Charm Decays

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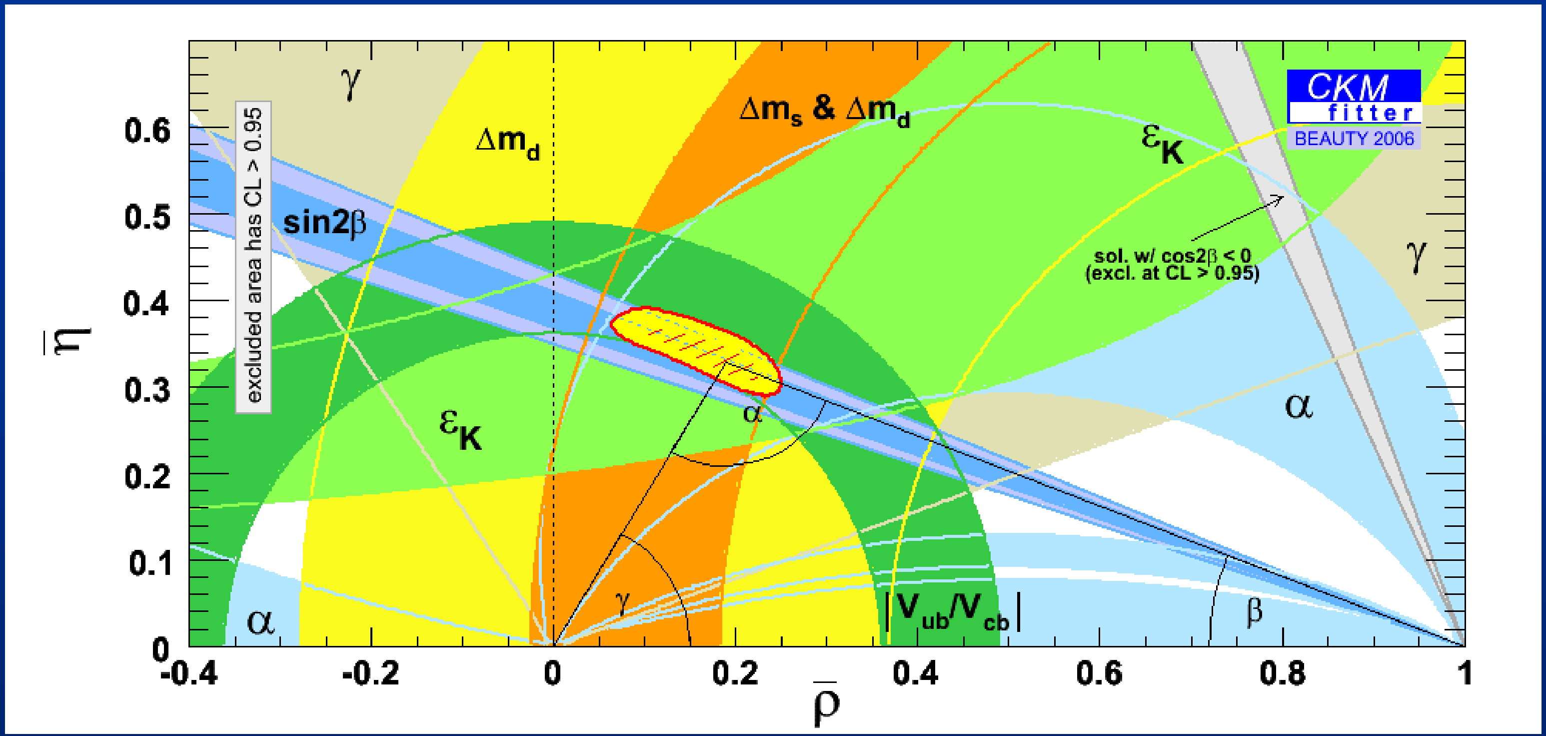
Outline

- Results from active experiments
  - BaBar, Belle, CLEO-c, (CDF, DØ), FOCUS
- Guiding principle: Charm's role in flavor physics
- Hadronic Charm Decays
  - D and D_s branching fractions
- Leptonic Charm Decays
  - decay constants from $D_{(s)} \to \mu\nu$ and $D_s \to \tau\nu$
- Semileptonic Charm Decays
  - branching fractions
  - hadronic form factors and CKM V_{cs} and V_{cd}
- Many interesting results not shown for lack of time
  - hadronic structure in multibody decays
  - rare D decays: CDF $D^0 \to \mu\mu$ search presented in session B14

Charm's role in flavor physics



Flavor physics:

- Overconstrain V_{CKM}
- Inconsistency → new physics

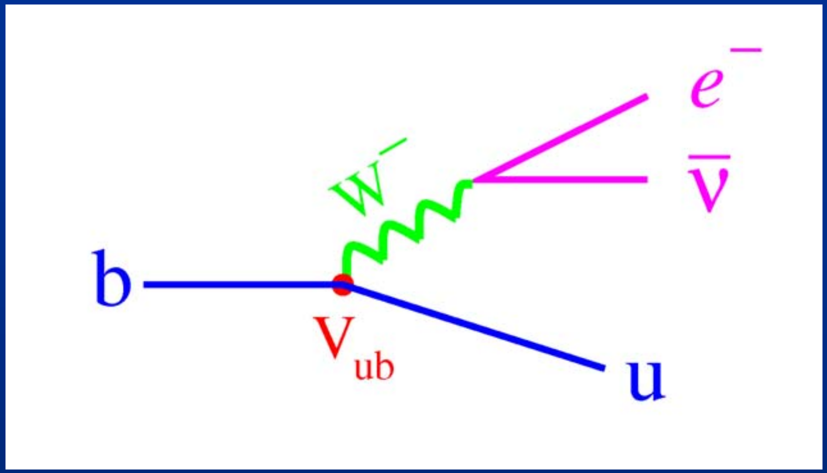
Unitarity Triangle Constraints

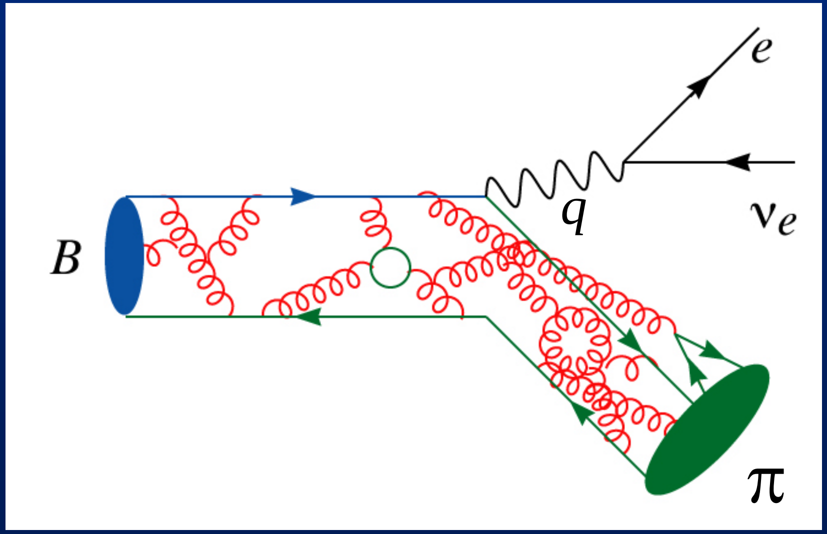
- Sin 2β is theoretically clean
- $|V_{ub}|$ is not
- B mixing is not

Hadronic uncertainties confound extraction of weak physics

Charm decay measurements can validate QCD corrections needed to extract weak physics parameters from experimental observables

$|V_{ub}|$ from semileptonic B decay





If quarks were like muons:

$$\Gamma(b \to u e \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{ub}|^2$$

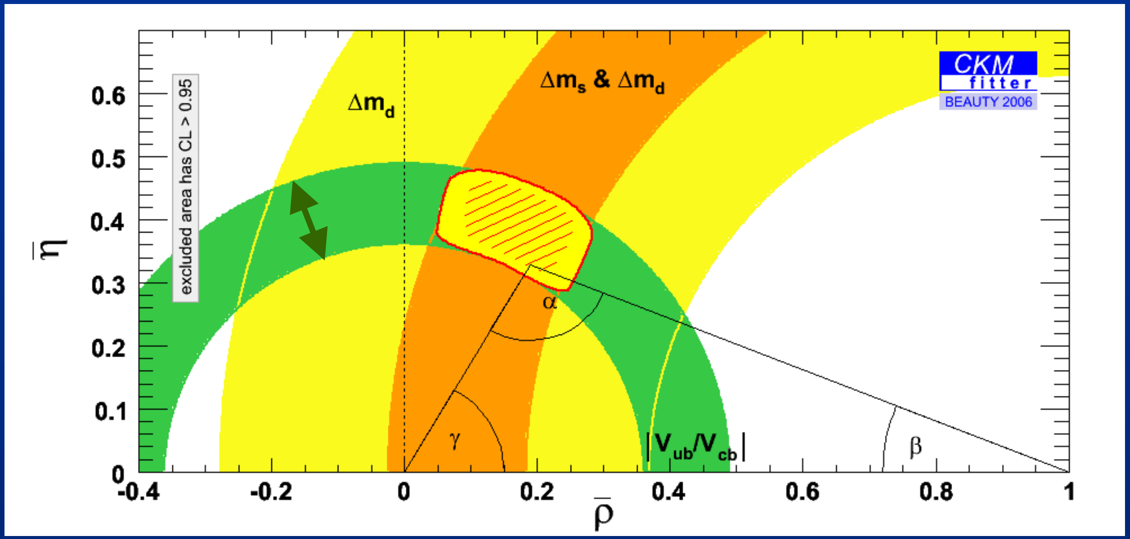
- Rate goes like $|V_{ub}|^2$

But quarks always in hadrons

- QCD form factor $f_+(q^2)$ needed to extract weak interaction physics

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

UT Constraint from $|V_{ub}|$



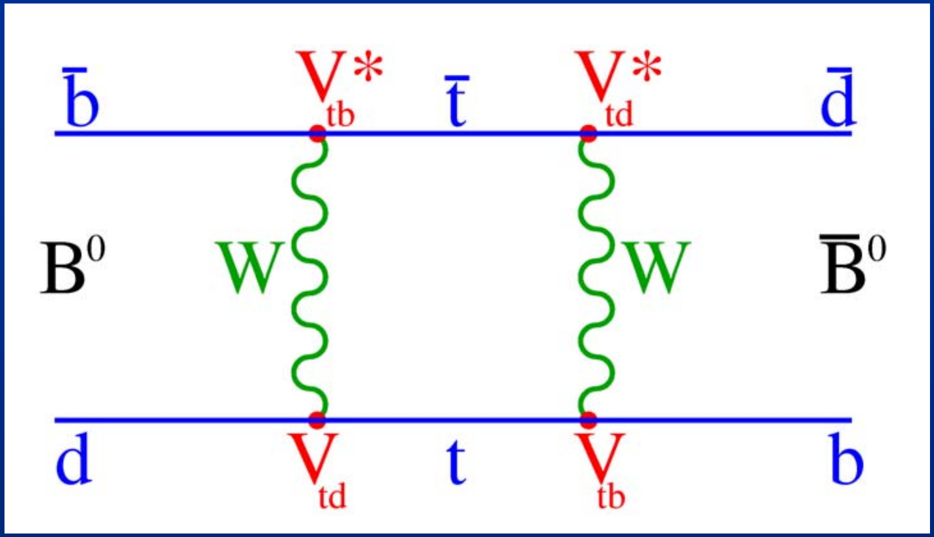
$|V_{ub}|$ from $B \to \pi \ell \nu$:

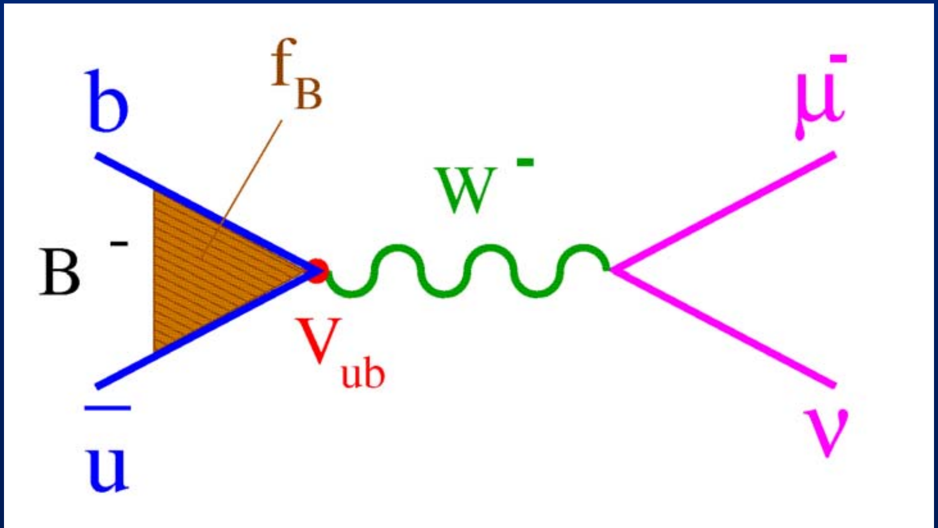
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 p_\pi^3 |f_+(q^2)|^2$$

Form factor $f(q^2)$:
- Hard to calculate
- Limits $|V_{ub}|$ precision
- Lattice QCD can do from first principles

- $D \to \pi\ell\nu$ to $B \to \pi\ell\nu$ are both "heavy to light" decays
- Precise measurement of $D \to \pi\ell\nu$ can calibrate LQCD and allow a precise extraction of $|V_{ub}|$ from $B \to \pi\ell\nu$
- Absolute rate and shape is a stringent test of theory

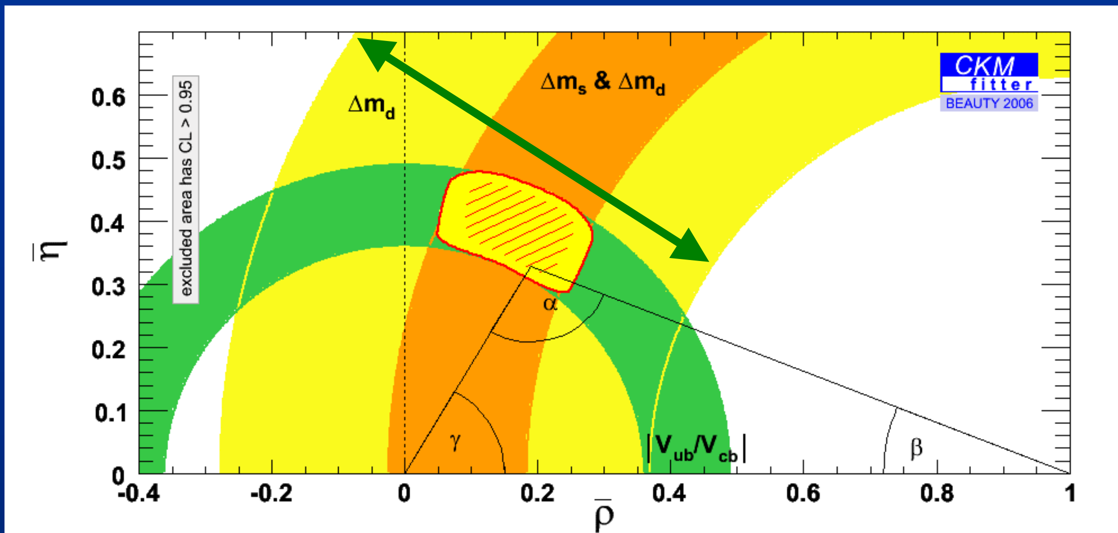
$|V_{td}|$ from B^0-$\overline{B^0}$ mixing





- Mixing rate depends on $|V_{td}|^2$
- QCD correction here is partly decay constant f_B
  - probability of wave function overlap ψ(r=0)
- Hard to calculate @ small q^2 low energy QCD
  - Lattice QCD to ~15%
- Same for meson decay
- Can measure annihilation decay
  - Belle: PRL 97, 251802 (2006) Evidence for $B^- \to \tau^- \nu$ (3.5 σ) f_B=229±36±37 MeV (20%)
- But would like a *precise* measurement

UT Constraint from B mixing



$$\Delta M_d = 0.50\,ps^{-1}\left[\frac{\sqrt{B_{B_d}}\,f_{B_d}}{200MeV}\right]^2\left[\frac{|V_{td}|}{8.8\times10^{-3}}\right]^2$$

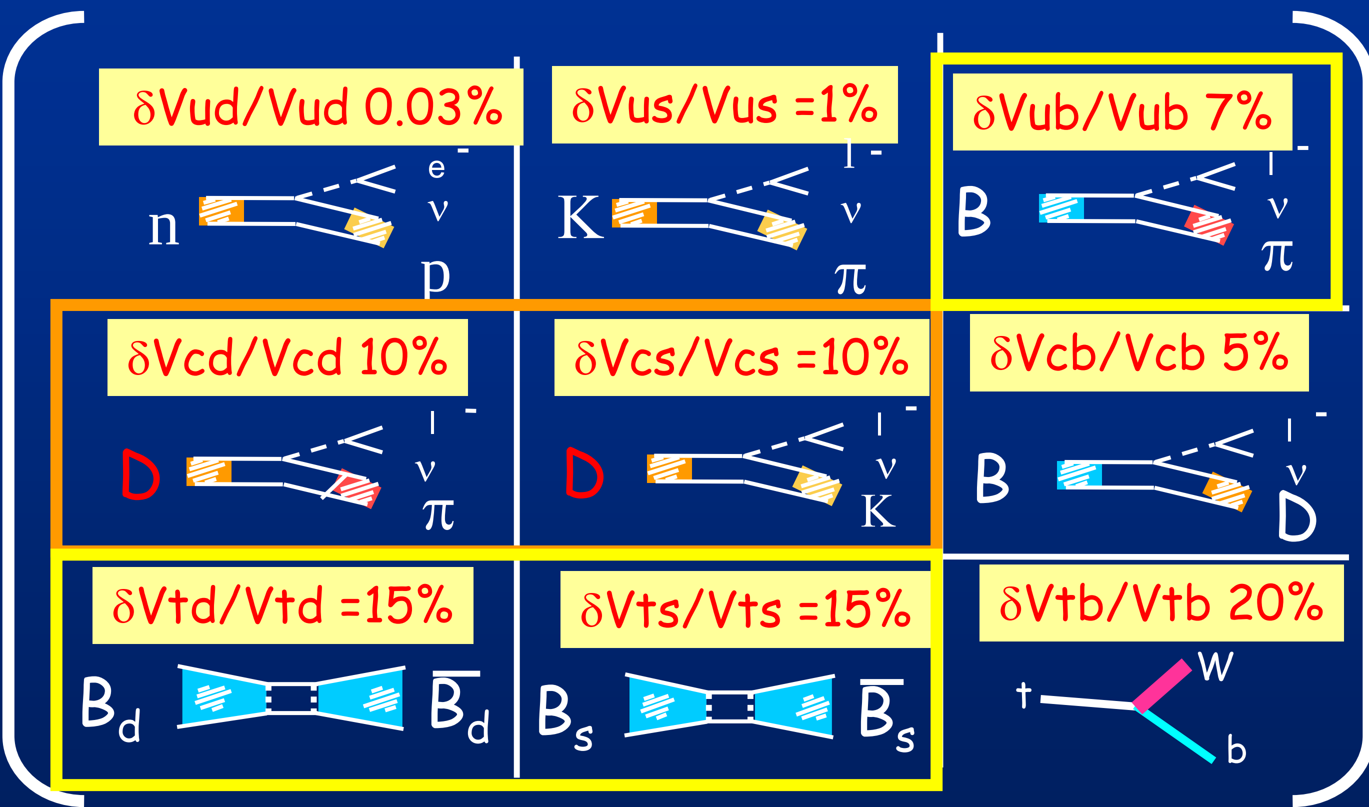
$$\frac{\sigma(|V_{td}|)}{|V_{td}|} = 0.5\frac{\sigma(\Delta M_d)}{\Delta M_d}\oplus\frac{\sigma(f_B\sqrt{B_{B_d}})}{f_B\sqrt{B_{B_d}}}$$

0.8% ~15% (LQCD)

- Lattice QCD predicts decay constants f_D & f_B
- Charm sector measurements of $f_{D(s)}$ from $D_{(s)}\rightarrow\mu\nu$ can increase our confidence in the non-perturbative QCD calculations of f_B needed to interpret Δm and Δm_s
  - direct measurement of $B\rightarrow\ell\nu$ is much harder!
- Better constraint on $|V_{ts}/V_{td}|$ from $\Delta m_s/\Delta m_d$
  - still want to check f_{Ds}/f_D

CKM Matrix

Current V_{CKM}
From direct
Measurements
-no unitarity
imposed



charm decay measurements:

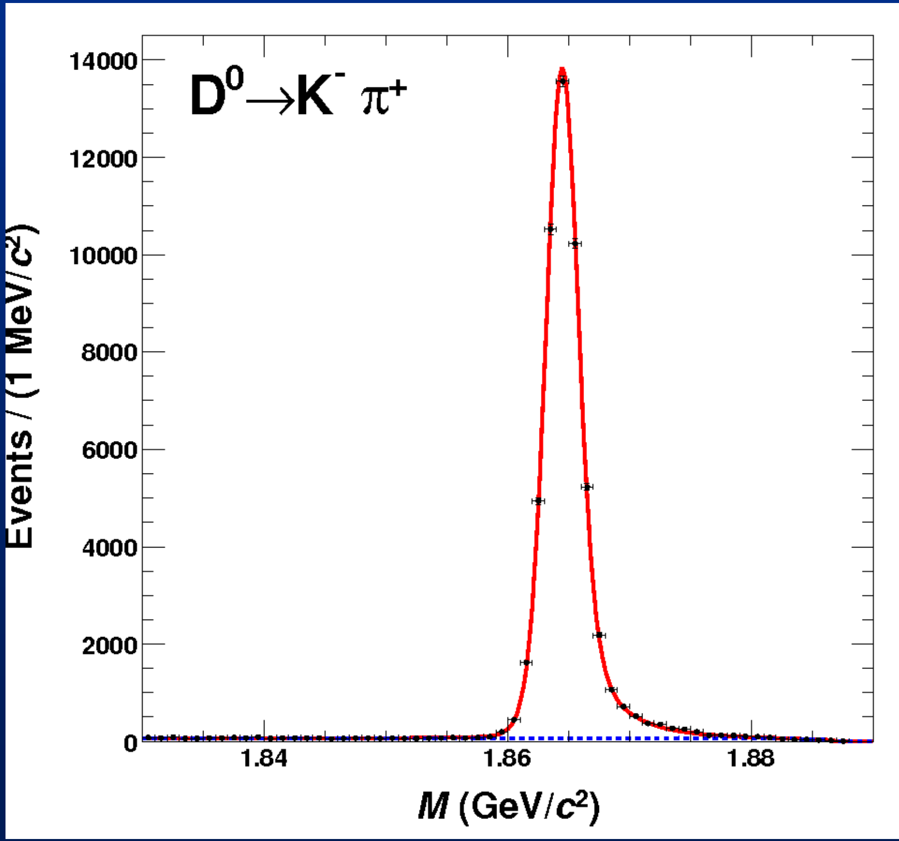
- direct access to 2nd generation elements
- enable improvements in 3rd generation elements

CLEO-c Hadronic D Decays

Presented in session B14 X.Shi

$e^+e^- \to \psi(3770) \to D\,\bar{D}$ ($D^0\bar{D}^0$ or D^+D^-)

- Just above threshold: no additional particles are produced
- Fully reconstruct one D in the event, e.g. $D^0 \to K^- \pi^+$



Energy and Momentum Conservation:

$$E_D = E_K + E_\pi$$

$$\vec{p}_D = \vec{p}_K + \vec{p}_\pi$$

$$\Delta E = E_{\text{beam}} - E_D$$

$$M(D) = \sqrt{E_{\text{beam}}^2 - \left|p_D\right|^2}$$

resolution:

7-10 MeV

1.3 MeV

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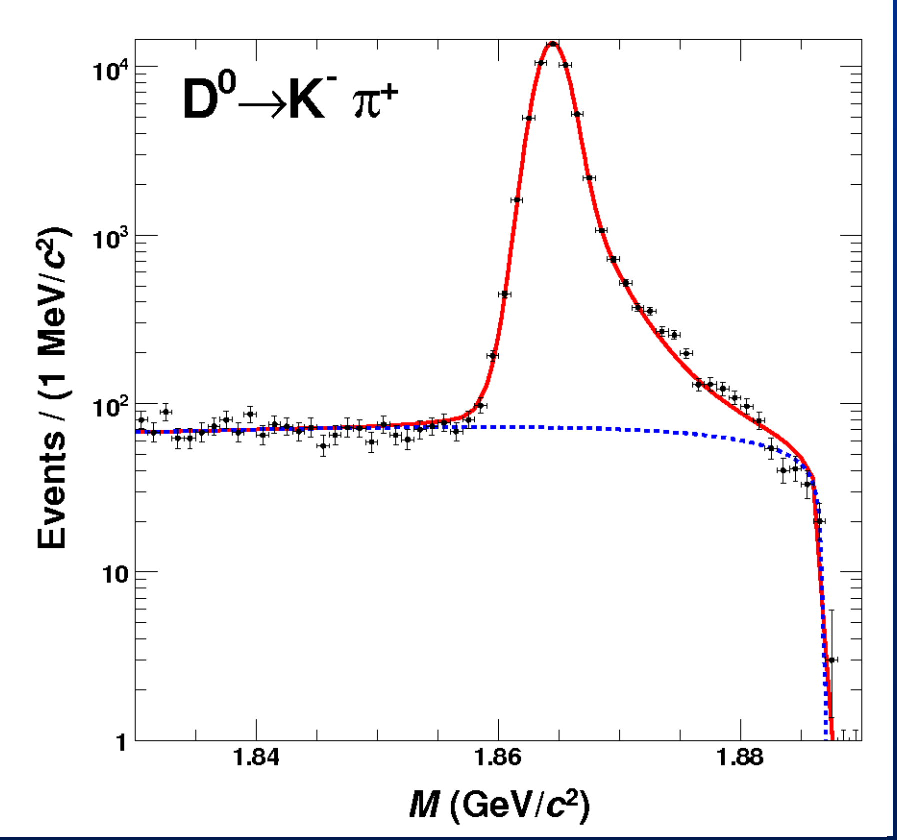

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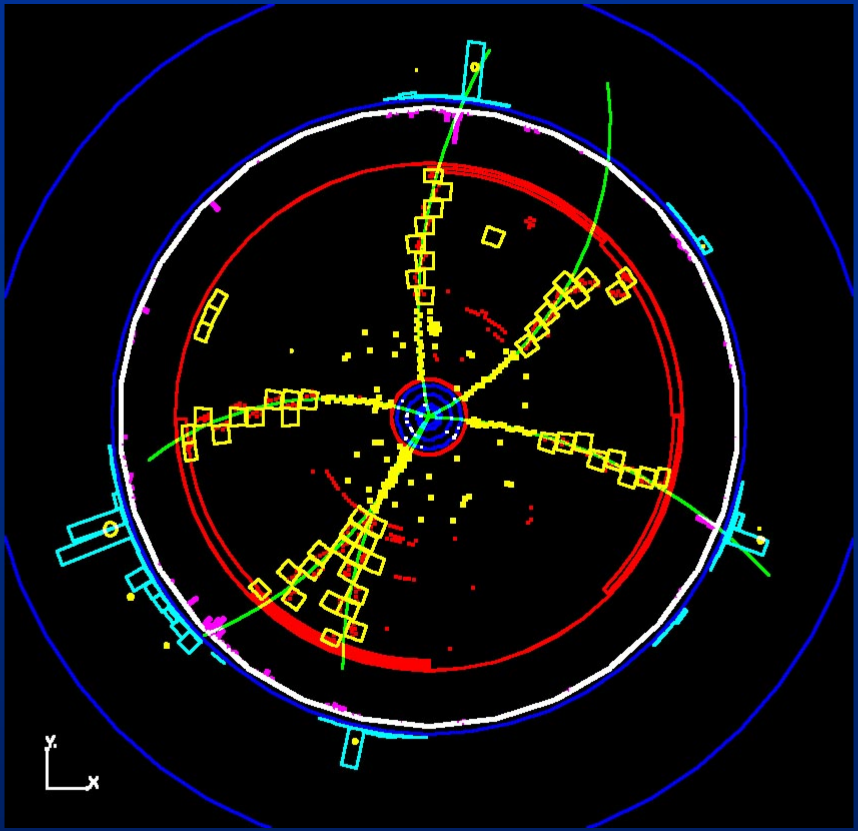
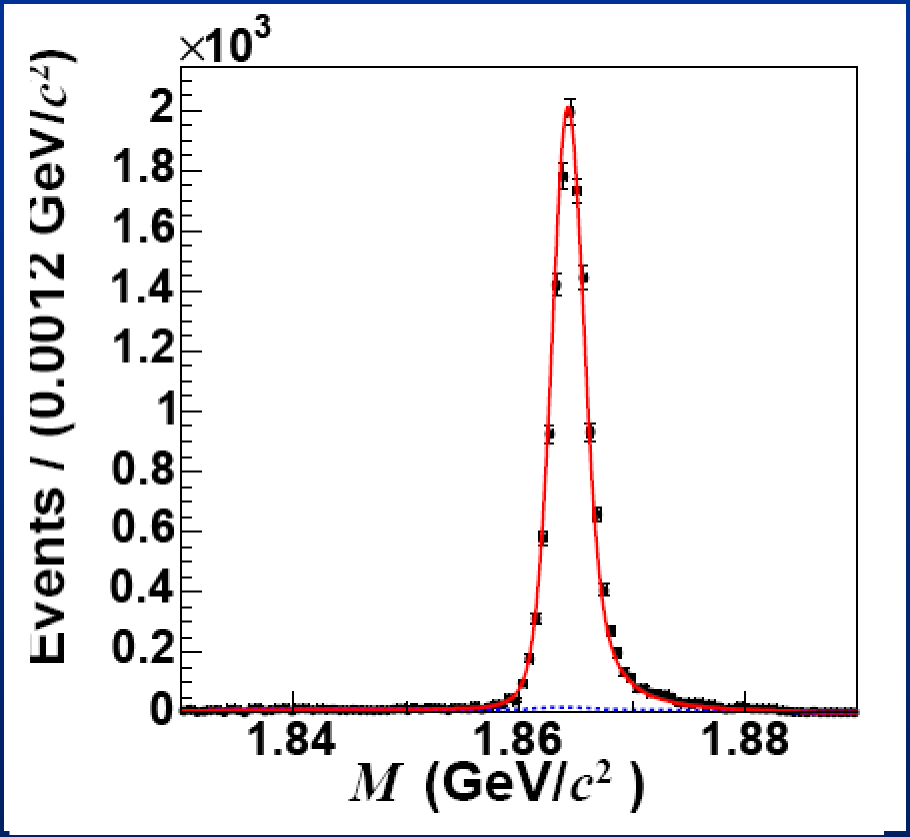
Double Tag Events

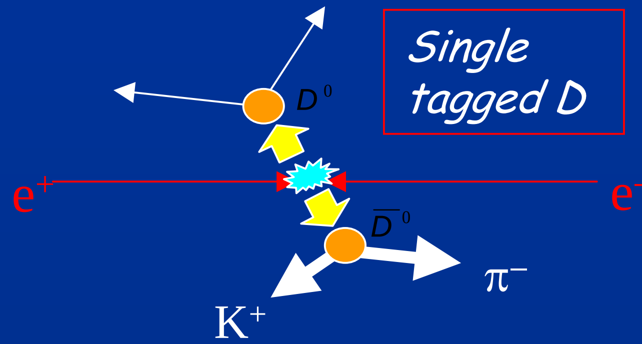


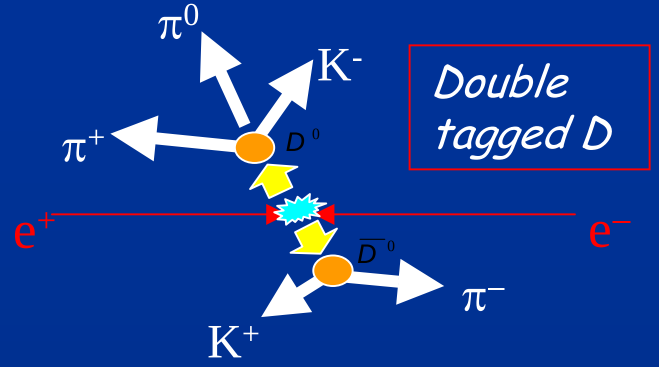


$D^+ \rightarrow K^-\pi^+\pi^+$ & $D^- \rightarrow K^+\pi^-\pi^-$

- Tagging effectively makes a single D beam
- Can tag ≈22% of D's produced!

$$\mathcal{B}(D \rightarrow X_i) = \frac{N(D \rightarrow X_i)}{\text{Efficiency} \times N_{\text{tags}}}$$





$$N_i = N_{D\bar{D}} B_i \varepsilon_i$$

$$N_{ij} = N_{D\bar{D}} B_i B_j \varepsilon_{ij}$$

$$B_i = \frac{N_{ij}}{N_j} \frac{\varepsilon_j}{\varepsilon_{ij}}$$

$$N_{D\bar{D}} = \frac{N_i N_j}{N_{ij}} \frac{\varepsilon_{ij}}{\varepsilon_i \varepsilon_j}$$

$$\varepsilon_{ij} \approx \varepsilon_i \varepsilon_j$$

ε_i=16—65%

D Decay Mode
$K^-\pi^+$
$K^-\pi^+\pi^0$
$K^-\pi^+\pi^+\pi^-$
$K^-\pi^+\pi^+$
$K^-\pi^+\pi^+\pi^0$
$K_S^0\pi^+$
$K_S^0\pi^+\pi^0$
$K_S^0\pi^+\pi^+\pi^-$
$K^+K^-\pi^+$

9 modes, simultaneous χ^2 fit including correlations on N, ε to extract 9 B_i & N(DD)

56 pb^{-1}: PRL 95 121801 (2005)

281 pb^{-1}: Preliminary results reported at this meeting (X.Shi)

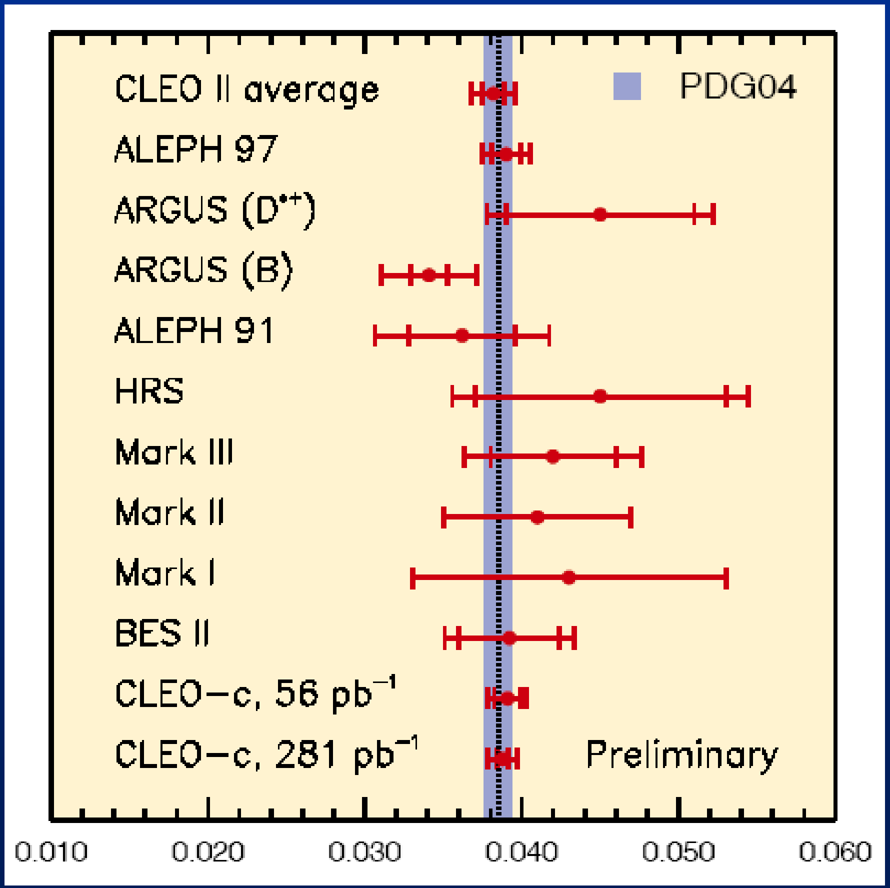
Additional data in hand now (~280 pb^{-1})

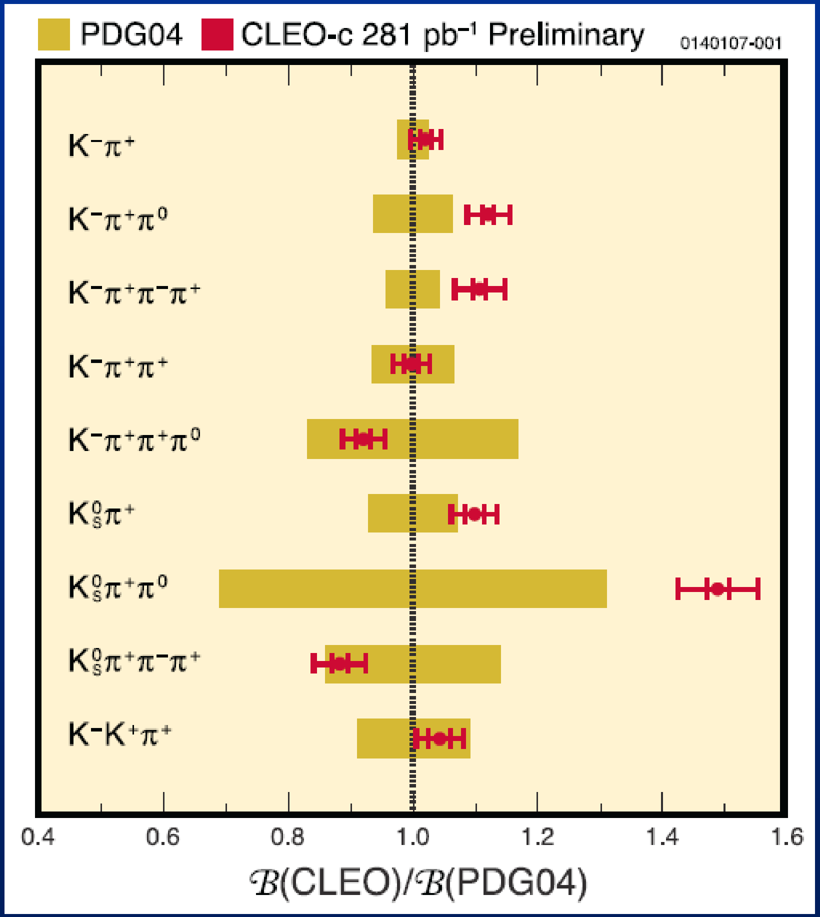
And from run through Mar'08 (~300 pb^{-1})

CLEO-c hadronic decay results

Comparison to other measurements

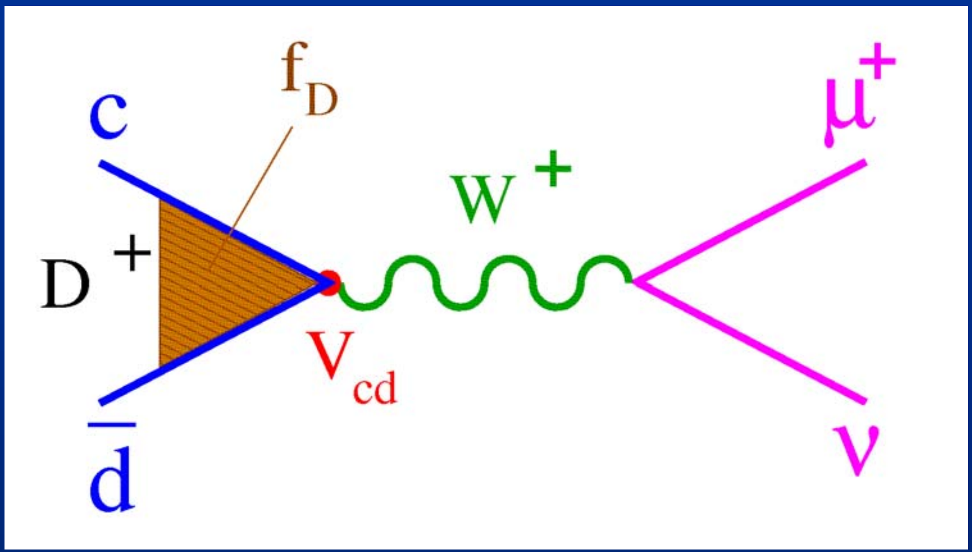
BF($D^0 \rightarrow K^-\pi^+$)





Precision measurements of many D^0, D^+ decay modes

Leptonic $D_{(s)}$ Decay



- Measure rate to extract f_D and f_{Ds}
- Useful to calibrate V_{td}/V_{ts} from $B_{(s)}^0$ mixing

$$\mathcal{B}(D \to \mu\nu) = \Gamma\tau_D \approx 4\times10^{-4}$$

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

$$\mathcal{B}(D \to \tau\nu) \approx 4\times10^{-3}$$

$$\mathcal{B}(D_s \to \mu\nu) \approx 6\times10^{-3}$$

$$\mathcal{B}(D_s \to \tau\nu) \approx 6\times10^{-2}$$

decay constant

measures overlap of quark wave functions

CLEO-c $D^+ \to \mu\nu$

281 pb^{-1} PRL 95, 251801 (2005)

Use 158k tagged D^- decays

Require

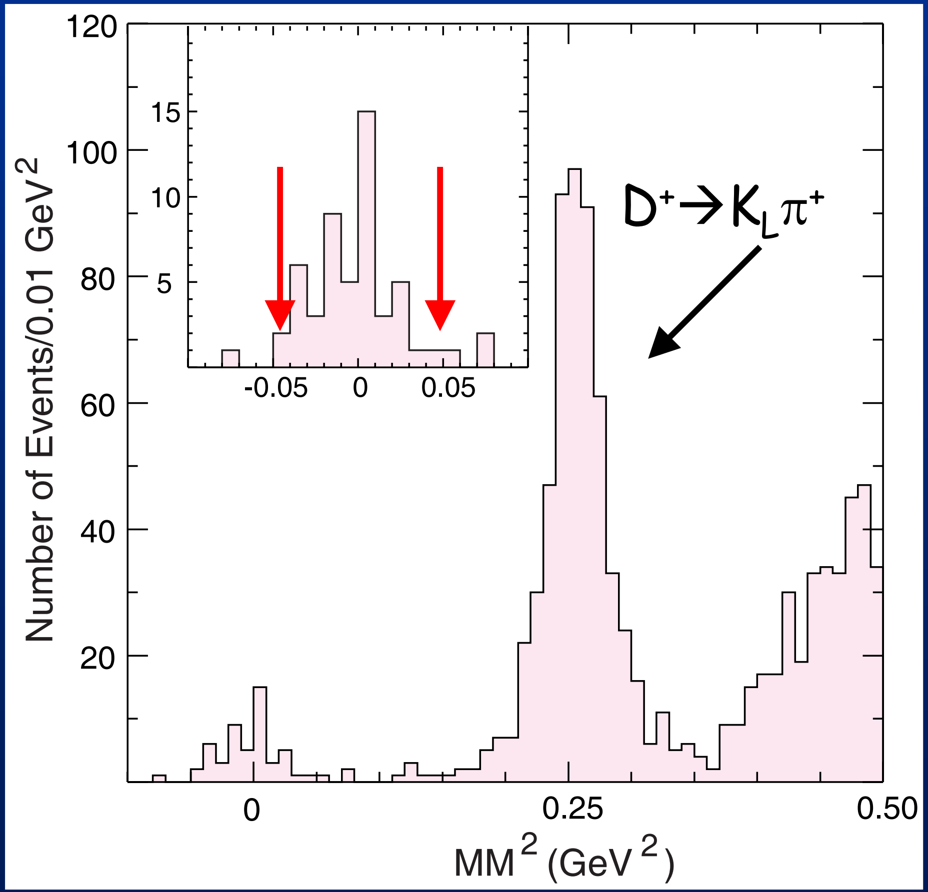
- one μ candidate with MIP-like shower
- no extra tracks
- no unmatched showers with $E_{CC} > 250$ MeV

$\mathcal{B} = (4.40 \pm 0.66\ ^{+0.09}_{-0.12}) \times 10^{-4}$

$f_D = (222.6 \pm 16.7\ ^{+2.8}_{-3.4})$ MeV

Unquenched Lattice QCD
201±3±17 MeV
PRL 95, 122002 (2005)

signal region: 50 events
2.8 estimated background



(Missing Mass)^2

BaBar $D_s \to \mu\nu$

hep-ex/0607094

$e^+e^- \to D_s^* D_{tag} X$; D_{tag} is fully reconstructed $D_{(s)}^{(*)}$

Then look for $D_s^* \to D_s \gamma$; $D_s \to \mu\nu$:

$\Delta M = M(\mu\nu\gamma) - M(\mu\nu)$ signal peak at 143 GeV

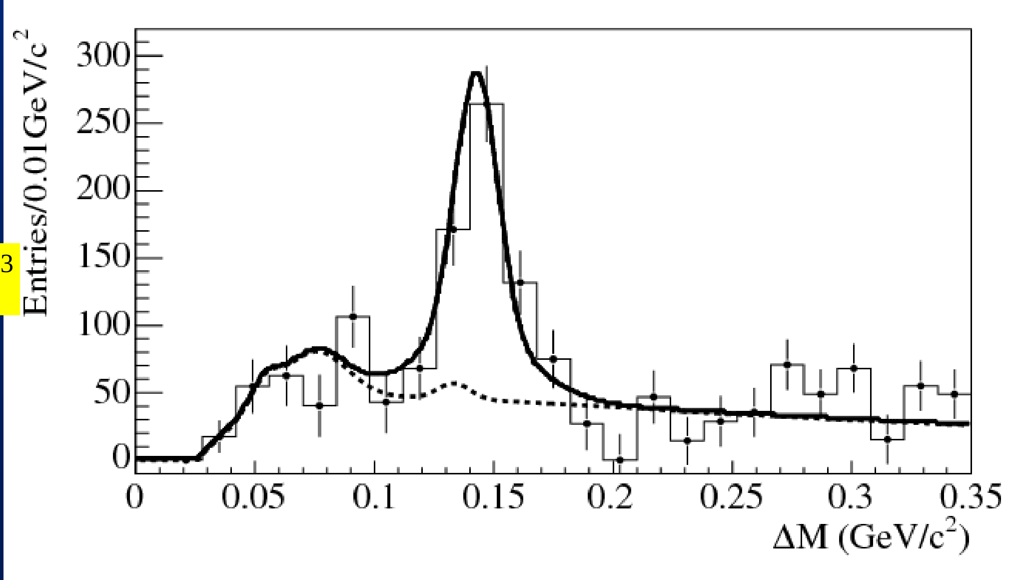
- Measure also $D_s \to \phi\pi$ to normalize
- Detailed systematic understanding

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

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

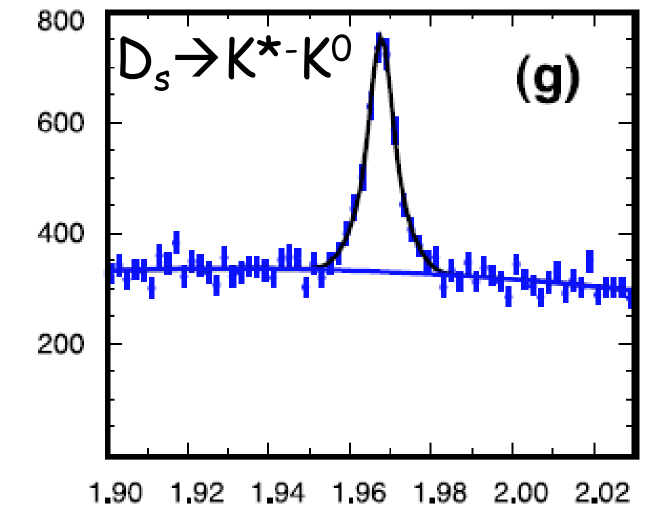
$$f_{D_s} = (283 \pm 17 \pm 7 \pm 14)\,\mathrm{MeV}$$

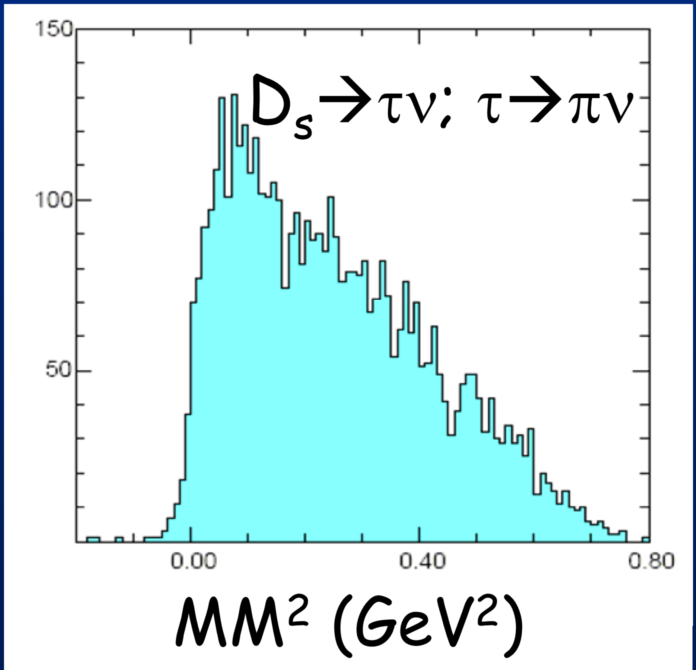
Unquenched Lattice QCD
249±3±16 MeV
PRL 95, 122002 (2005)



CLEO-c $D_s \to \mu\nu$ & $D_s \to \tau\nu$; $\tau \to \pi\nu$

- $e^+e^- \to D_s D_s^*$ @ $\sqrt{s}$=4170 MeV
  314 pb^{-1}
- Fully Reconstruct
  - 19k D_s tags (8 modes)
  - Recoil Mass peaks at D_s^*
    - count tags by fit
- Add a single track
  - μ: MIP-like in Calorimeter
  - π: sometimes E_{CC}>200 MeV
  - MM^2 peaks at 0 for $\mu\nu$
  - and near 0 for $\tau\nu$; $\tau \to \pi\nu$
- Veto events with
  - extra tracks
  - extra neutral energy
- Kinematic Fit
  - improved resolution
  - resolve ambiguity: $D_s^* \to D_s\gamma$ on tag or signal side





CLEO-c f_{D_s} Results

Case	Region (GeV^2)	Signal	Background
i	$-0.05 < MM^2 < 0.05$	92	3.5 ± 1.4
i	$0.05 < MM^2 < 0.20$	31	2.5 ± 1.1
ii	$-0.05 < MM^2 < 0.20$	25	3.0 ± 1.3
Sum	$-0.05 < MM^2 < 0.20$	148	9.0 ± 2.3

arXiv:0704.0437 (to PRD)

arXiv:0704.0629 (to PRL)

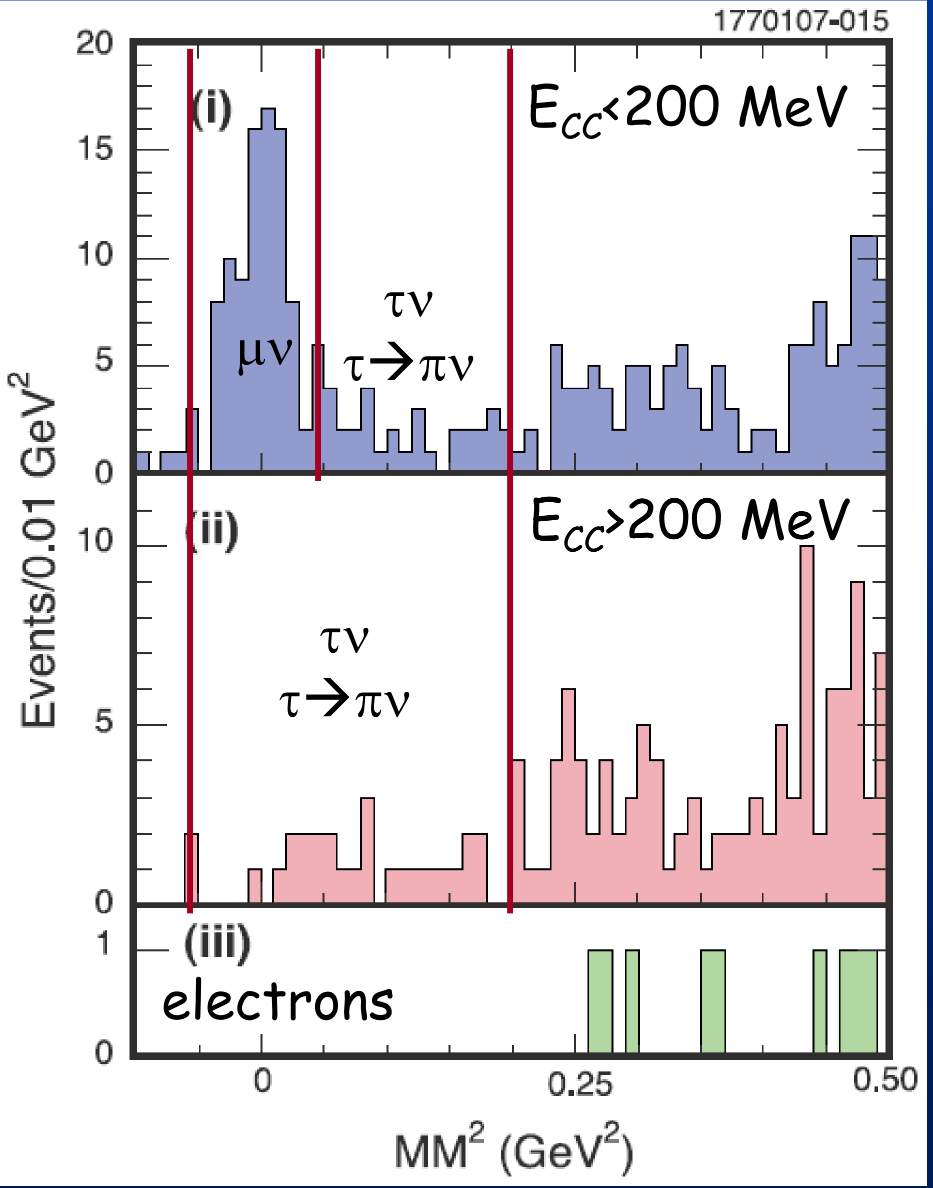
$\mathcal{B} = (0.638 \pm 0.059 \pm 0.033)\%$

$f_{D_s} = (274 \pm 13 \pm 7)$ MeV

Unquenched Lattice QCD
$249 \pm 3 \pm 16$ MeV
PRL 95, 122002 (2005)

$$\frac{f_{D_s}}{f_D} = 1.23 \pm 0.11 \pm 0.04$$

ULQCD
$1.24 \pm 0.01 \pm 0.07$



CLEO-c $D_s^+ \to \tau^+\nu$; $\tau^+ \to e^+\nu\nu$

2nd Complementary Analysis with $\tau^+ \to e^+\nu\nu$

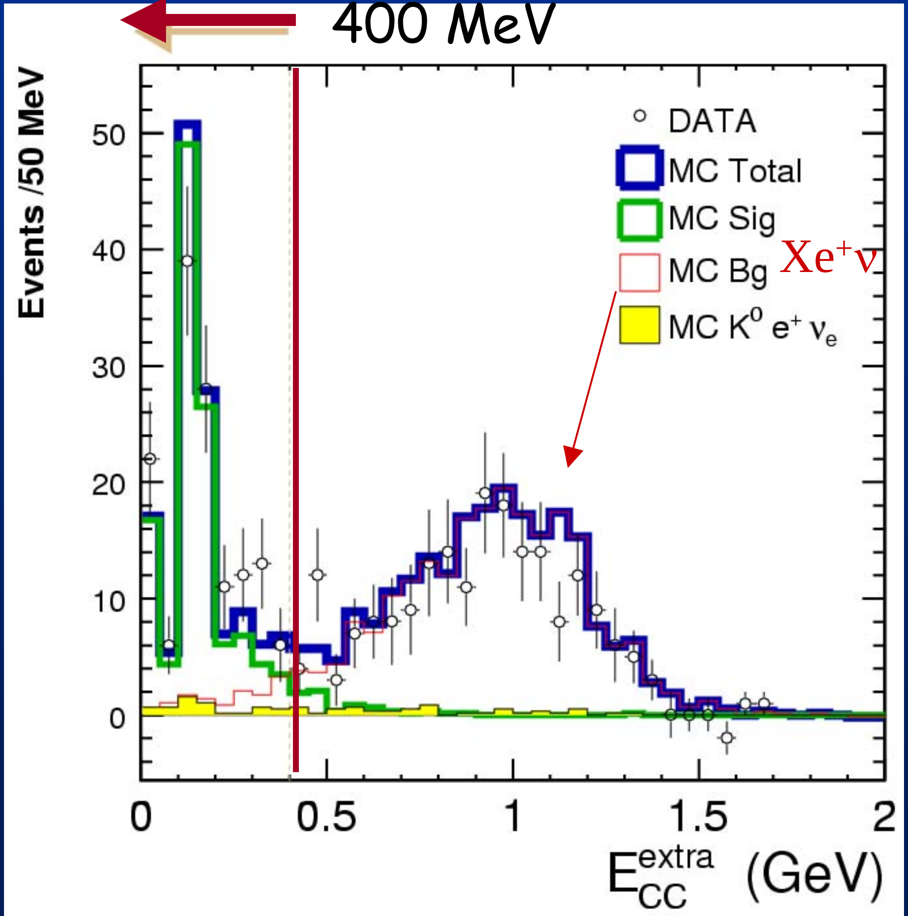
- Signal production of e+: $B(D_s^+ \to \tau^+\nu)B(\tau^+ \to e^+\nu\nu)$~1.3%
- Background: $B(D_s^+ \to Xe^+\nu)$~8%

Technique:

- Use D_s^- tags and e^+
- Suppress background
  - no additional tracks and
  - Σ Ecal < 400 MeV
- No need to find γ from D_s^*
- $B(D_s^+ \to \tau^+\nu)$ =(6.29±0.78±0.52)%
- f_{Ds}=278±17±12 MeV

Preliminary @ ICHEP 06

195 pb^{-1} near $\sqrt{s}$=4170 MeV



$f_{D(s)}$: Comparison to Theory

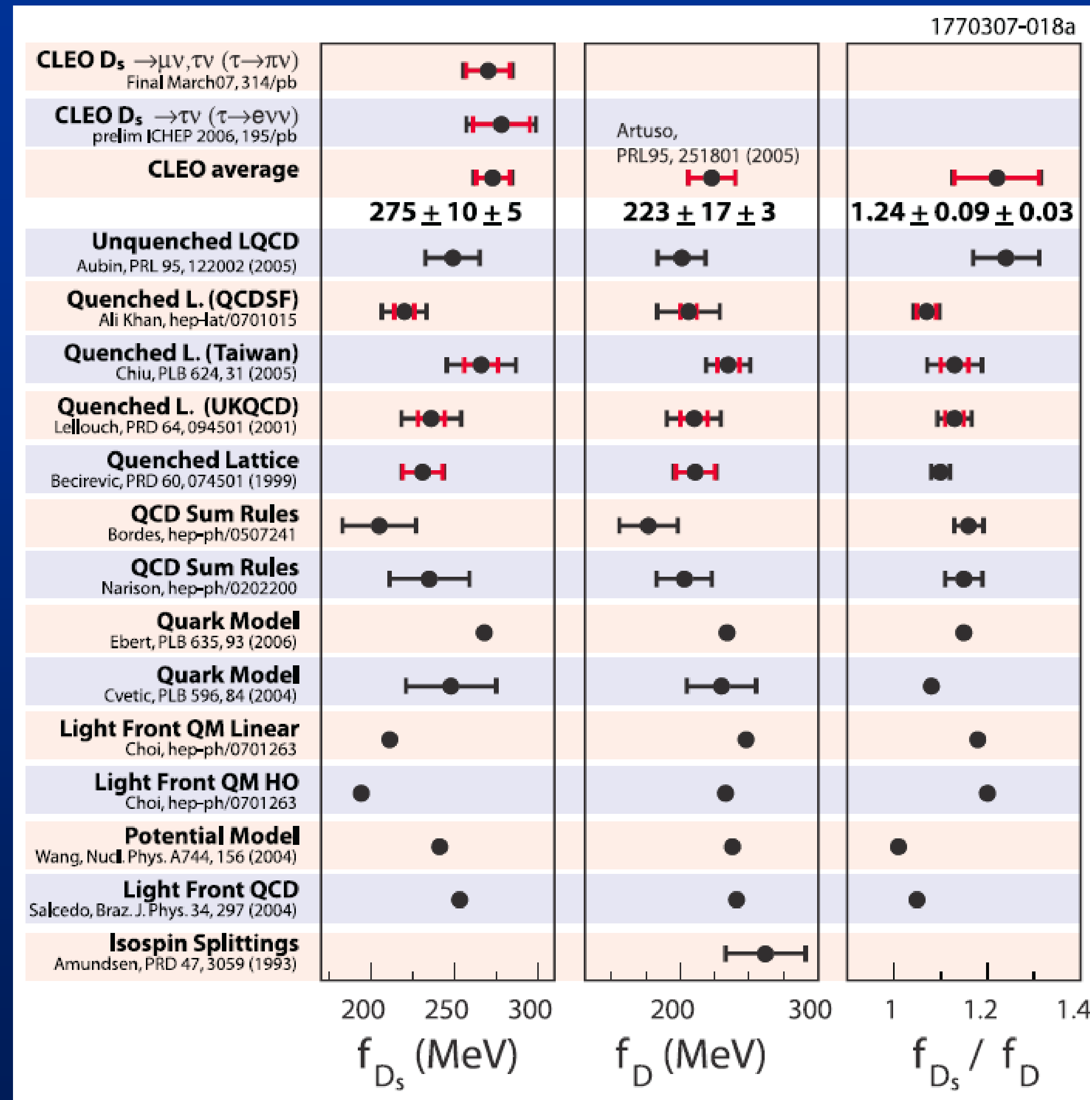
CLEO results

- Good agreement with unquenched LQCD

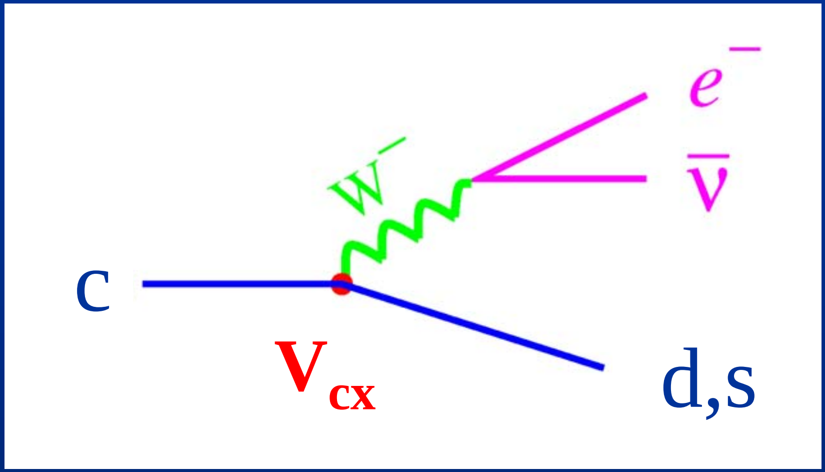
Calculations

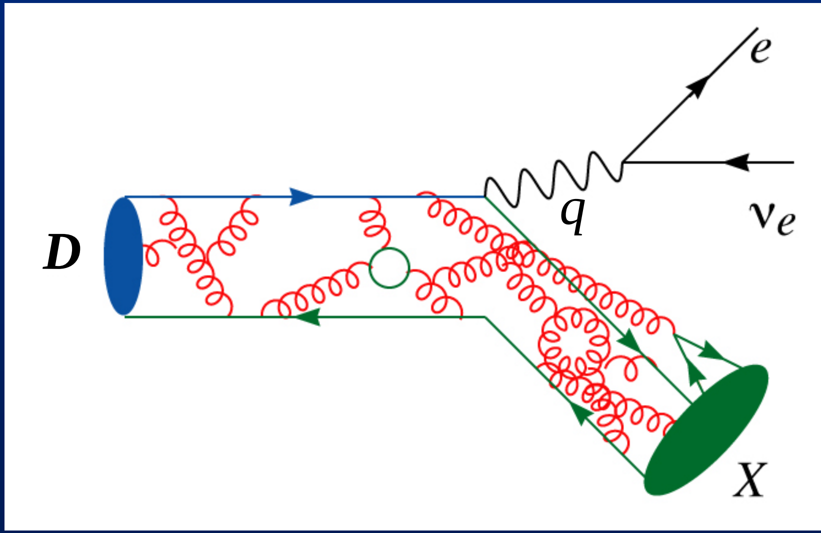
- Comparable uncertainties already!

More data to come!



Semileptonic Decays





Focus on recent results in Pseudoscalar final states: K, π

Will not show:

- D→ηen/η'en/ϕen (J.Ge) presented in session B14
- D→V e ν ; V =K*,ρ

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

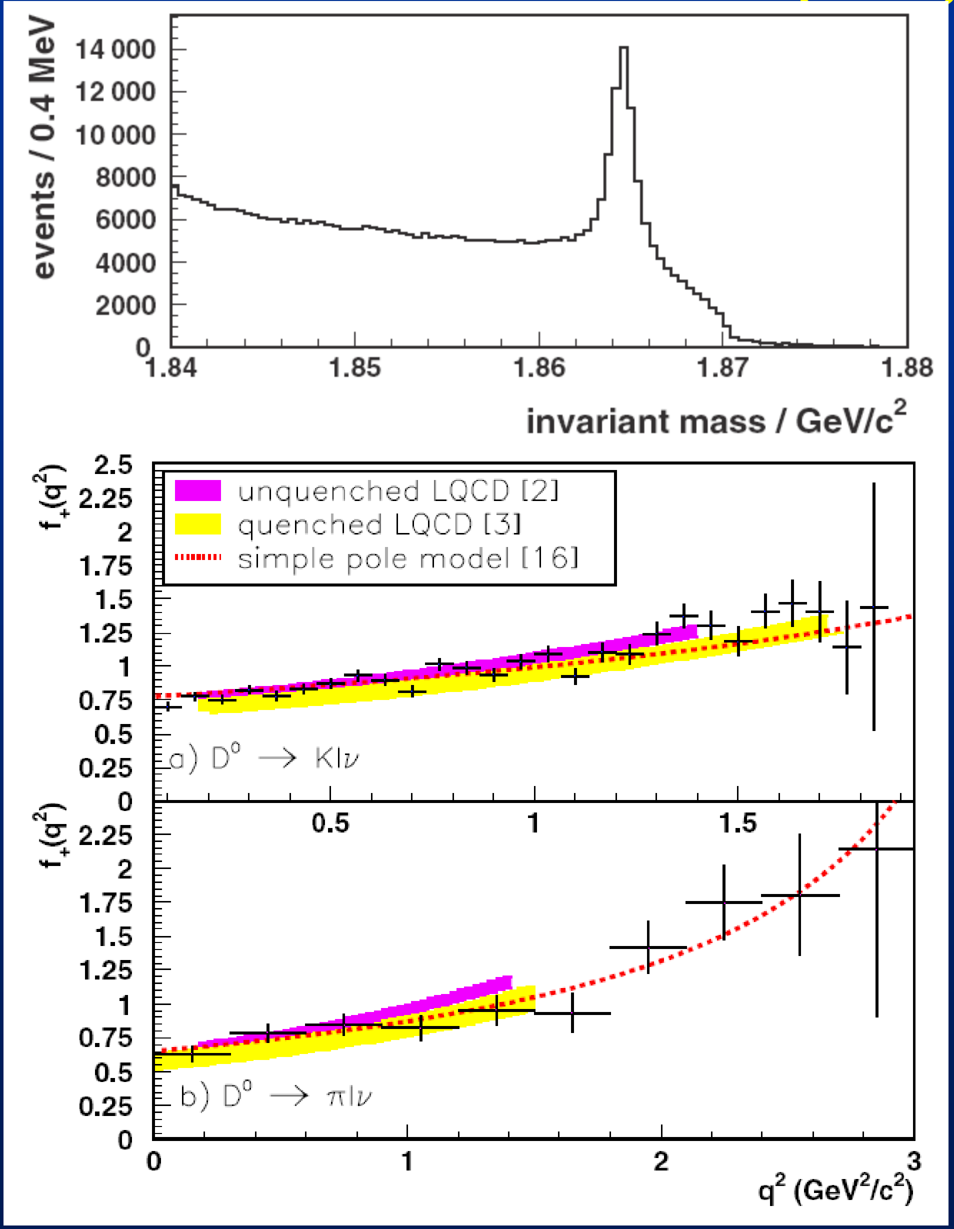
$$q^2 = (p_D - p_X)^2$$
$$= M_D^2 + M_X^2 - 2E_X M_D + \vec{p}_D \cdot \vec{p}_X$$

Belle $D^0 \to \pi^- \ell^+ \nu$ & $D^0 \to K^- \ell^+ \nu$

PRL 97 061804(2006)

- Fully reconstructed
  - $e^+e^- \to D^{(*)}D^*X$ events
  - $\sqrt{s}$=10.6 GeV
- Allows count of D^0 independent of decay
- Neutrino inferred from missing E,p
- $D^{*+} \to D^0\pi^+$ used to improve S/N
- Excellent q^2 resolution:
  - $\sigma(q^2)$=0.017 GeV^2
- Measure rate directly

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

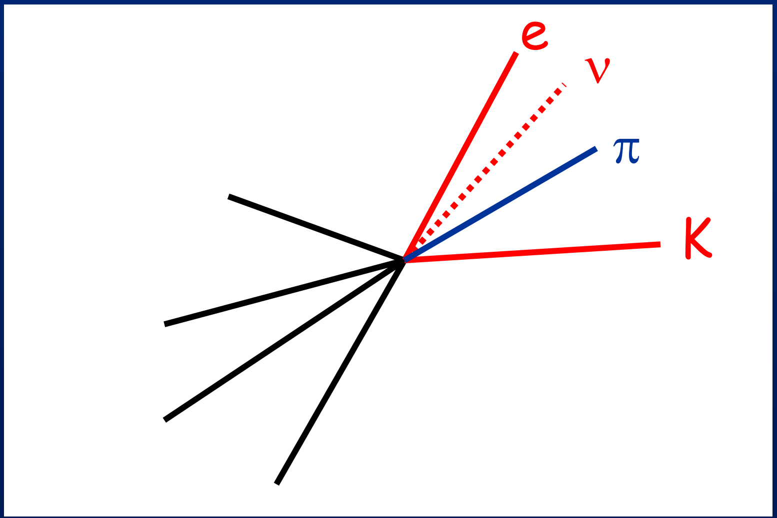


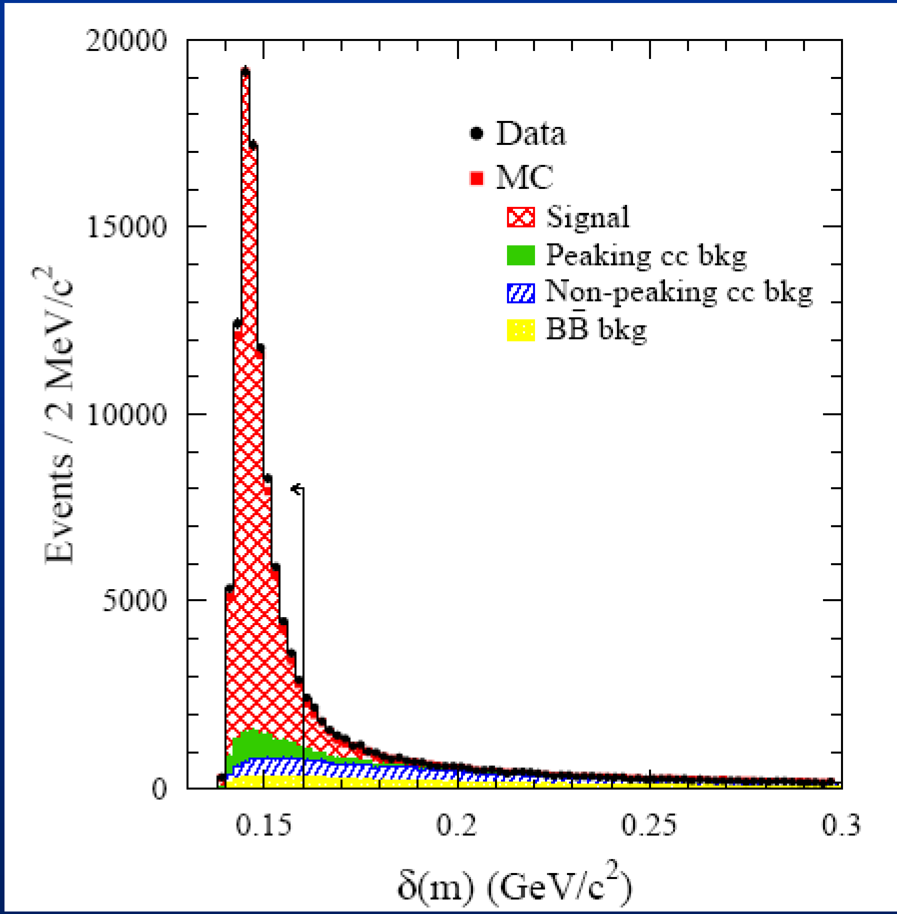
BaBar $D^0 \to K^- e^+ \nu$

arXiv:0704.0020
75 fb^{-1}

$e^+e^- \to c\bar{c}$ at $\sqrt{s}$=10.6 GeV

- Reconstruct $D^{*+} \to \pi^+ D^0$ and signal $D^0 \to K e \nu$
- Estimate p_D and E_ν with remaining event & kinematic fits
- Use Neural Nets to suppress backgrounds



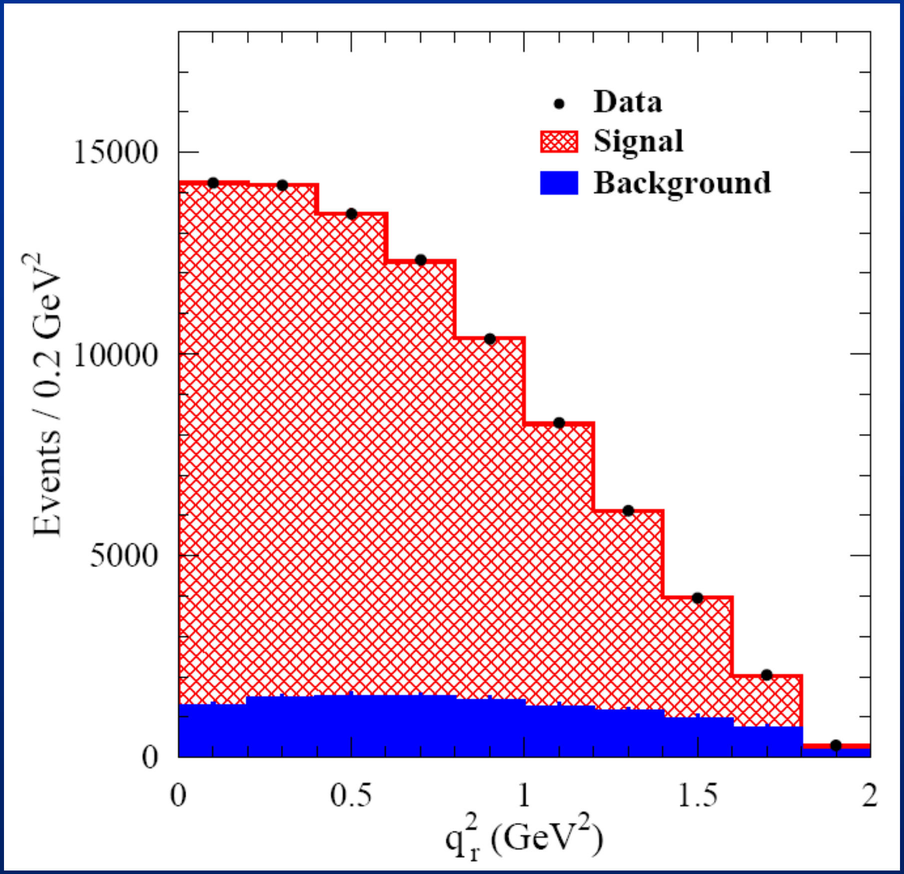


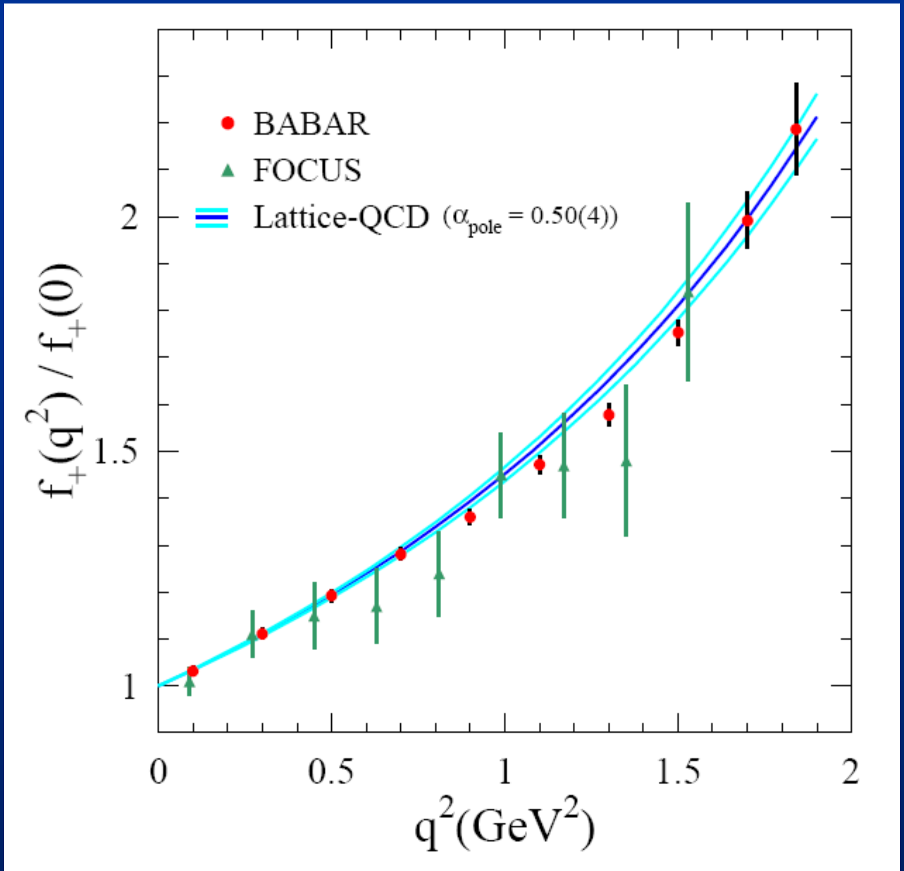
$\delta m = M(D^*) - M(D)$

- high statistics
- good S/N

BaBar $f_+(q^2)$ $D^0 \to K^- e^+ \nu$

arXiv:0704.0020
75 fb^{-1}





$$q^2 = (p_D - p_X)^2$$

85k signal/11k background

- Corrected spectrum compared to LQCD[1], FOCUS[2]

[1] Aubin et al. PRL 94, 011601 (2005)

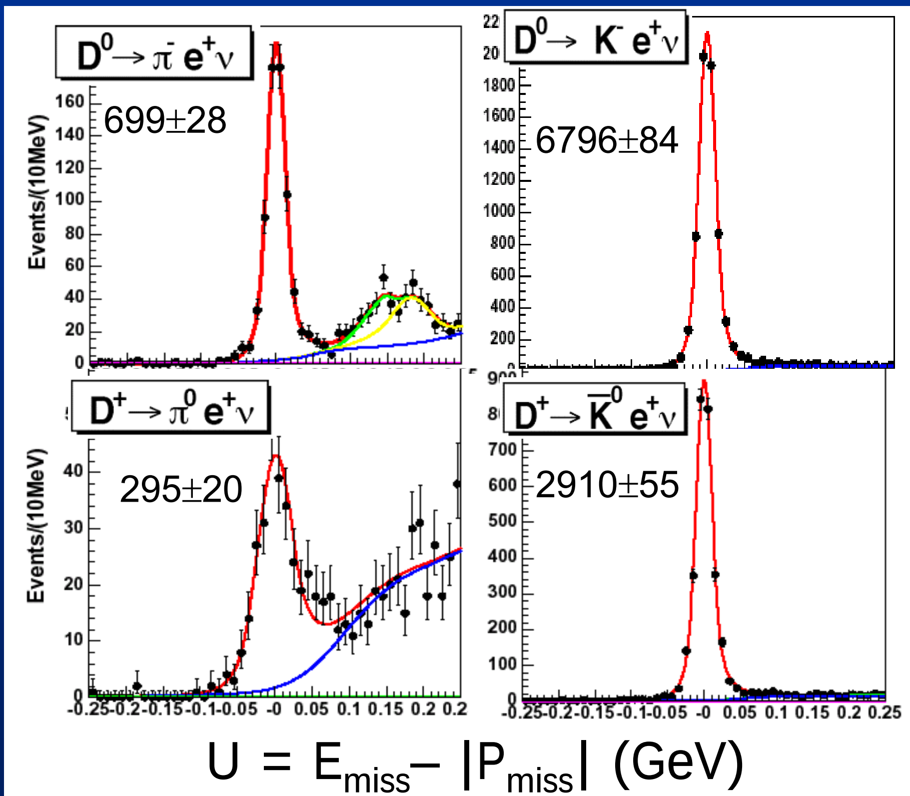
[2] PLB607, 233 (2005)

CLEO-c $D \to \pi e^+ \nu$ & $D \to K e^+ \nu$

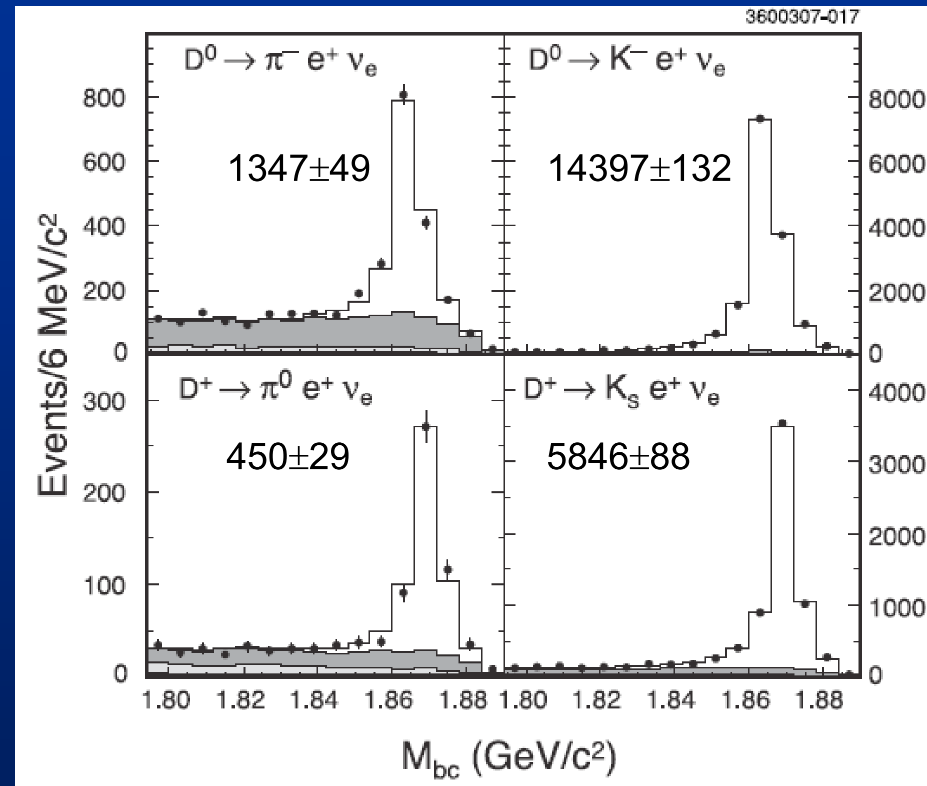
Presented by B.Xin Session B14

Preliminary
281 pb^{-1}

<u>Tagged Analysis</u>



<u>Neutrino Reconstruction</u>

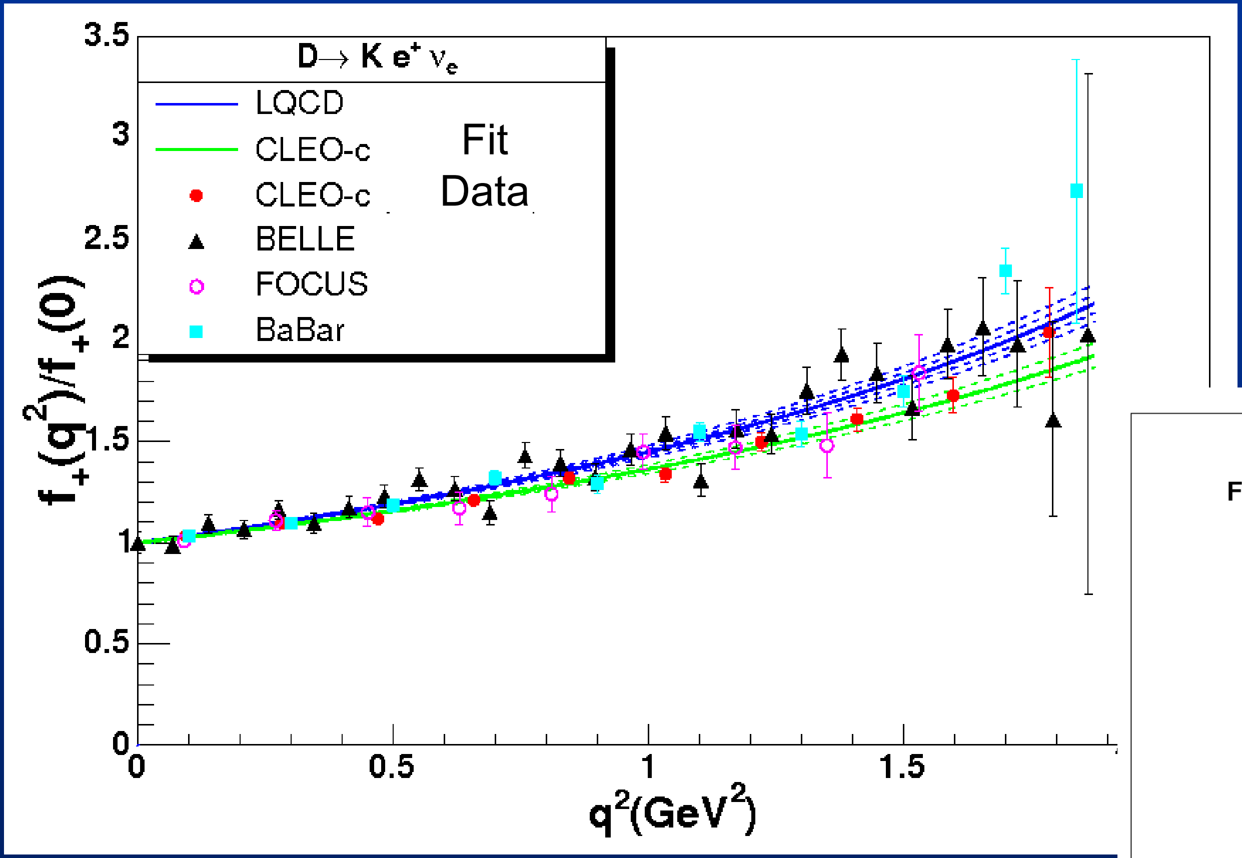


- extremely clean
- well separated backgrounds
- q2 resolution: σ=0.012 GeV^2

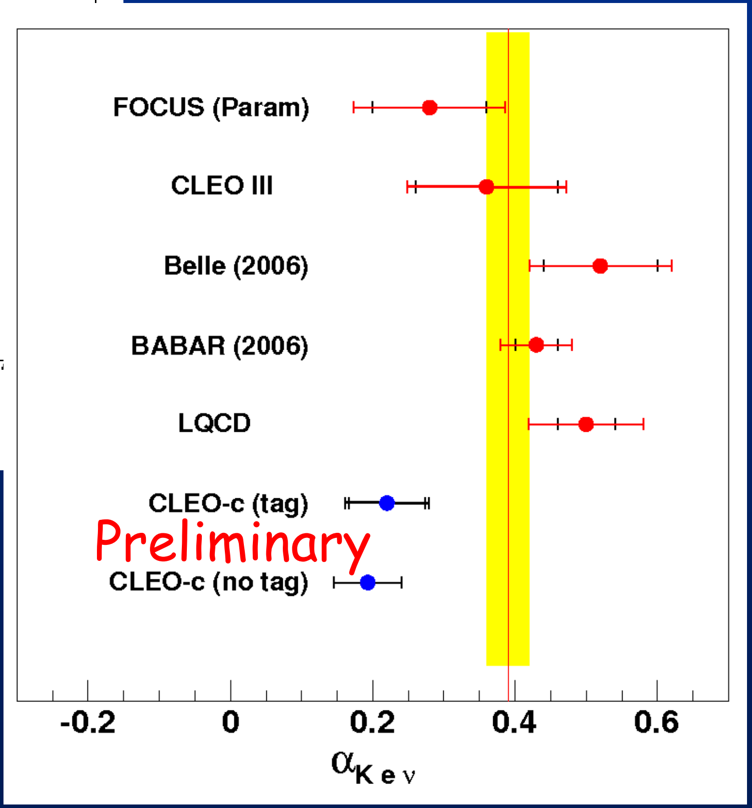
- better statistics
- larger systematic uncertainty

~40% overlap in event samples

$D^0 \to K^- e^+ \nu$ Form Factor Comparisons



Single parameter fit
“modified pole”

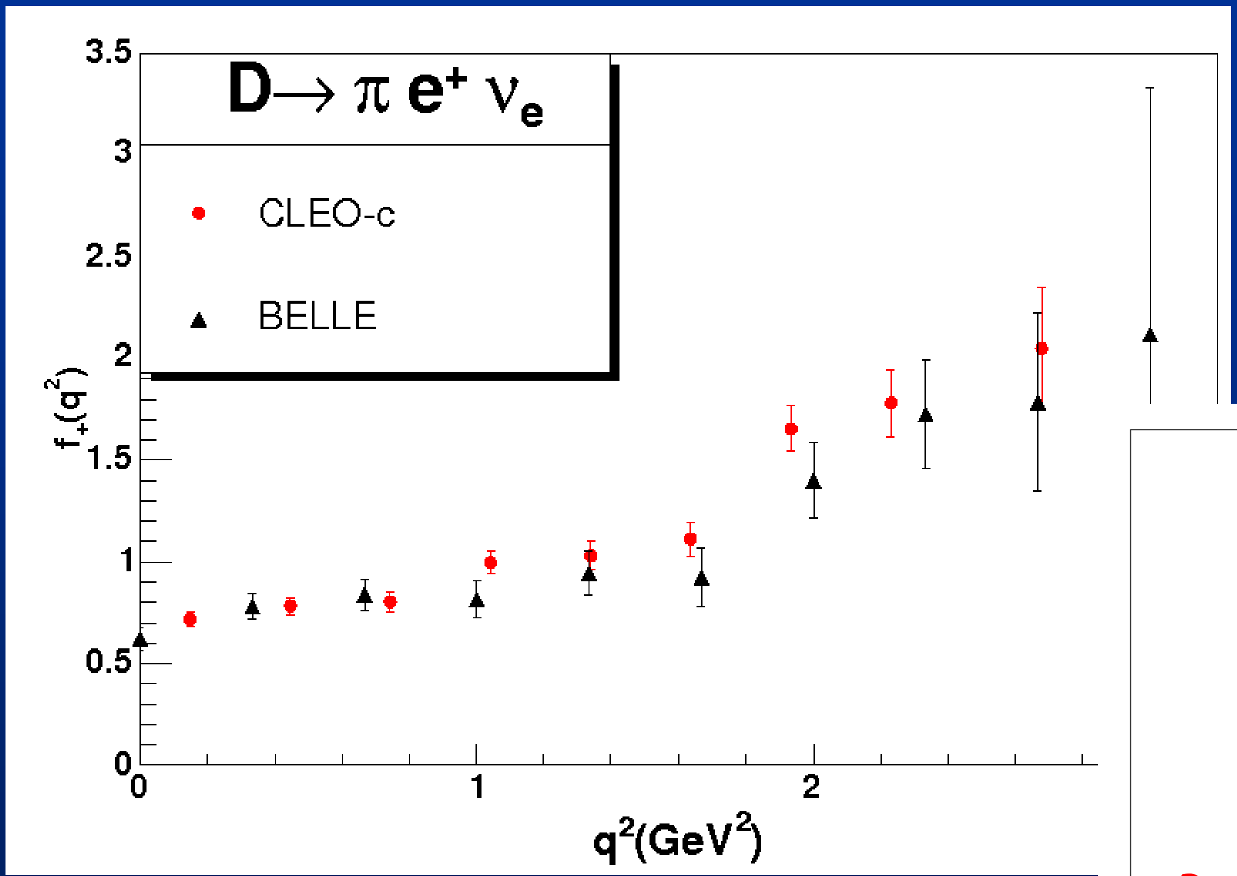


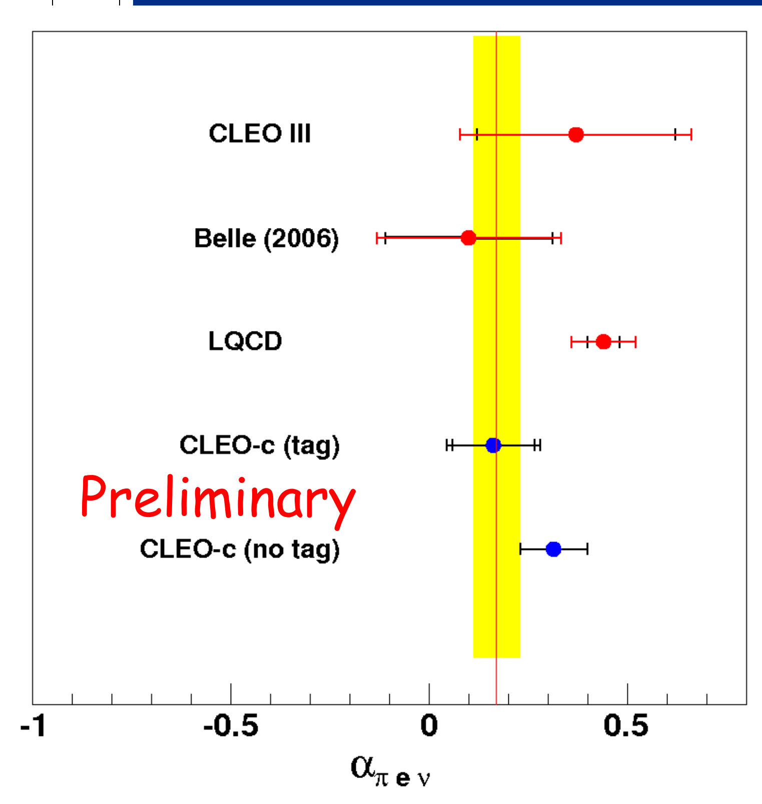
LQCD: Aubin et al. PRL **94** 011601 (2005)

High statistics test of shape

CLEO prefers smaller slope α

$D^0 \to \pi^- e^+ \nu$ Form Factor Comparisons





CLEO & Belle agree well

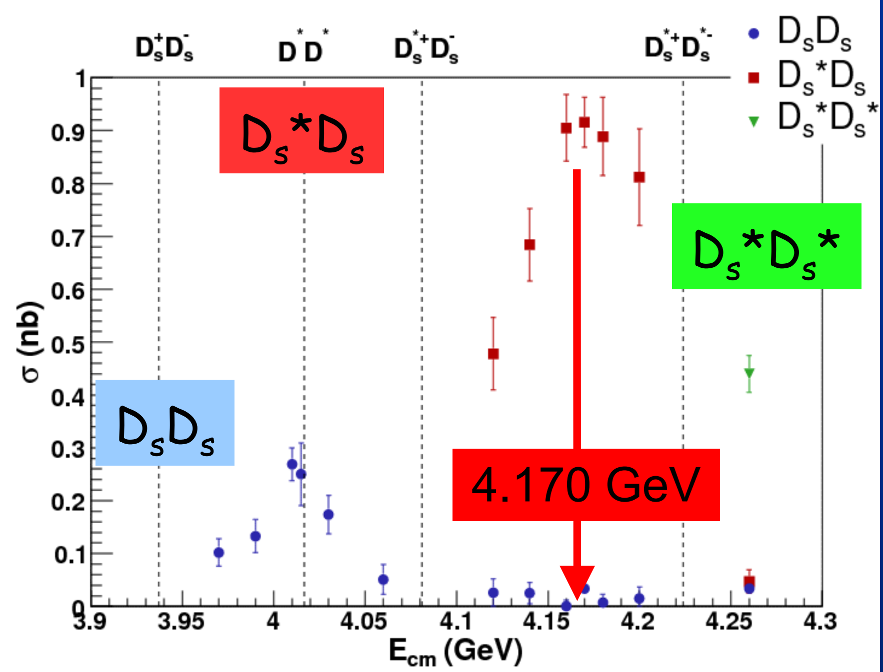
Compatible with LQCD

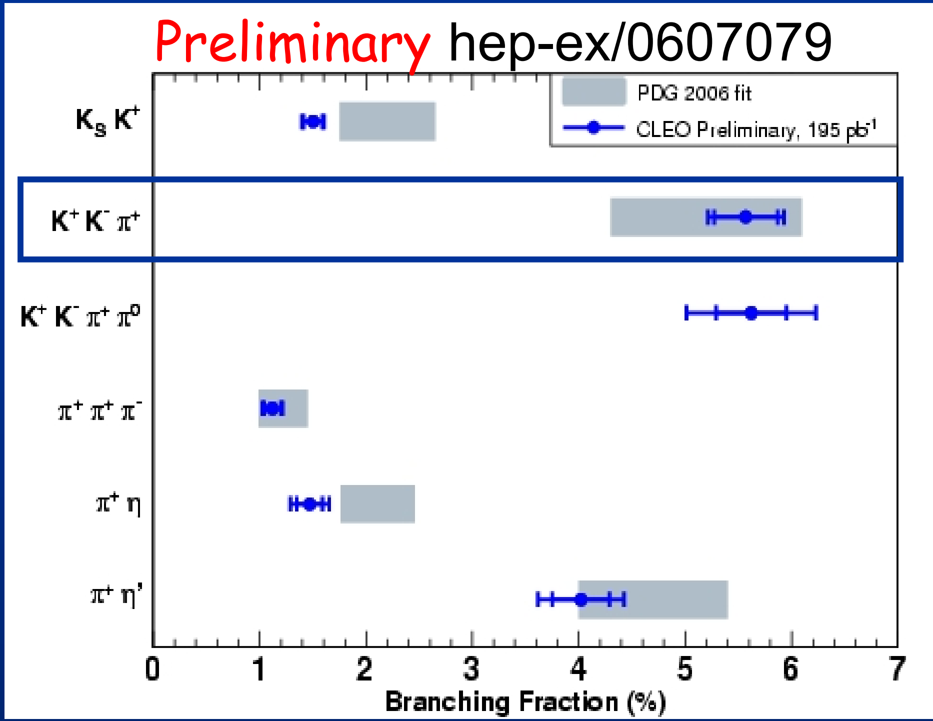
Summary & Conclusions

- Charm decays are measured with precision
- Charm measurements complement flavor physics investigations in the b sector
  - aid interpretation of B mixing
  - assist extraction of V_{CKM} especially V_{ub}
  - by constraining QCD effects
- Unquenched Lattice QCD decay constant results appear trustworthy but…
  - experimental precision exceeds current LQCD
  - hints of differences for semileptonic Form factors
    - $Ke\nu$ experimental discrepancy?
  - normalization of form factor → 10% uncertainty on V_{cx}
- Additional data from BaBar, Belle, CLEO
  - more precise results to come!

Additional Slides

CLEO-c D_s Hadronic results



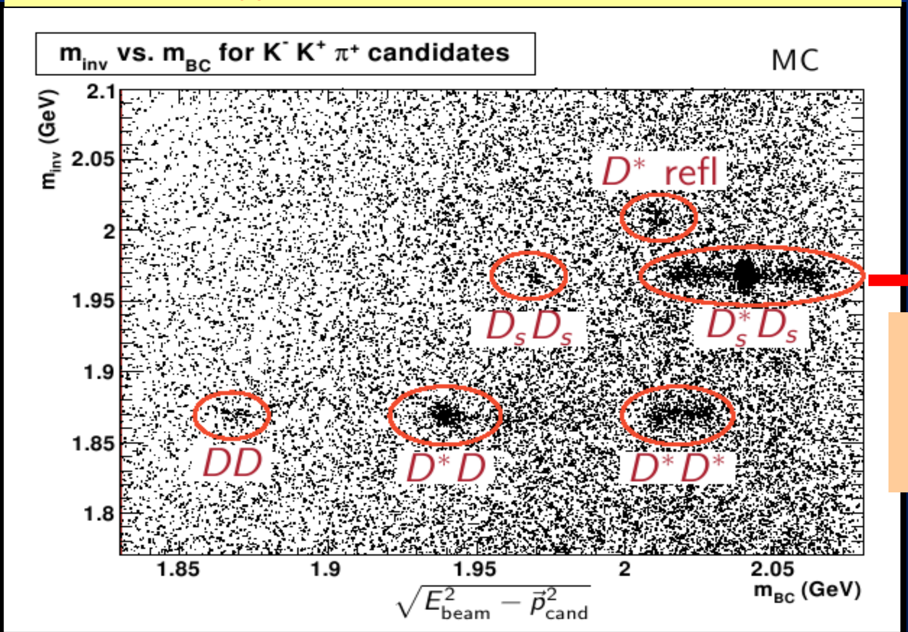


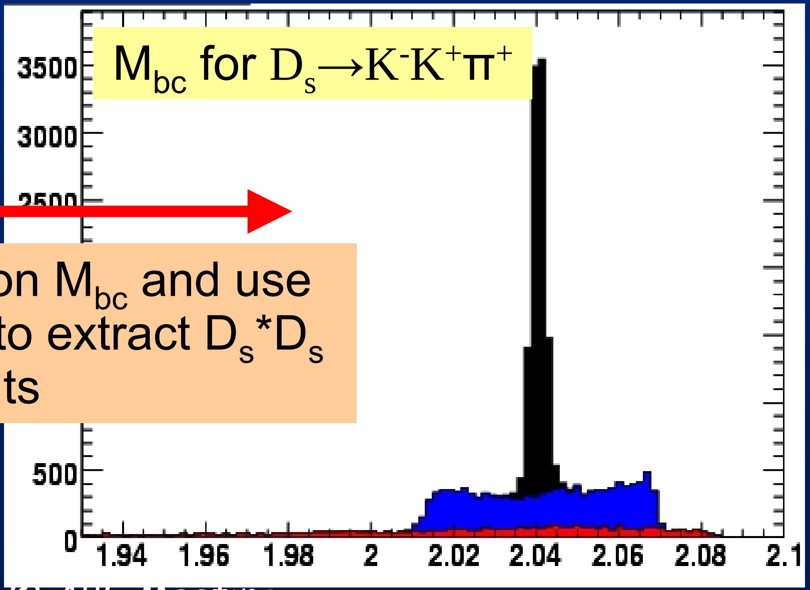
- Tagging with $D_sD_s^*$
- $D_s^* \to D_s \gamma$

Partial BF for $D_s \to \phi\pi$
interference with $f_0(980)$
$M(KK)=M_\phi \pm 10$ MeV
BF=(1.98 ± 0.12 ± 0.09)%
$M(KK)=M_\phi \pm 20$ MeV
BF=(2.25 ± 0.13 ± 0.12)%

CLEO-c D_s Hadronic Decays

M_{inv} vs. M_{bc} for $K^-K^+\pi^+$ candidates in MC

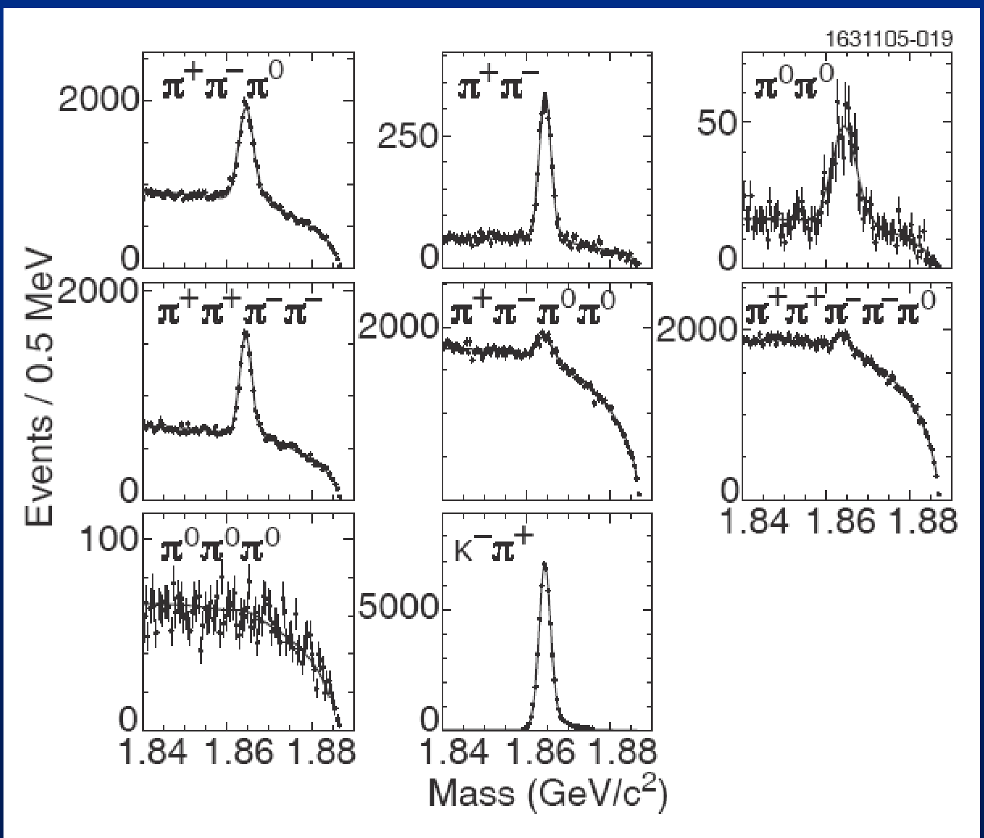


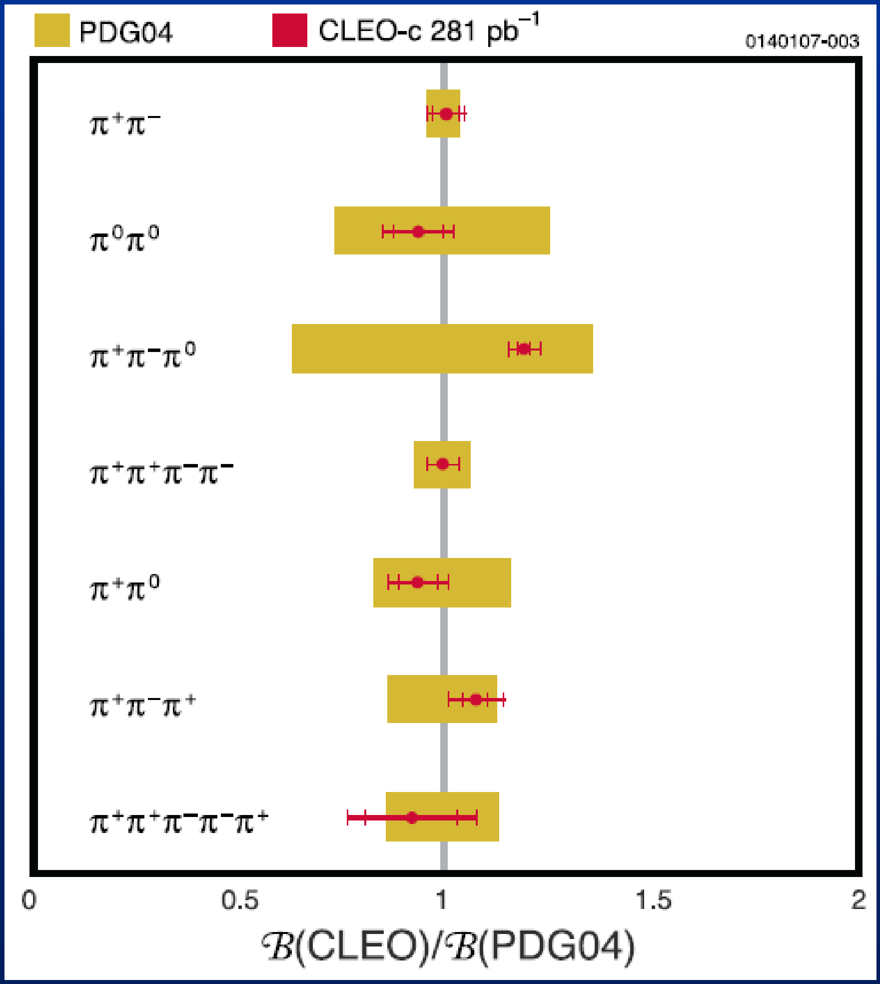


Cut on M_{bc} and use M_{inv} to extract $D_s^*D_s$ events

Additional Hadronic Decays

- Additional modes from CLEO-c
  - PRL 96, 081802 (2006)
  - Single Tag Measurement





D^0 modes shown on left