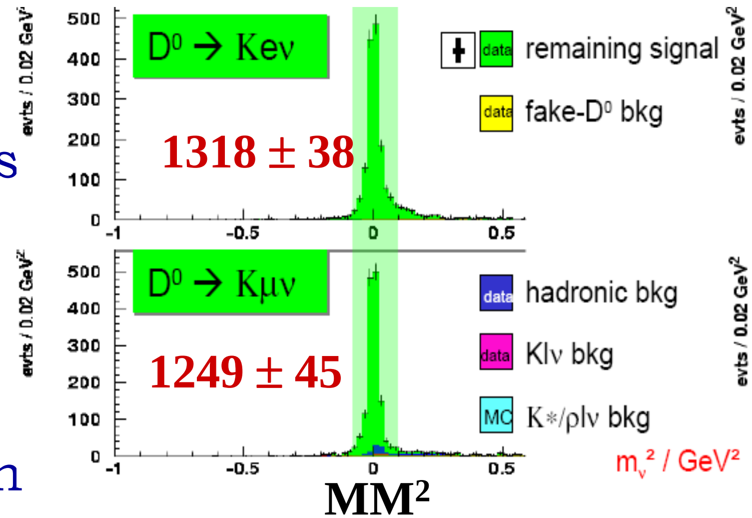
[analogous to neutrino reconstruction at the Υ(4S)]

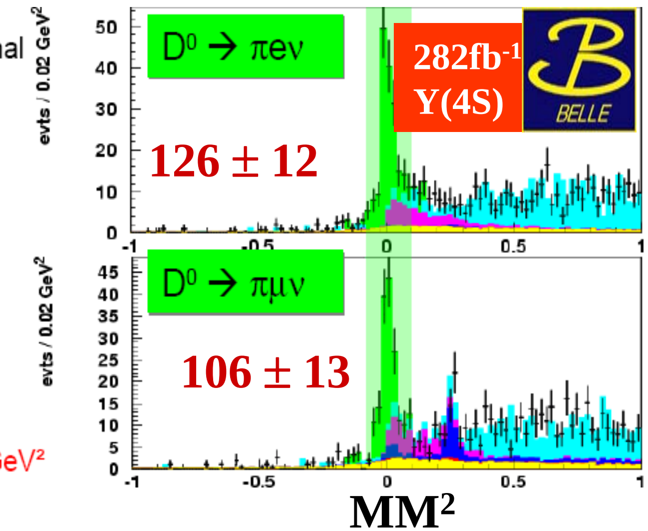


The untagged analysis has larger signal yields but larger systematic uncertainties

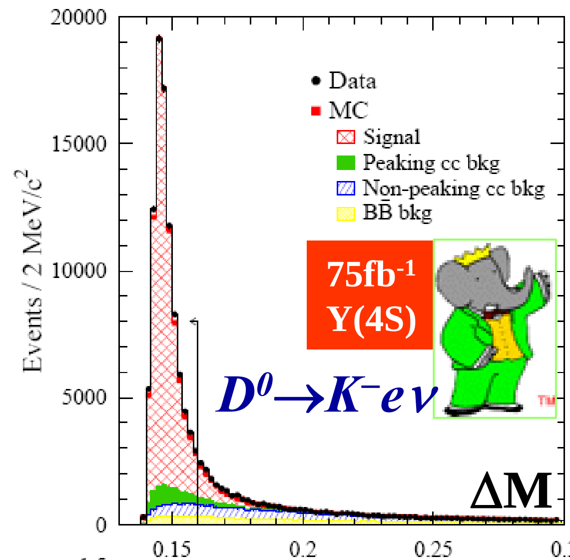
$D \to K/\pi\, e^{+}\nu$ at the Y(4S)

- Tagged $e^{+}e^{-} \to D^{(*)}_{tag} D^{*-} X$ events (about 56×10^{3} tags in total)
- Similar to the CLEO-c tagged analysis
- Excellent q^2 resol'n

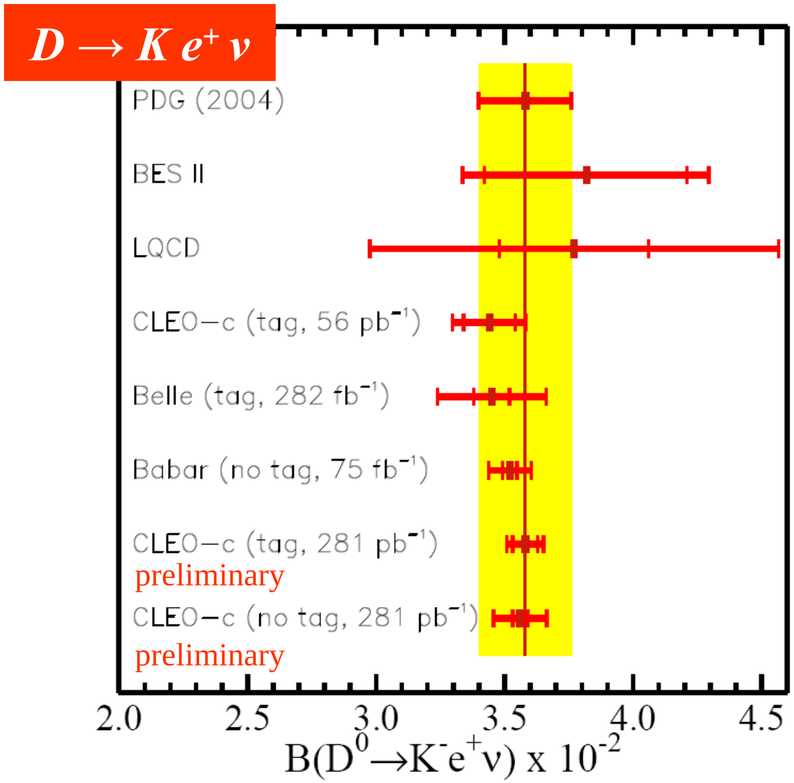


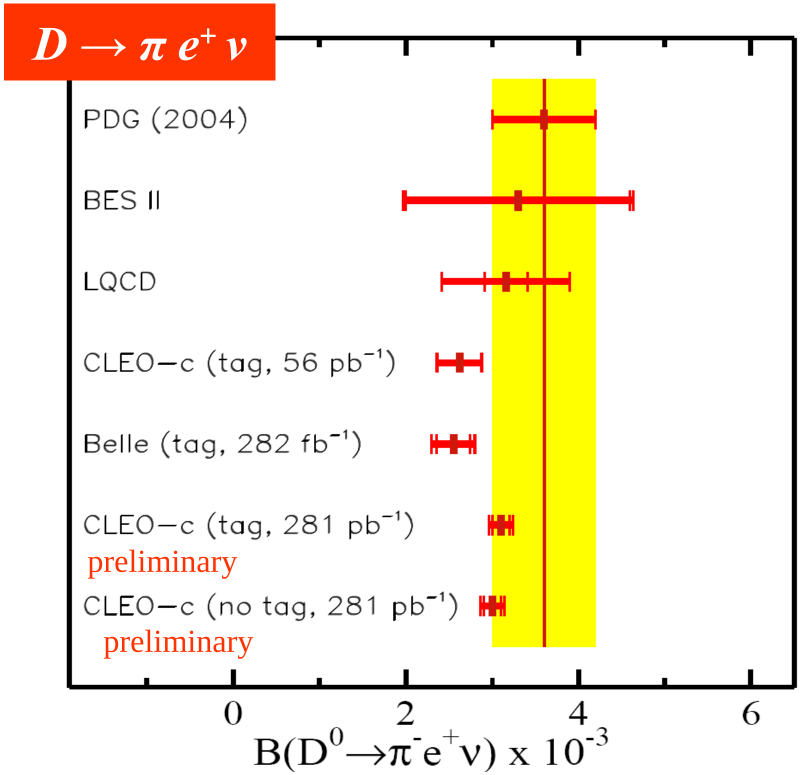


- Similar to the CLEO III untagged $D\to K/\pi\, e^{+}\nu$
- The neutrino momentum is estimated using all other particles in the event (no tag required)
- The $D^{0} \to K^{-}e^{+}\nu$ signal mode is combined with π_{slow} : $D^{*-} \to D^{0}\pi_{slow}$
- Plot on the right: $\Delta M \equiv M(D^{*-}) - M(D^{0})$ with about 74×10^{3} signal events



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





Babar measures:

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

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

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

Good consistency between measurements
LQCD precision lags experiment

Form Factor Models

- The Simple Pole Model:

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

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

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

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

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

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

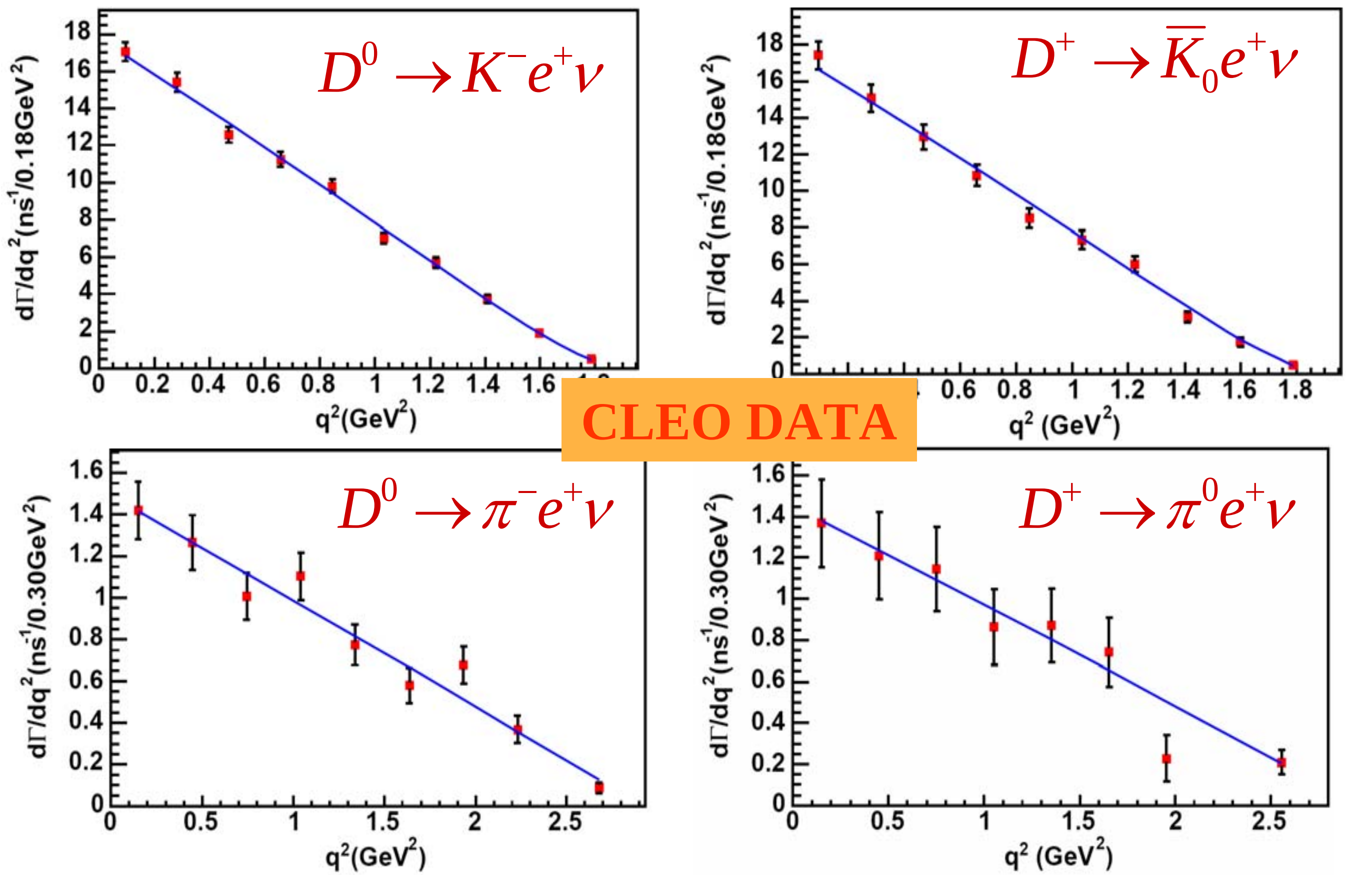
$D \to K/\pi\, e^+\nu$: CLEO-c fits (tagged analysis)

CLEO

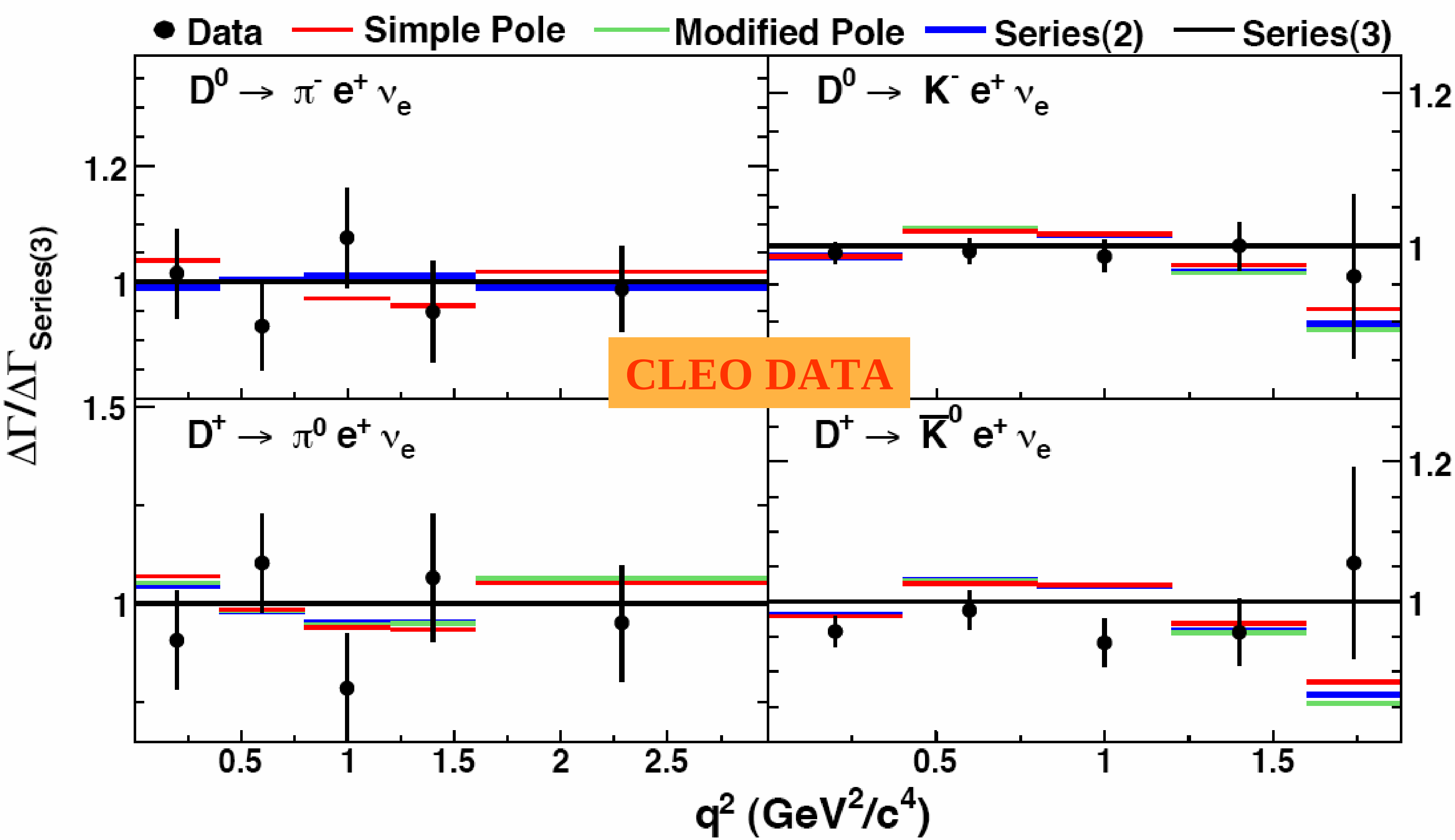
CESR

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

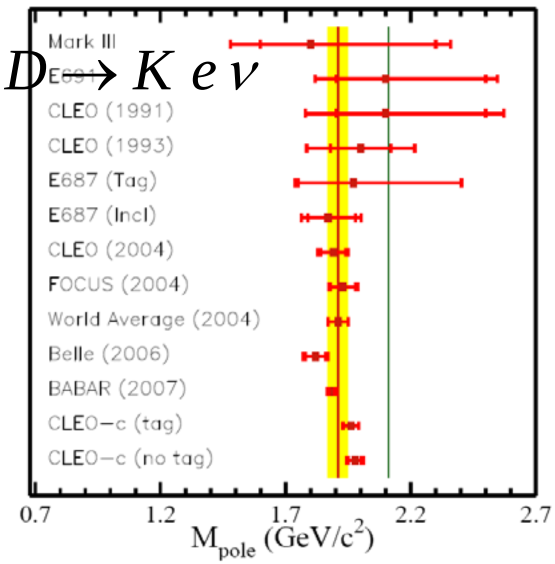
Simultaneous fits to isospin conjugate pairs for the simple pole model:

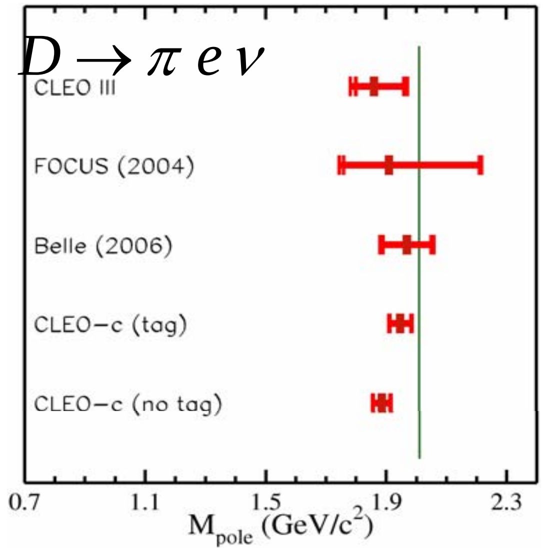


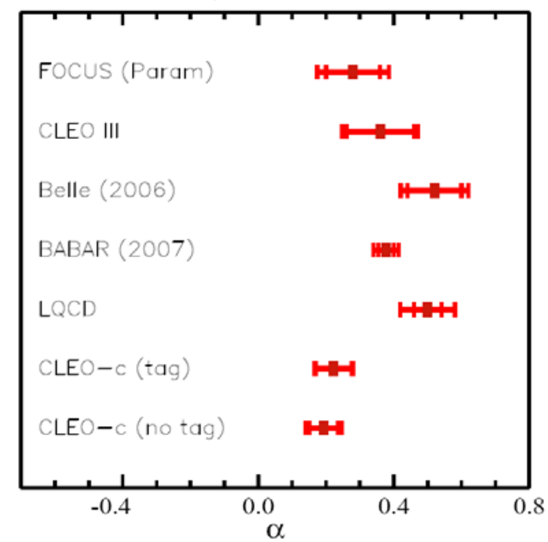
$D \to K/\pi\, e^+ \nu$: CLEO-c fits (untagged analysis)

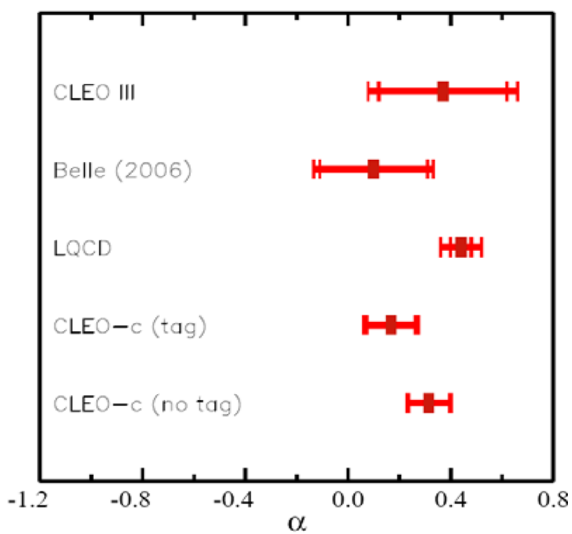


$D \to K/\pi\, e^+ \nu$: form factor shape results









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

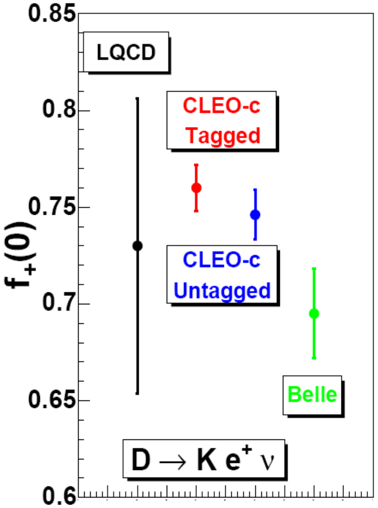
Some tension between CLEO-c and Babar/Belle meas'nts; LQCD precision is comparable to experiment

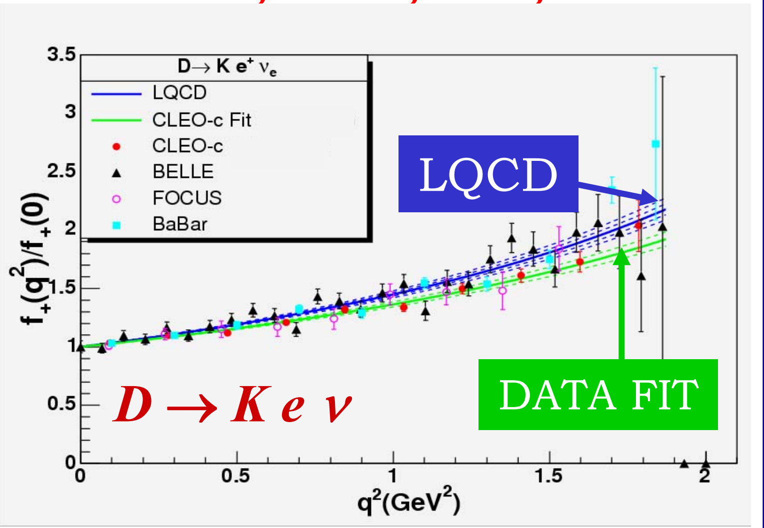
$D \to K / \pi e^+ \nu : \quad f_+(q^2)$

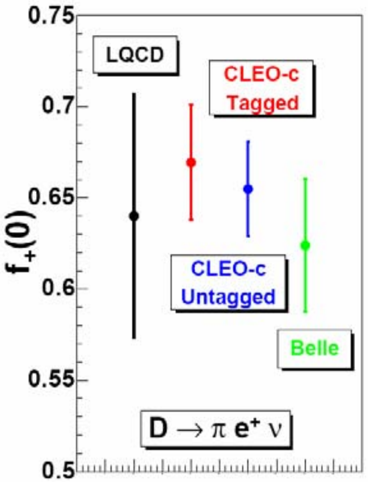
- Plotted LQCD results (blue) are recent results of FNAL+MILC unquenched three flavor LQCD [C. Aubin *et al.*, PRL **94** 011601 (2005)]
  - ✓ Lattice systematic uncertainties dominate:
  - ✓ $LQCD(D \to K e \nu)$:
    $f_+(0) = 0.73 \pm 0.03 \pm 0.07;$
    $\alpha = 0.50 \pm 0.04 \pm 0.07.$
  - ✓ $LQCD(D \to \pi e \nu)$:
    $f_+(0) = 0.64 \pm 0.03 \pm 0.06;$
    $\alpha = 0.44 \pm 0.04 \pm 0.07.$
- The green lines are untagged CLEO-c fits
- Babar result for $f_+(0)$:

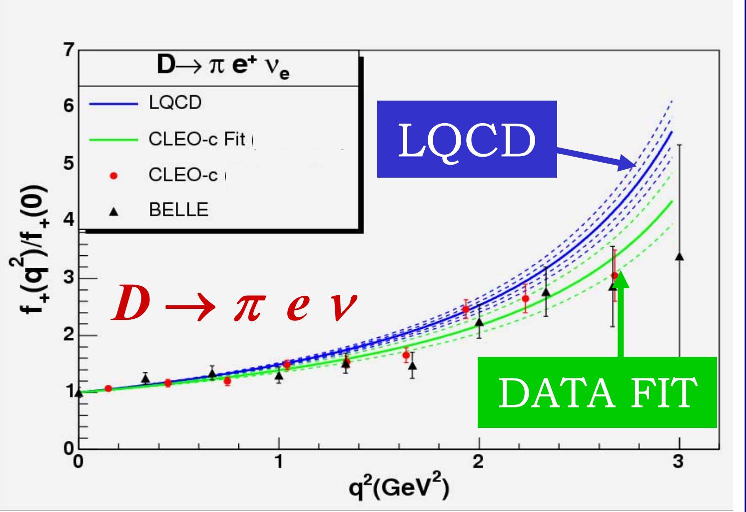
$$f_+(0) = 0.727 \pm 0.007 \pm 0.005 \pm 0.007$$

CLEO-c, Babar, Belle, FOCUS





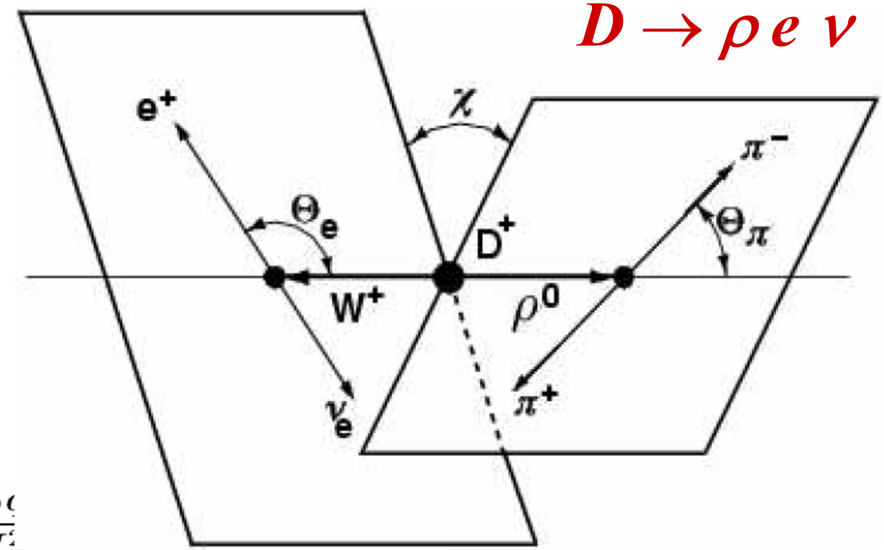




- Five kinematic variables describe the decay rate (plot):

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

$D \to \rho e \nu$



- The decay rate we make a fit to:

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

- 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):

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

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

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

- 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.

CLEO

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

CESR

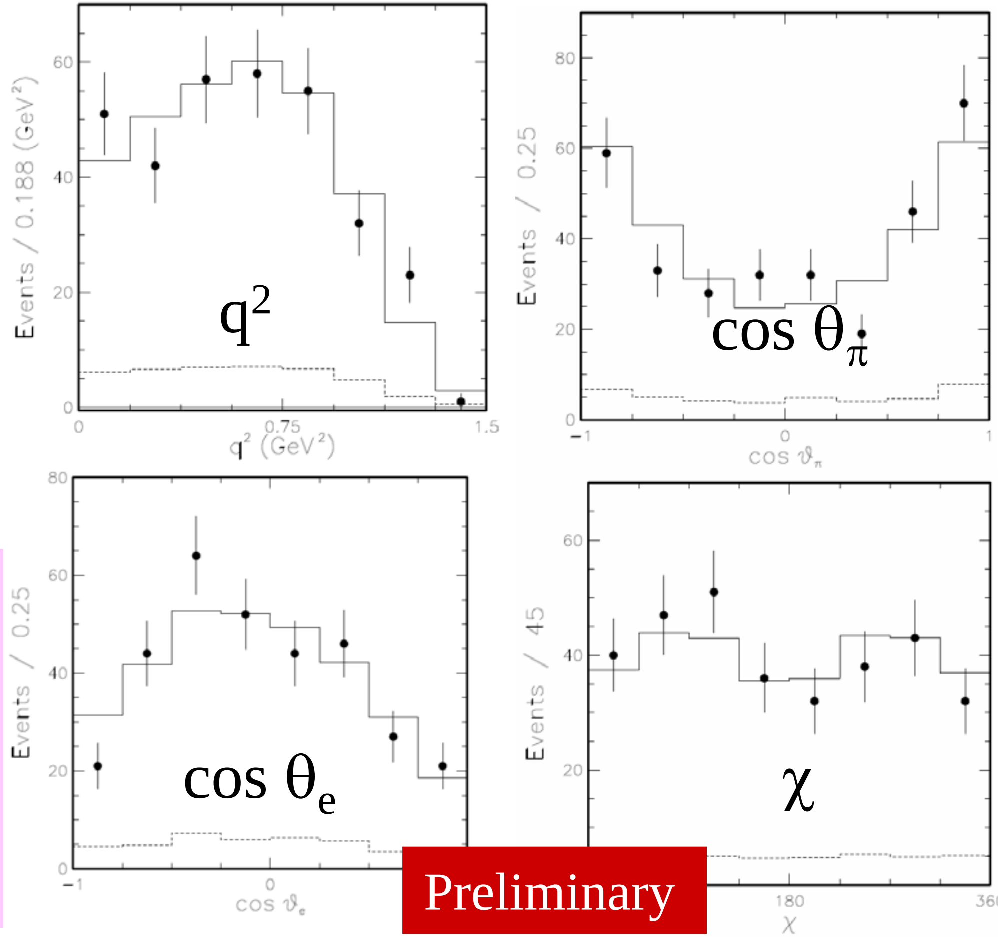
- Two isospin conjugate modes $D^+ \to \rho^0 e \nu$ and $D^0 \to \rho^- e \nu$ (~300 events) are fit simultaneously:

$R_V = 1.40 \pm 0.25\,(stat) \pm 0.03(syst)$

$R_2 = 0.57 \pm 0.18\,(stat) \pm 0.06(syst)$

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

$B(D^0 \to \rho^- e^+ \nu) = (1.56 \pm 0.16 \pm 0.09) \times 10^{-3}$
$B(D^+ \to \rho^0 e^+ \nu) = (2.32 \pm 0.20 \pm 0.12) \times 10^{-3}$
Isospin average:
$\Gamma(D^0 \to \rho^- e^+ \nu) = (0.41 \pm 0.03 \pm 0.02) \times 10^{-2}$ ps^{-1}
this analysis
$\Gamma(D^0 \to \rho^- e^+ \nu) = (0.44 \pm 0.06 \pm 0.02) \times 10^{-2}$ ps^{-1}
FOCUS PLB 637,32 (2006)

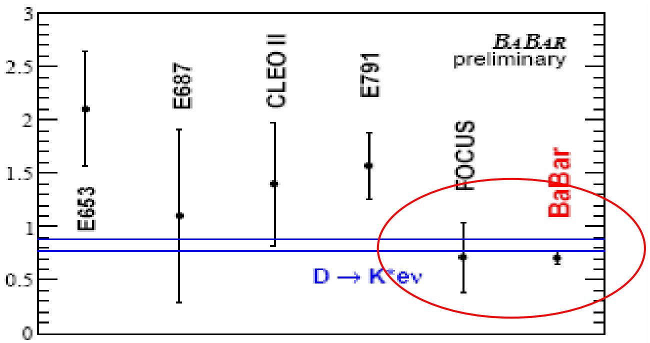


$D_S \to \phi e^+ \nu$ with 79 fb^{-1} at the Y(4S)

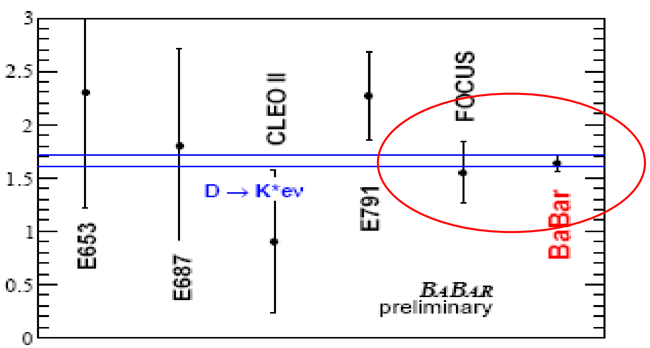
- A fit to about reconstructed 13,000 signal events:

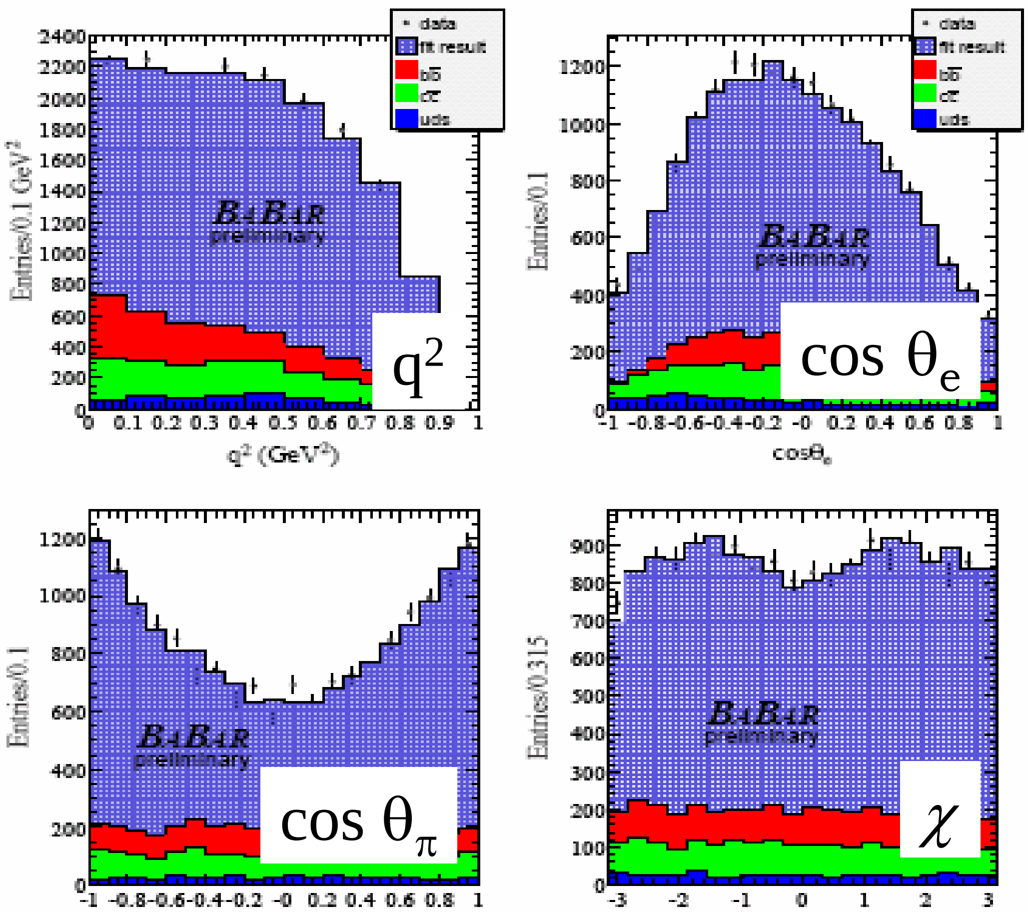
$$R_V = 1.64 \pm 0.07\,(stat) \pm 0.04(syst)$$
$$R_2 = 0.71 \pm 0.06\,(stat) \pm 0.03(syst)$$

R_2



R_V





Preliminary

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

- Results:

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

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

- Consistent with the isospin symmetry:

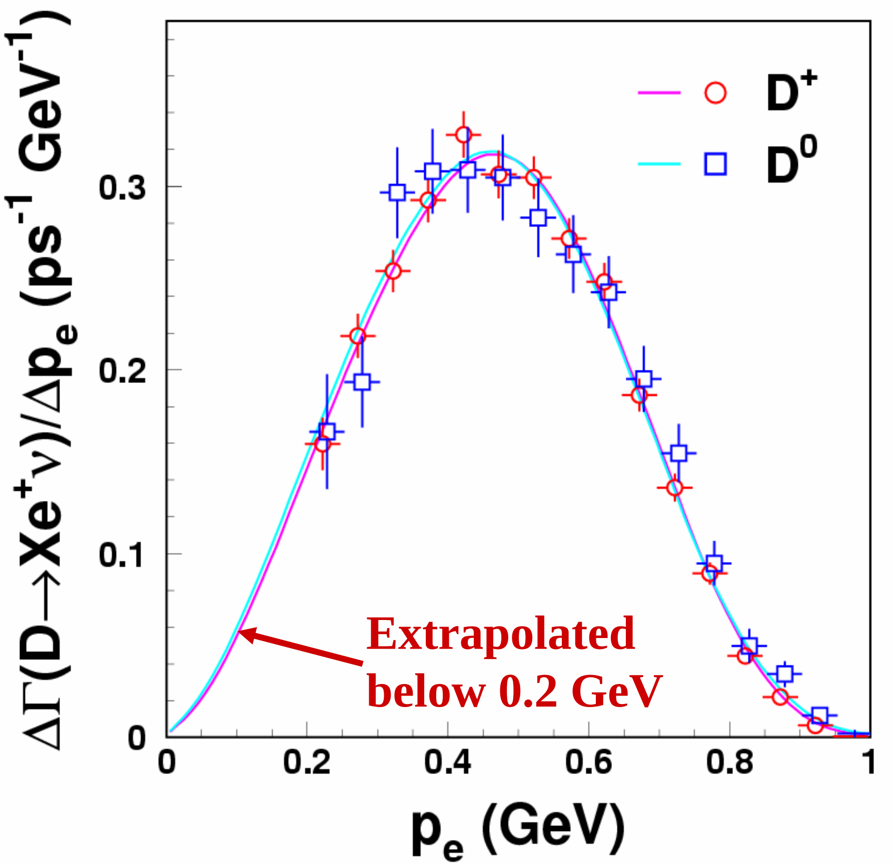
$$\frac{\Gamma^{SL}_{D^+}}{\Gamma^{SL}_{D^0}} = \frac{B^{SL}_{D^+}}{B^{SL}_{D^0}} \times \frac{\tau_{D^0}}{\tau_{D^+}} = 0.985 \pm 0.028 \pm 0.015$$

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

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

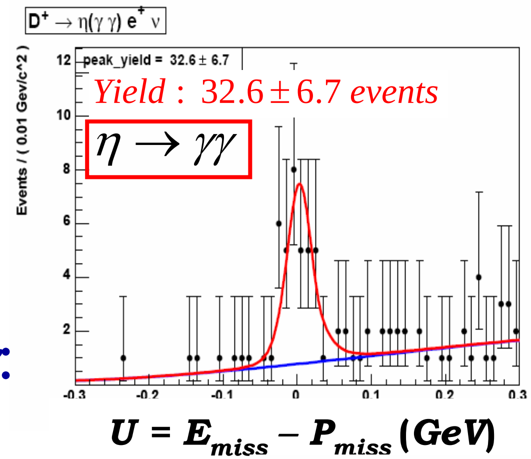
$$\sum B(D^+_{excl\ semil}) = (15.1 \pm 0.5 \pm 0.5)\%$$

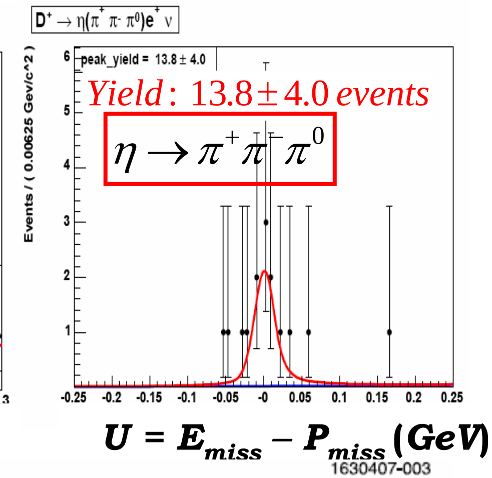
which excludes the possibility of new D SL modes with large branching fractions



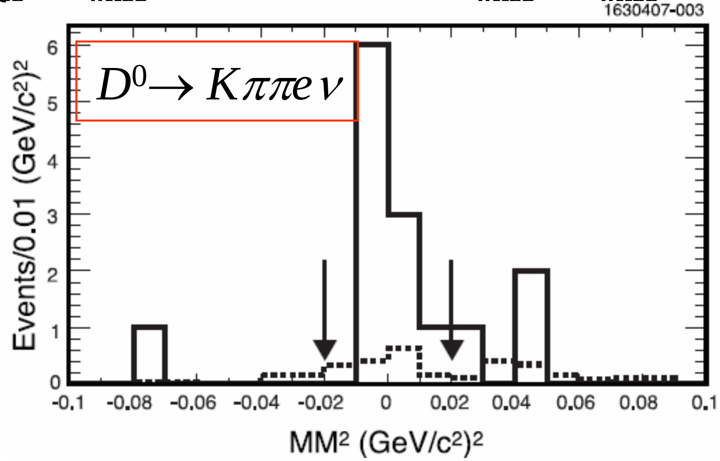
Observation of $D^+ \to \eta e^+ \nu$
Evidence for $D^+ \to K^- \pi^+ \pi^- e^+ \nu$

- Search for $D^+ \to \eta e \nu$, $\eta' e \nu$ and $\phi e \nu$ (allows to study η-η' and ω-ϕ mixing):





- Search for $D^0 \to K^- \pi^+ \pi^- e^+ \nu$: 10 candidates; ~1.8 bkg events (about 4.0 σ significance)



- Results:

Preliminary

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

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

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

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

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

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

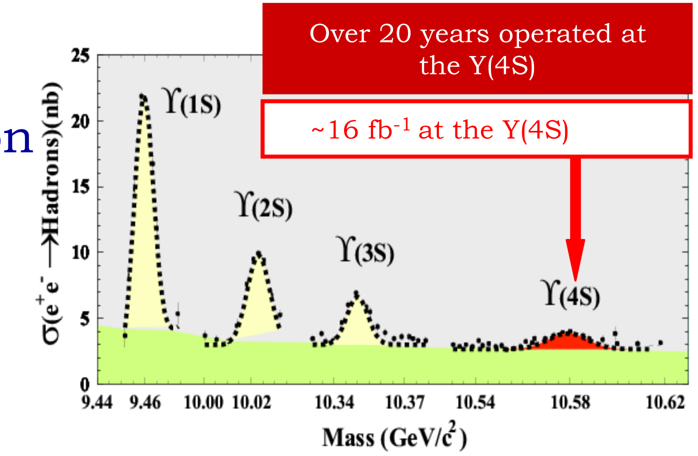
Conclusions and Outlook

- 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.

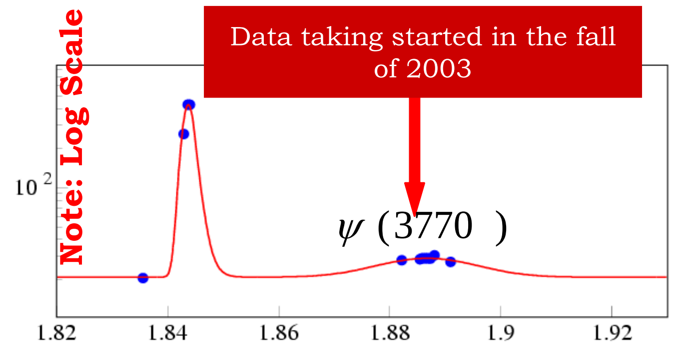
Additional Slides

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: 1.3×10^{33} cm^{-2}s^{-1}
  - ✓ Total integrated luminosity at the Υ(4S): 16 fb^{-1}
  - ✓ Lots of important discoveries, e.g., *Υ*(nS), $b\to s\gamma$, $b\to uW$.



- In 2003, CLEO started running at the *ψ*(3770), ~40 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: ~7×10^{31} cm^{-2}s^{-1}

Why a Charm Factory?

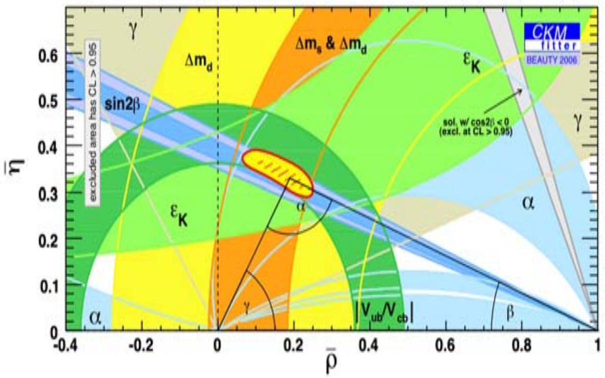
The main task of the CLEO-c open charm program:

Calibrate and Validate Lattice QCD

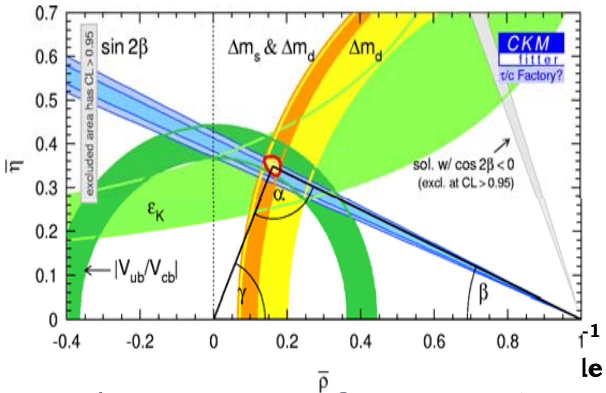
- Help heavy flavor physics constrain the CKM matrix now:
  - ✓ Precision tests of the Standard Model or
  - ✓ Discovery of new physics beyond the SM in *b* or *c* quark decays

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 <u>**tested**</u> **LQCD**



- Help LHC search for and interpret new physics (future)

Why now?

- C. Davies at EPS-2005:

"There has been a revolution in LQCD…"

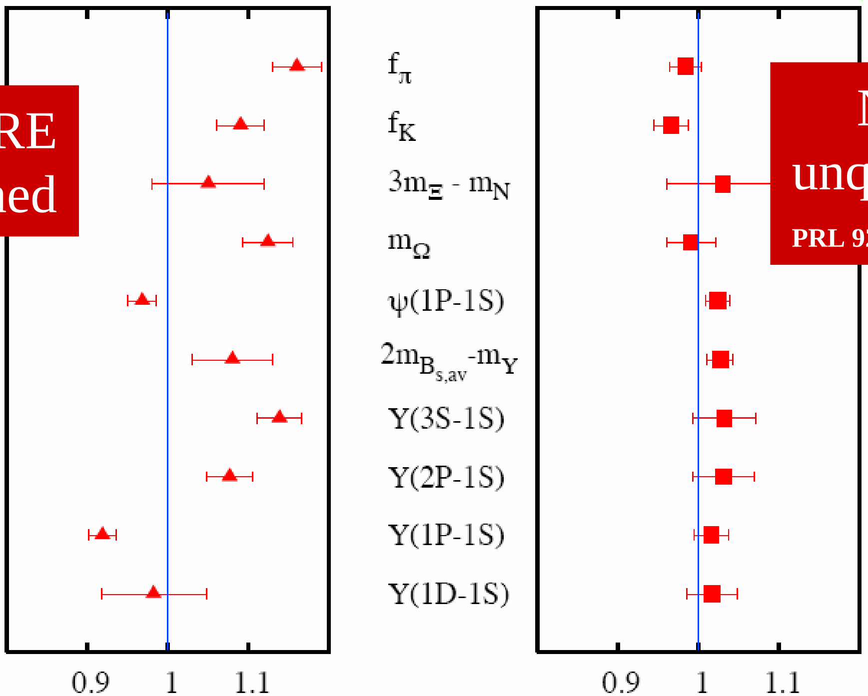
LQCD demonstrated that it can reproduce a wide range of mass differences and decay constants in unquenched calculations. **These were postdictions.**

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

NOW unquenched
PRL 92, 022001 (2004)



$$\frac{LQCD}{exp.}$$ $$\frac{LQCD}{exp.}$$