CLEO-c at the Precision Frontier of Charm

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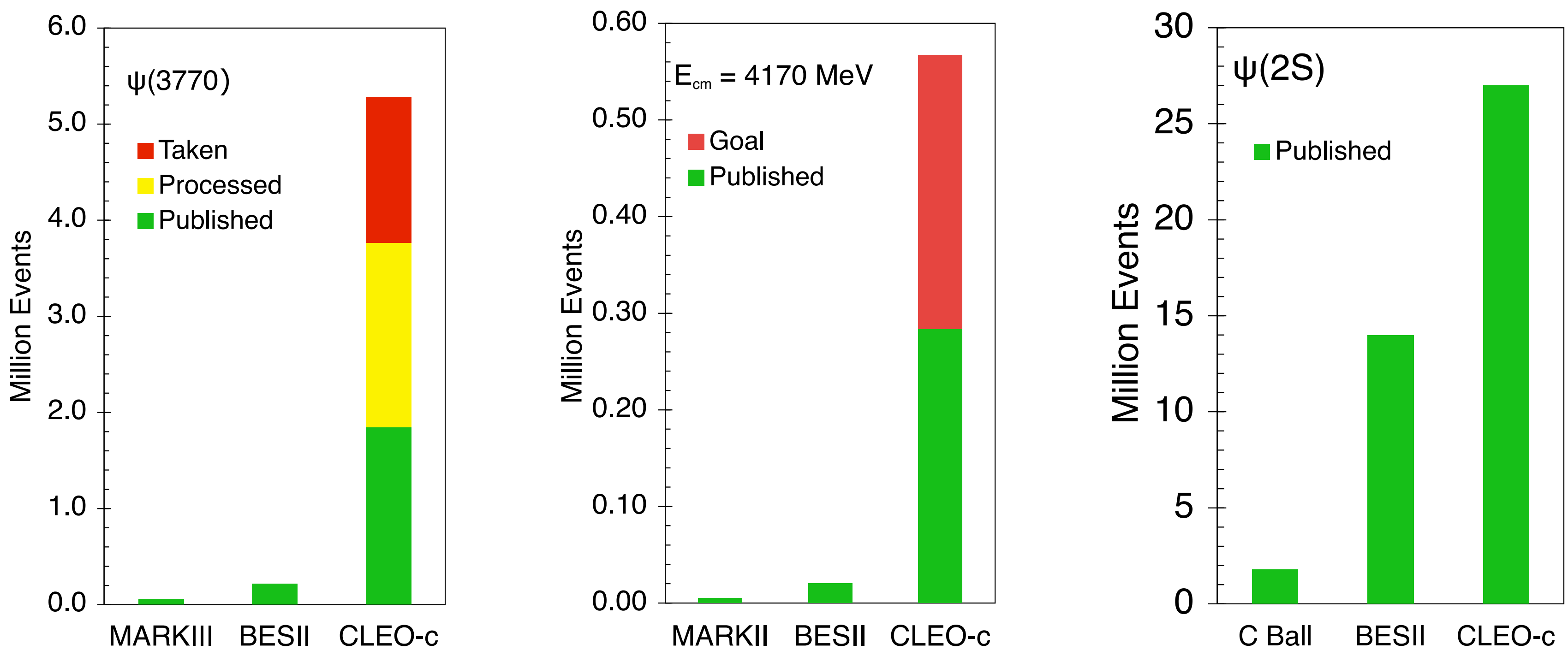
- D^0, D^+, and D_s Absolute Hadronic Branching Fractions
- D^0 and D^+ Semileptonic Branching Fractions
- D^+ and D_s Leptonic Branching Fractions and f_D and f_{D_s}
- Some Charmonium Results
- Summary and Conclusions

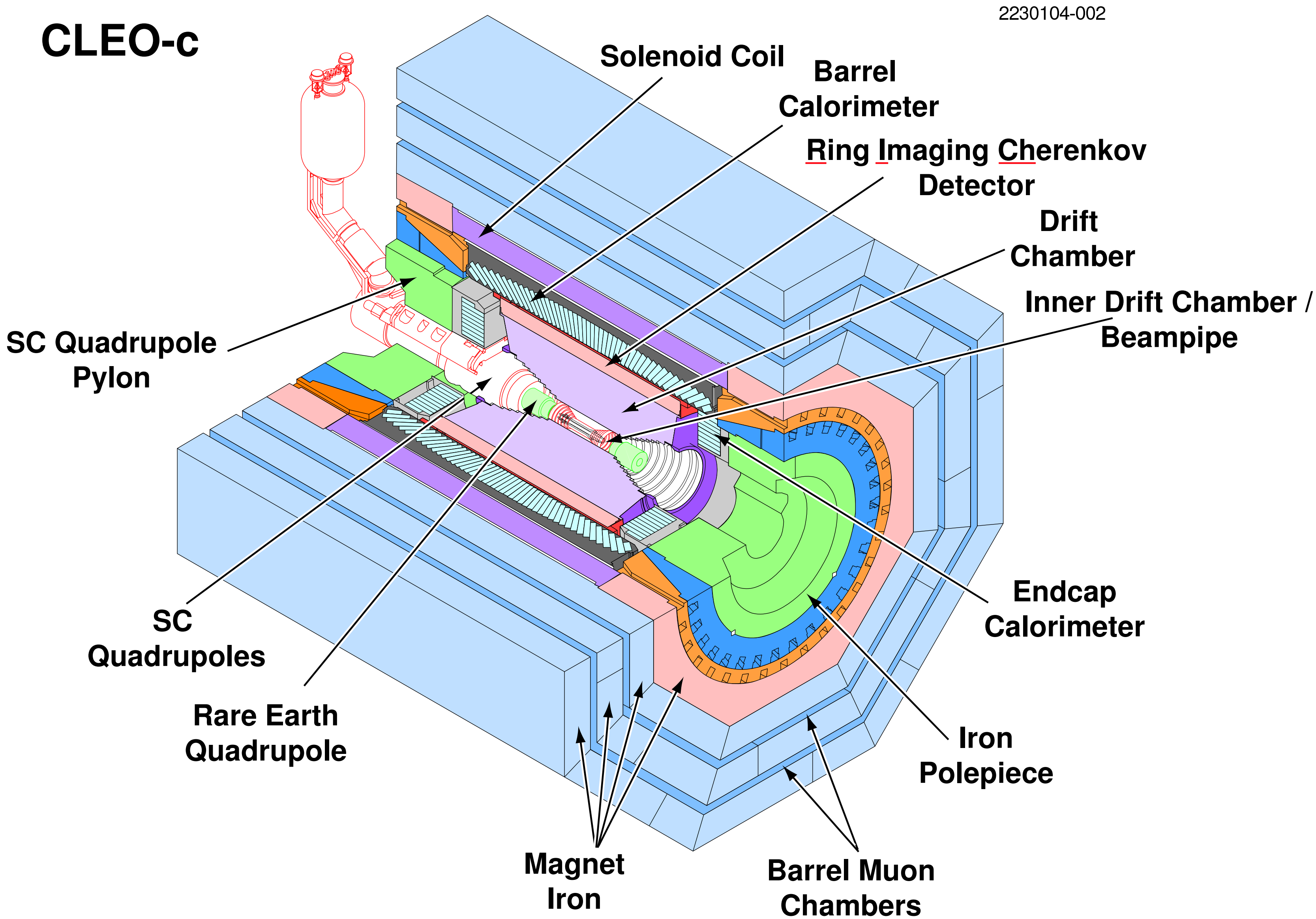
281 pb^{-1} 298 pb^{-1}



DESY Seminar – October 2, 2007

The CLEO-c Detector

- Excellent Particle Identification (dE/dx and RICH): $0 < p < 1$ GeV/c
- Tracking: $\sigma_p/p = 0.6\%$ at $p = 1$ GeV/c
- CsI Calorimeter: $\sigma_E/E = 6\%$ at $E_\gamma = 100$ MeV and 2.2% at 1 GeV



Quark Decay in the Standard Model

$$
\begin{array}{lccccc}
 & & & & Q/e & \\
\text{Leptons} & \begin{pmatrix}\nu_e \\ e\end{pmatrix} & \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix} & \begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix} & \begin{matrix}0 \\ -1\end{matrix} & \updownarrow W \\
\text{Quarks} & \begin{pmatrix}u \\ d'\end{pmatrix} & \begin{pmatrix}c \\ s'\end{pmatrix} & \begin{pmatrix}t \\ b'\end{pmatrix} & \begin{matrix}+2/3 \\ -1/3\end{matrix} & \updownarrow W
\end{array}
$$

For $Q = -1/3$ quarks

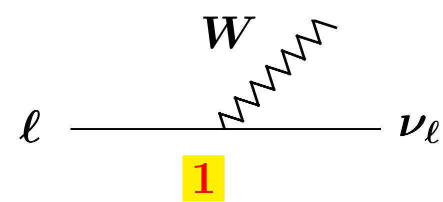
- the unitary CKM matrix V relates
  - q' – weak "eigenstates" to
  - q – strong "eigenstates"

$$
\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}
$$

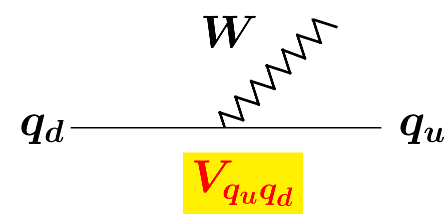
Leptons and quarks decay via W emission

- Relative couplings for quark decay are elements of the CKM matrix
- CP is conserved if V is real ($V_{q_u q_d} = V^*_{q_u q_d}$)

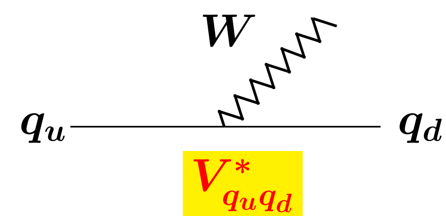
$\ell \longrightarrow \nu_\ell W^-$



$q_d \longrightarrow q_u W^-$



$q_u \longrightarrow q_d W^+$



Wolfenstein Approximation of the CKM Matrix and the Unitarity Triangle

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cong \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

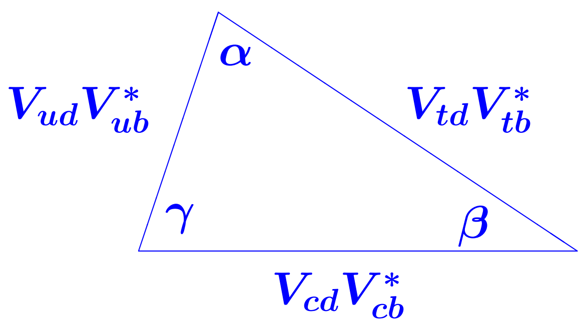
$\lambda \cong 0.22$

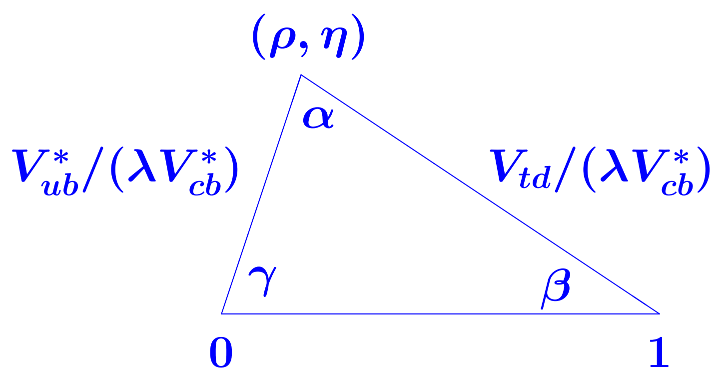
$A \cong 1$

$\eta \neq 0 \Leftrightarrow \mathrm{SM}\ \not{C}\not{P}$

Apply unitarity to columns 1 and 3:

- $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ defines a triangle in the complex plane:
- CP is conserved in the SM if the area of the triangle is zero
- The triangle apex is at (ρ, η) in the ρ–η plane in the Wolfenstein approximation





- Conventional (CP conserving) B decay measurements determine the lengths of the nontrivial sides
- Some CP violation asymmetries in B decay determine angles of the triangle

Inconsistency between sides and angles would imply CP Violation beyond the SM, but imperfect knowledge of theoretical parameters required to determine CKM elements from experiment restricts the sensitivity of these comparisons.

Example Determining V_{td} from $B^0\bar{B}^0$ Mixing

The measured mass difference due to $B^0\bar{B}^0$ mixing is related to V_{td} by:

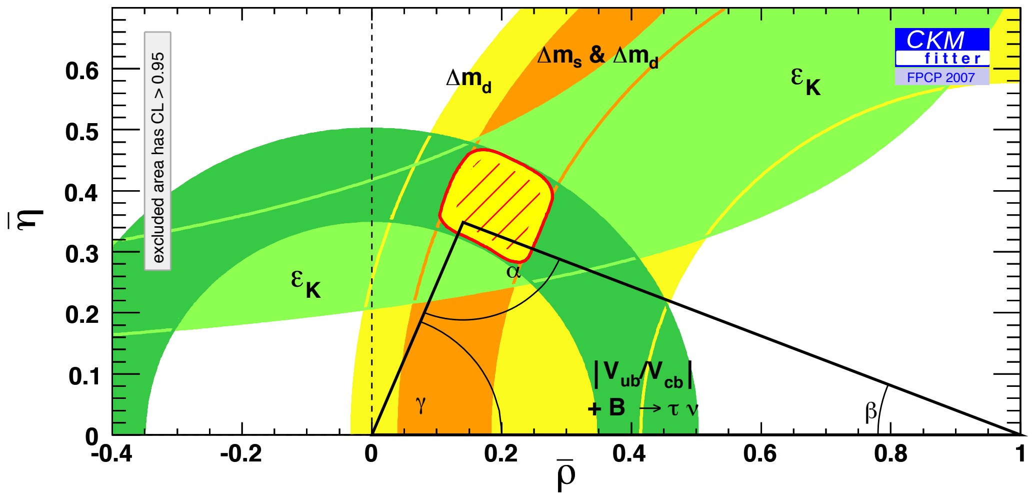
$$\Delta m_d = \frac{G_F^2}{6\pi^2}\,\eta_{QCD}\,M_B\,f_B^2 B_B\,m_t^2\,F(\frac{m_t^2}{m_W^2})\,V_{td}^2\,V_{tb}^2$$

- Everything in this expression, except the decay constant f_B and the bag constant B_B, is quite well known
- Theoretical uncertainties in $f_B^2 B_B$ determine the width of the region in the ρ-η plane allowed by measurements of Δm_d.
- f_B could be measured in $B^- \to \ell^- \bar{\nu}$ decay, but – due to Cabibbo suppression – the branching fraction is very small for μ or τ and reconstructing $B^- \to \tau^- \bar{\nu}$ is very difficult.
- Analogous parameters f_D (f_{D_s}) can be measured much more easily in $D^+ \to \ell^+ \nu$ ($D_s \to \ell^+ \nu$) decay, which are less seriously (not) Cabibbo suppressed
  - Measurements of f_D (f_{D_s}) constrain or validate QCD calculations of f_B.

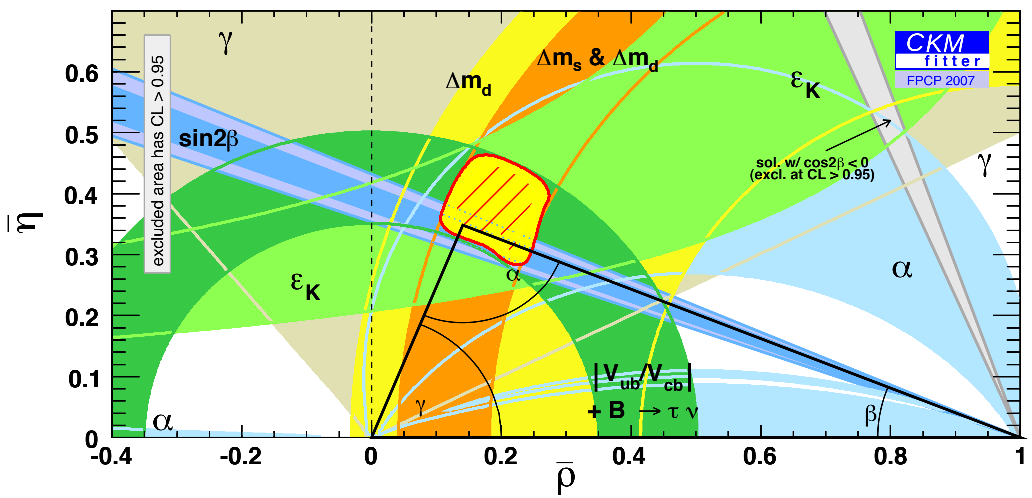
Furthermore, measurements of form factors in semileptonic D decay check or validate theoretical calculations of form factors required to determine V_{ub} from measurements of semileptonic B decay.

Importance of Precision in Charm Physics

$\bar{\rho}\bar{\eta}$ plane without CP violating angles



$\bar{\rho}\bar{\eta}$ plane with CP violating angles

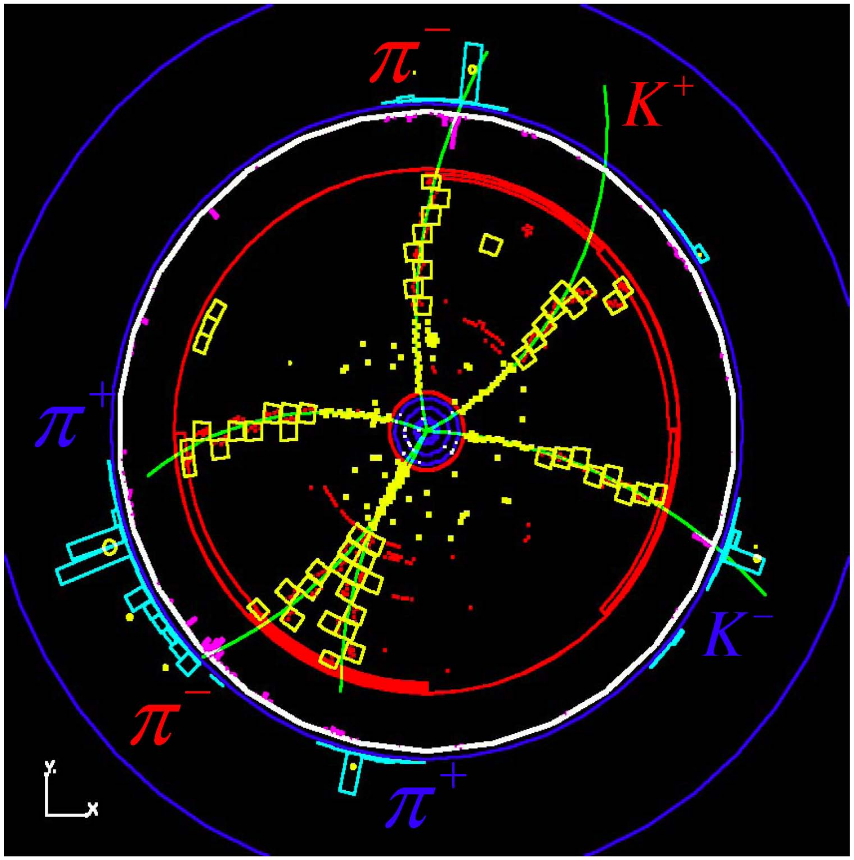


- Theoretical uncertainties dominate the widths of the Δm_d, ϵ_K, and $|V_{ub}/V_{cb}|$ bands and contribute significantly to the width of the Δm_d & Δm_s band.
- Precision D decay measurements can constrain or validate the theories used in determining the widths of these bands.
- D decay measurements at the $\psi(3770)$ can also reduce γ uncertainties

$e^+e^- \to \psi(3770) \to D\bar{D}$ Events and Analyses

$e^+e^- \to \psi(3770) \to D^+D^-$

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



- CLEO-c uses D^+ and D^0 decays from $e^+e^- \to \psi(3770) \to D^+D^-$ or $D^0\bar{D}^0$
  - No additional pions produced
  - Extremely clean events
- We measure leptonic, semileptonic, and key hadronic branching fractions with a double tagging technique
  - Other branching fractions are usually measured relative to a reference mode, generally $D^0 \to K^-\pi^+$ or $D^+ \to K^-\pi^+\pi^+$
- We published absolute branching fractions for key Cabibbo Favored hadronic modes with 56 $pb^{-1}$of data.
  - Update submitted with 281 pb^{-1}.
- Some other branching ratios utilizing 281 pb^{-1} are already published or submitted for publication

Absolute D^0 and D^+ Hadronic Branching Fractions

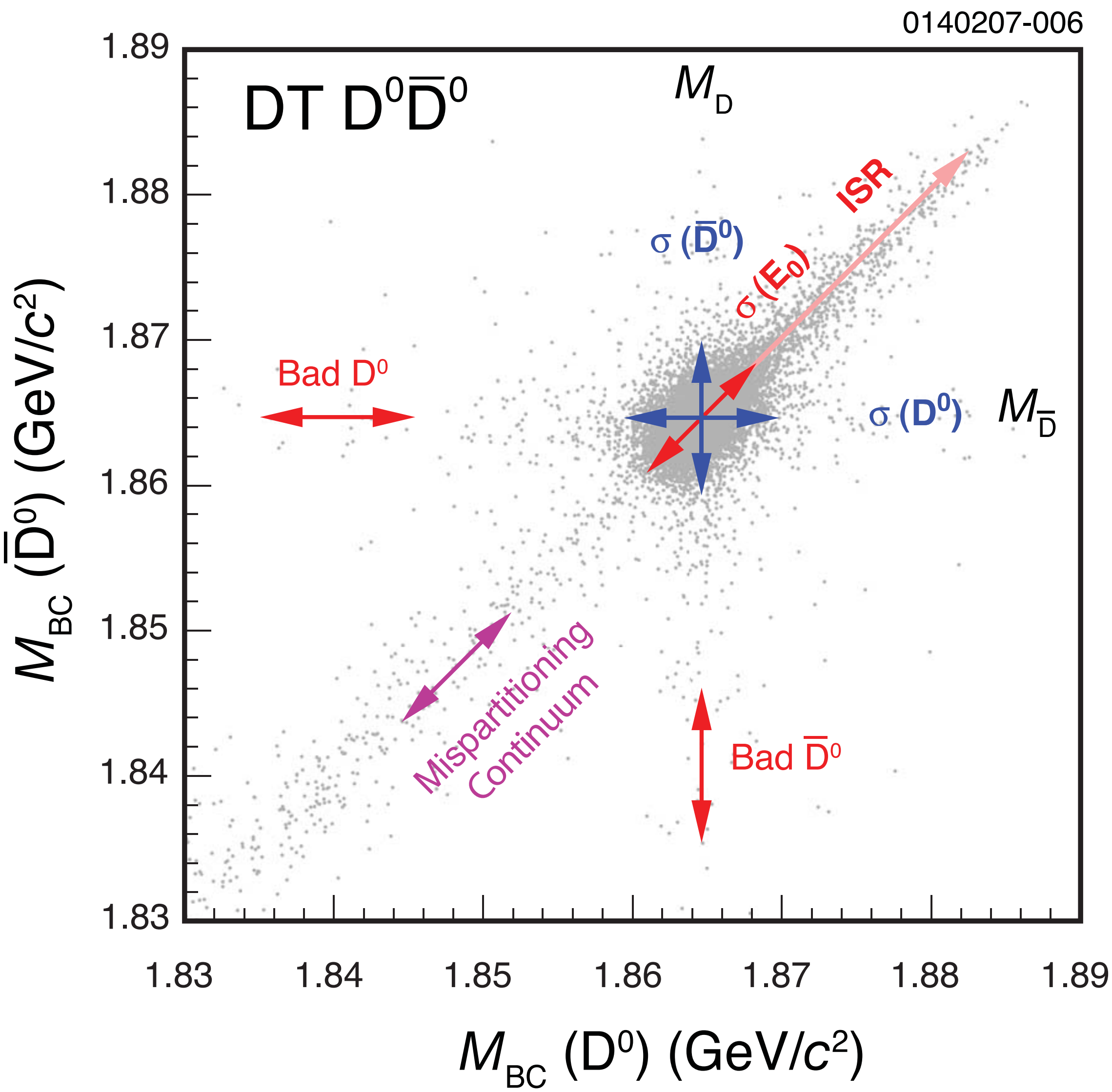
We utilize a technique pioneered by MARK III

- Single Tag (ST) Yields $D \to i$ and $\bar{D} \to X$ $\quad y_i = N_{D\bar{D}} \mathcal{B}_i \epsilon_i$
- Double Tag (DT) Yields $D \to i$ and $\bar{D} \to \bar{j}$ $\quad y_{i\bar{j}} = N_{D\bar{D}} \mathcal{B}_i \mathcal{B}_{\bar{j}} \epsilon_{i\bar{j}}$
  - Compute branching fractions and $N_{D\bar{D}}$
    $$\mathcal{B}_i = \frac{y_{i\bar{j}}}{y_{\bar{j}}} \frac{\epsilon_{\bar{j}}}{\epsilon_{i\bar{j}}} \quad \text{and} \quad N_{D\bar{D}} = \frac{y_i y_{\bar{j}}}{y_{i\bar{j}}} \frac{\epsilon_{i\bar{j}}}{\epsilon_i \epsilon_{\bar{j}}}$$
  - $\epsilon_{i\bar{j}} \approx \epsilon_i \epsilon_{\bar{j}}$ so $\mathcal{B}_i$ is nearly independent of efficiencies for $\bar{j}$.
  - Branching fraction values independent of luminosity or $N_{D\bar{D}}$ measurements.
  - Do a χ^2 fit including all yields and all errors – correlated and uncorrelated.
  - Input y_i and $y_{\bar{i}}$ separately, but constrain $\mathcal{B}_i = \mathcal{B}_{\bar{i}}$
- Determining yields
  - Cut on $\Delta E \equiv E(D) - E_0$ (candidate energy - beam energy)
  - Obtain ST and DT yields from fits to beam constrained mass $M_{bc}^2 \equiv E_0^2 - p(D)^2$ distributions (substitute the beam energy for the candidate energy for better resolution)

Yields from 281 pb^{-1}

- ST all modes: 232,000 $D^0/\bar{D}^0$ 168,000 D^+/D^-
- DT all modes: 13,600 $D^0\bar{D}^0$ 8,900 D^+D^-

M_{bc} Distributions



M_{bc} Signal Lineshape is due to:

- $\psi(3770)$ Natural Line Shape
- Initial State Radiation (ISR)
- Beam Energy Spread $\sigma(E_0)$
- D Mass Resolution $\sigma(D)$ ($p(D)$ Resolution)

Background Fits:

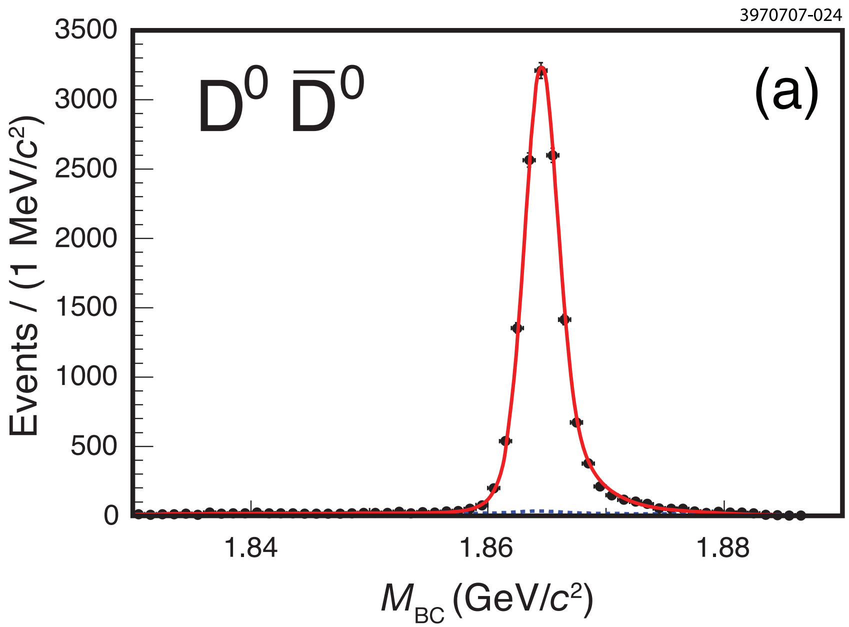
- Modified ARGUS functions

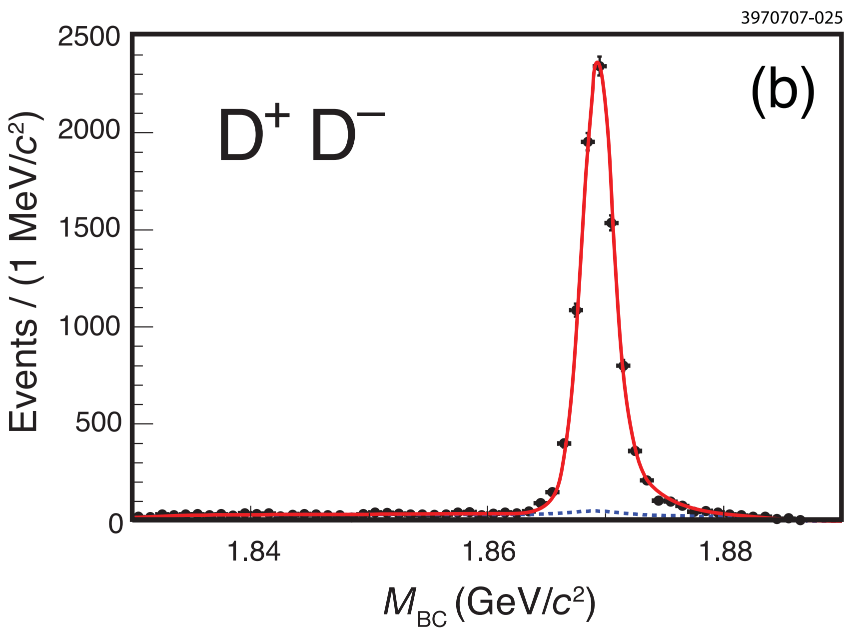
Radiation effects:

- ISR reduces the momenta of the D and $\bar{D}$, so the value of M_{bc} calculated from $M_{bc}^2 \equiv E_0^2 - p(D)^2$ it greater than it would have been.
- Final State Radiation (FSR) reduces the energy of the D and can lead to loosing candidates due to the ΔE cut

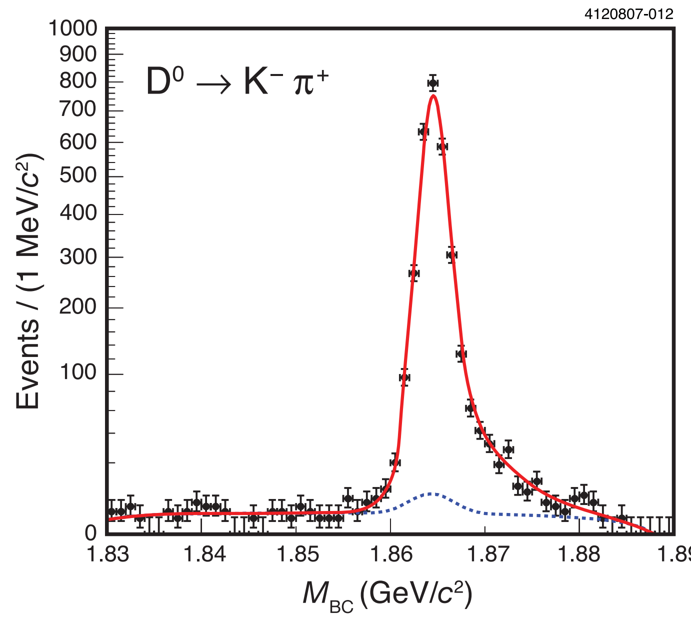
Double Tag Fits

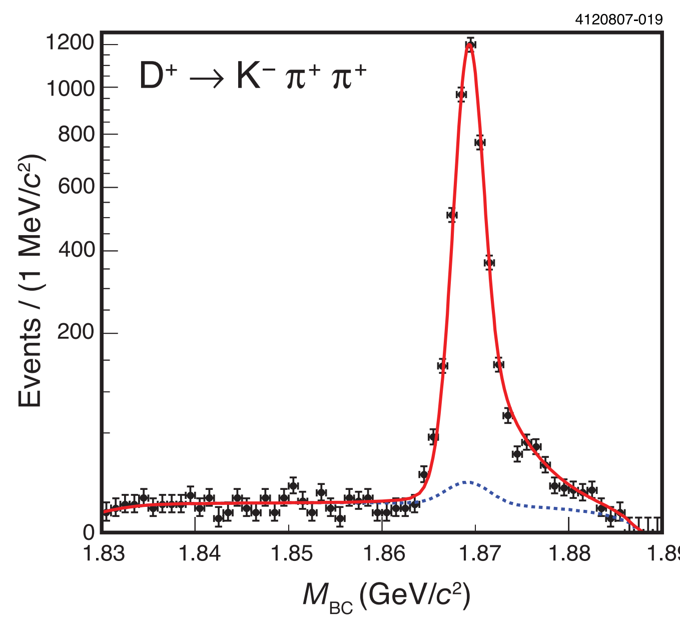
All Double Tags: Linear Scales





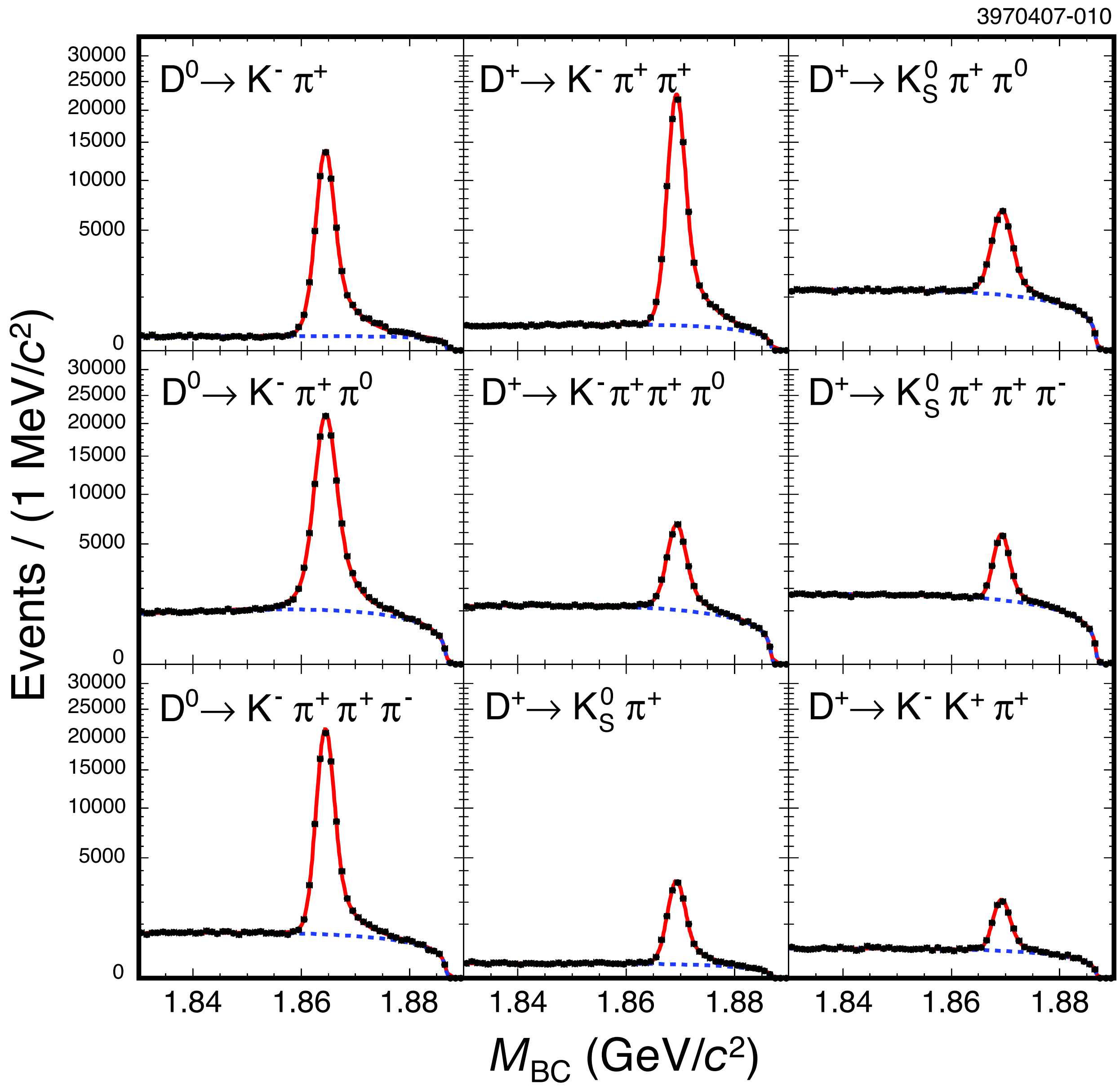
Key Double Tags: Square Root Scales





Single Tag Fits

All Single Tag Fits: Square Root Scales



Absolute Hadronic D^0 and D^+ Branching Fractions

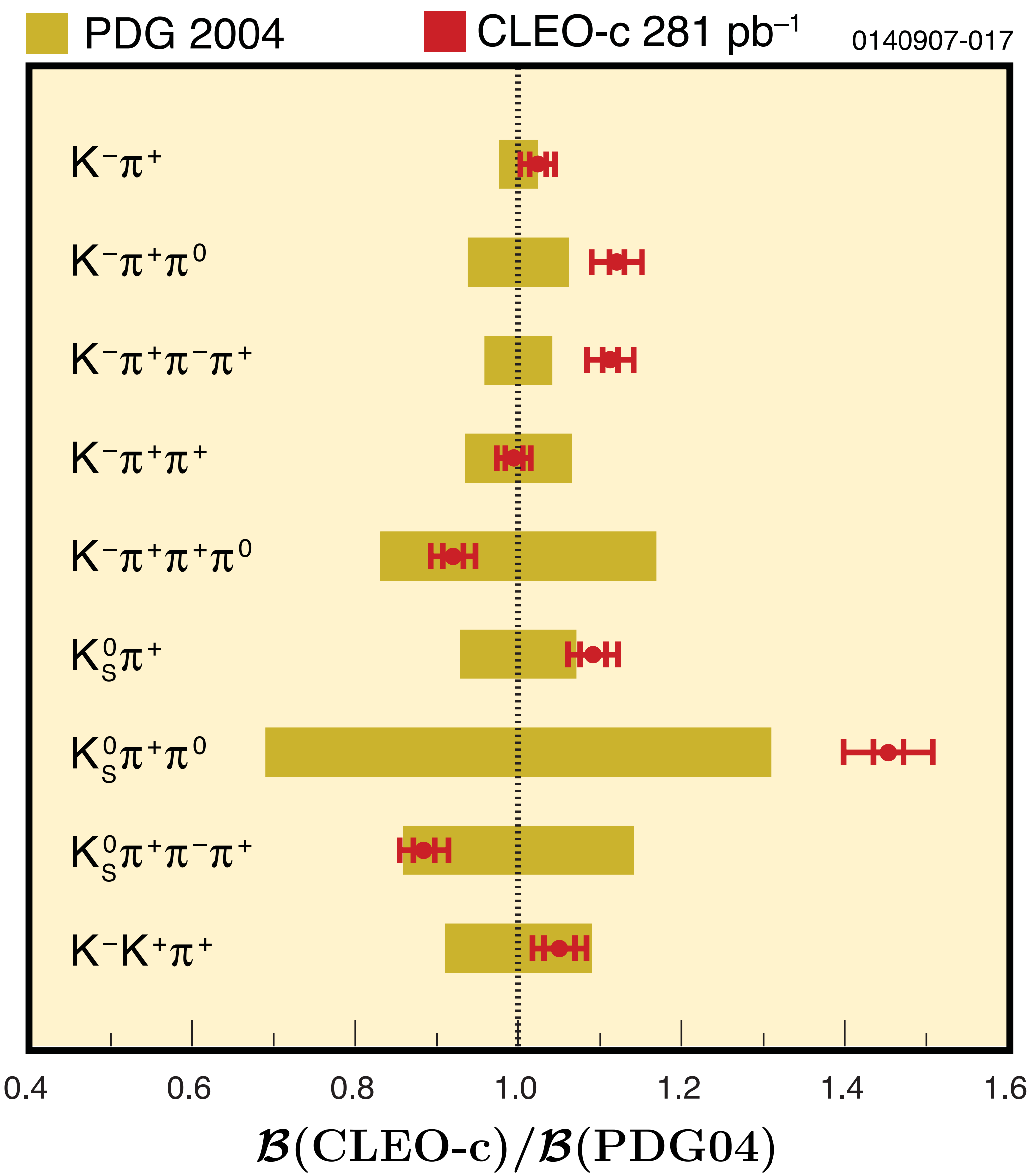
CLEO-c 281 pb^{-1}

Mode	$\mathcal{B}$ (%)	Δ_{FSR} (%)
$D^0 \to K^-\pi^+$	$3.891 \pm 0.035 \pm 0.059 \pm 0.035$	-3.0
$D^0 \to K^-\pi^+\pi^0$	$14.57 \pm 0.12 \pm 0.38 \pm 0.05$	-1.1
$D^0 \to K^-\pi^+\pi^+\pi^-$	$8.30 \pm 0.07 \pm 0.19 \pm 0.07$	-2.4
$D^+ \to K^-\pi^+\pi^+$	$9.15 \pm 0.10 \pm 0.16 \pm 0.07$	-2.3
$D^+ \to K^-\pi^+\pi^+\pi^0$	$5.98 \pm 0.08 \pm 0.16 \pm 0.02$	-1.0
$D^+ \to K_S^0\pi^+$	$1.539 \pm 0.022 \pm 0.037 \pm 0.009$	-1.8
$D^+ \to K_S^0\pi^+\pi^0$	$7.05 \pm 0.09 \pm 0.25 \pm 0.01$	-0.4
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$3.149 \pm 0.046 \pm 0.094 \pm 0.019$	-1.9
$D^+ \to K^+K^-\pi^+$	$0.935 \pm 0.017 \pm 0.024 \pm 0.003$	-1.2

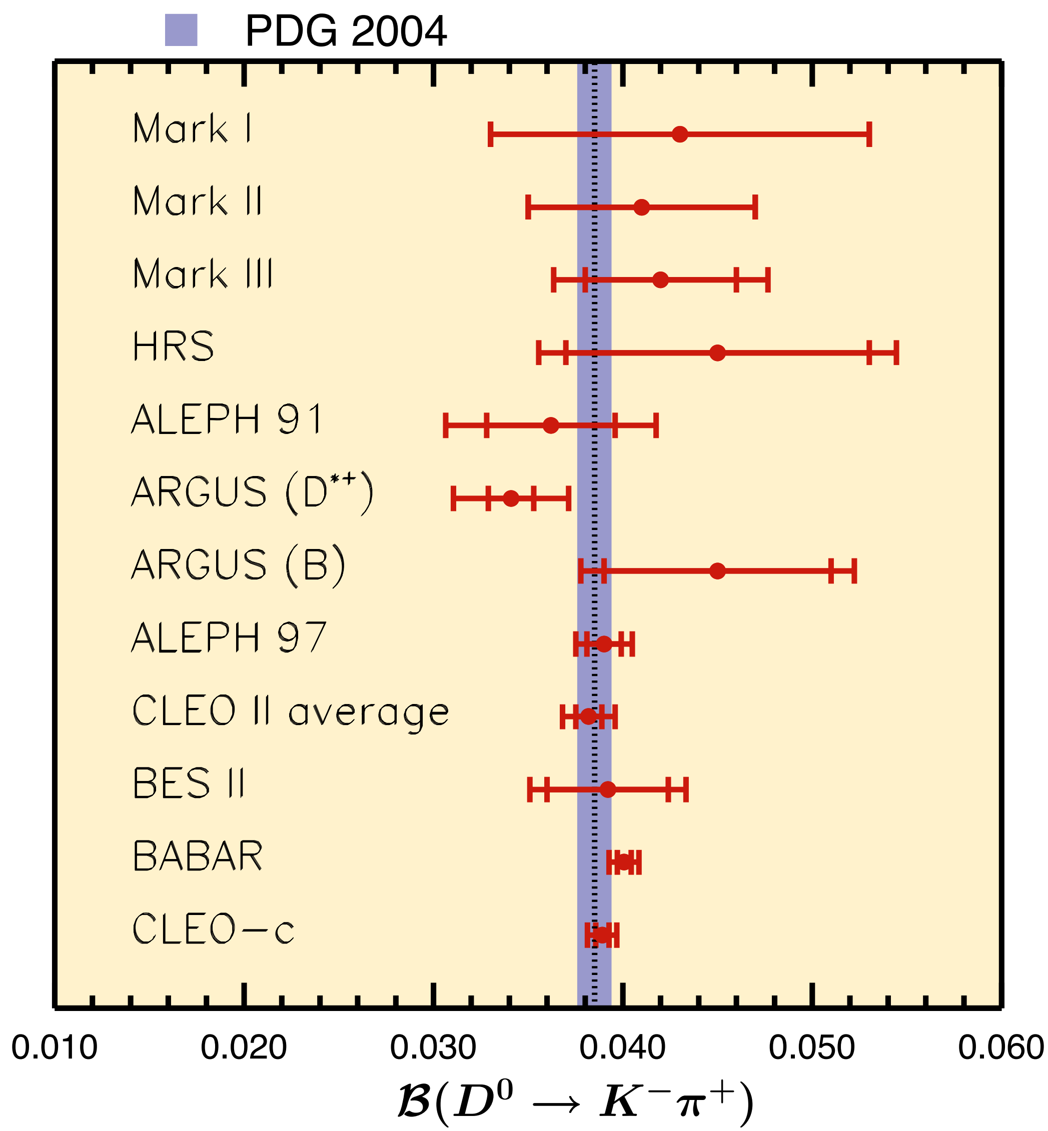
- Errors are statistical, experimental, and FSR
- Systematic errors dominate
- Final State Radiation is significant and is included in our MC estimates of efficiencies
  - Branching fractions would change by Δ_{FSR} if FSR were ignored.
  - Many earlier experiments ignored FSR
  - Ignoring FSR decreases $\mathcal{B}$'s

Compare CLEO-c results to PDG2004

Compare to PDG04 because PDG06 includes CLEO-c 56 pb^{-1} in averages

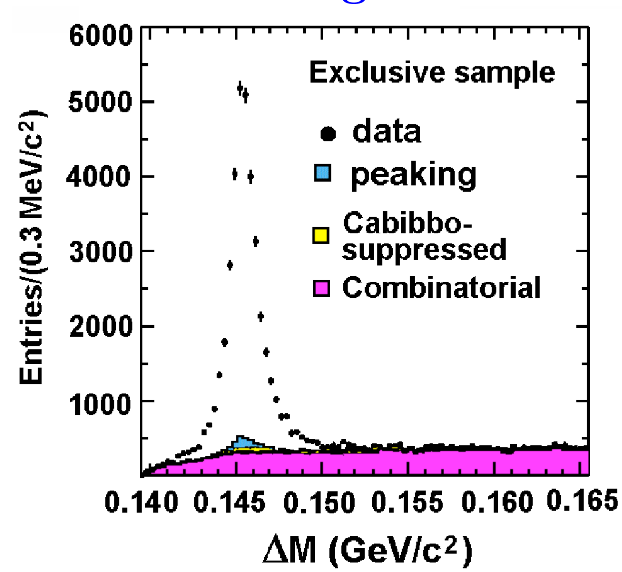


The Reference Branching Fraction $\mathcal{B}(D^0 \to K^-\pi^+)$

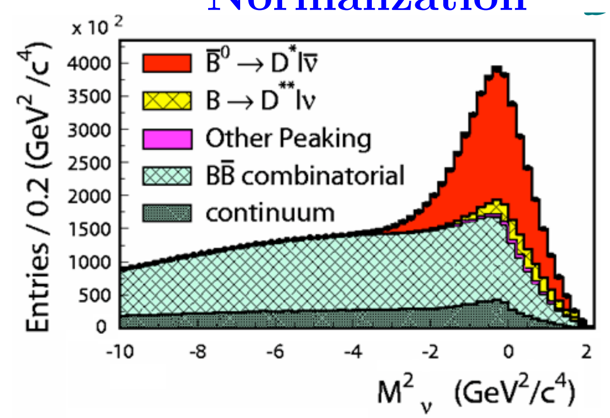


BaBar $\mathcal{B}(D^0 \to K^-\pi^+)$

Signal



Normalization



BaBar $\mathcal{B}(D^0 \to K^-\pi^+) = (4.007 \pm 0.037 \pm 0.070)\%$

CLEO-c $\mathcal{B}(D^0 \to K^-\pi^+) = (3.891 \pm 0.035 \pm 0.059 \pm 0.035)\%$

Comparison of $D \to K^0_S\pi$ and $D \to K^0_L\pi$ Decay Rates

Cabibbo-Favored and Doubly-Cabibbo-Suppressed amplitudes for $D \to K^0\pi$.

- Observed final states are K^0_S and K^0_L
- Interference between CF and DCS amplitudes can lead to different rates for $D \to K^0_S\pi$ and $D \to K^0_L\pi$ (Bigi and Yamamoto)
- Reconstruct $D \to K^0_L\pi$ from missing mass

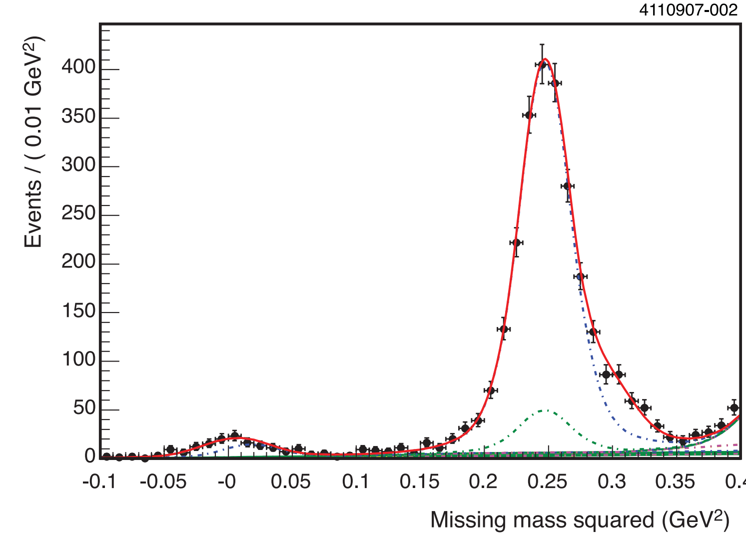
$$R(D) \equiv \frac{\mathcal{B}(D \to K^0_S\pi) - \mathcal{B}(D \to K^0_L\pi)}{\mathcal{B}(D \to K^0_S\pi) + \mathcal{B}(D \to K^0_L\pi)}$$

CLEO-c Preliminary

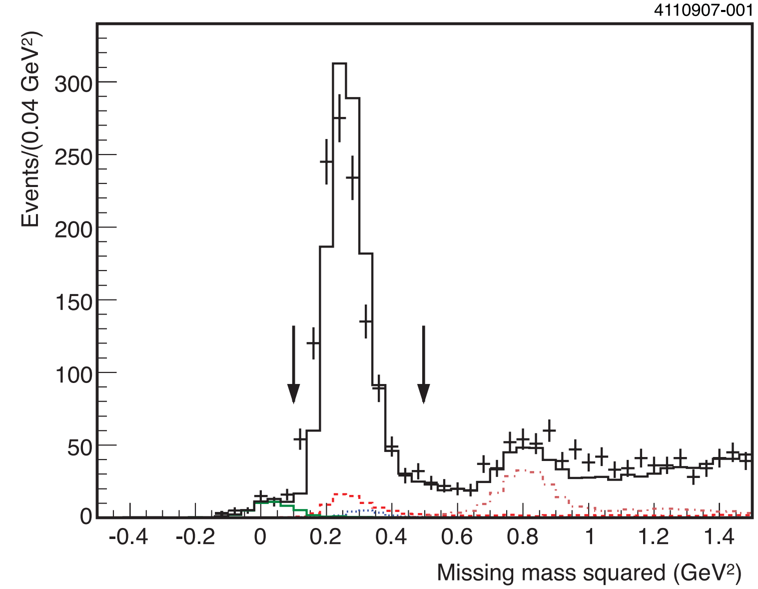
$R(D^+)$	$0.030 \pm 0.023 \pm 0.025$
$R(D^0)$	$0.122 \pm 0.024 \pm 0.030$

- U-spin and SU(3) predict $R(D^0) = 2\tan^2(\theta_c)$ which gives $R(D^0) = 0.109 \pm 0.001$
- $R(D^+)$ not so simple:
  $D^+ \to \bar{K}^0\pi^+$ external & internal spectator
  $D^+ \to K^0\pi^+$ internal spectator & annihilation

$D^+ \to X\pi^+$



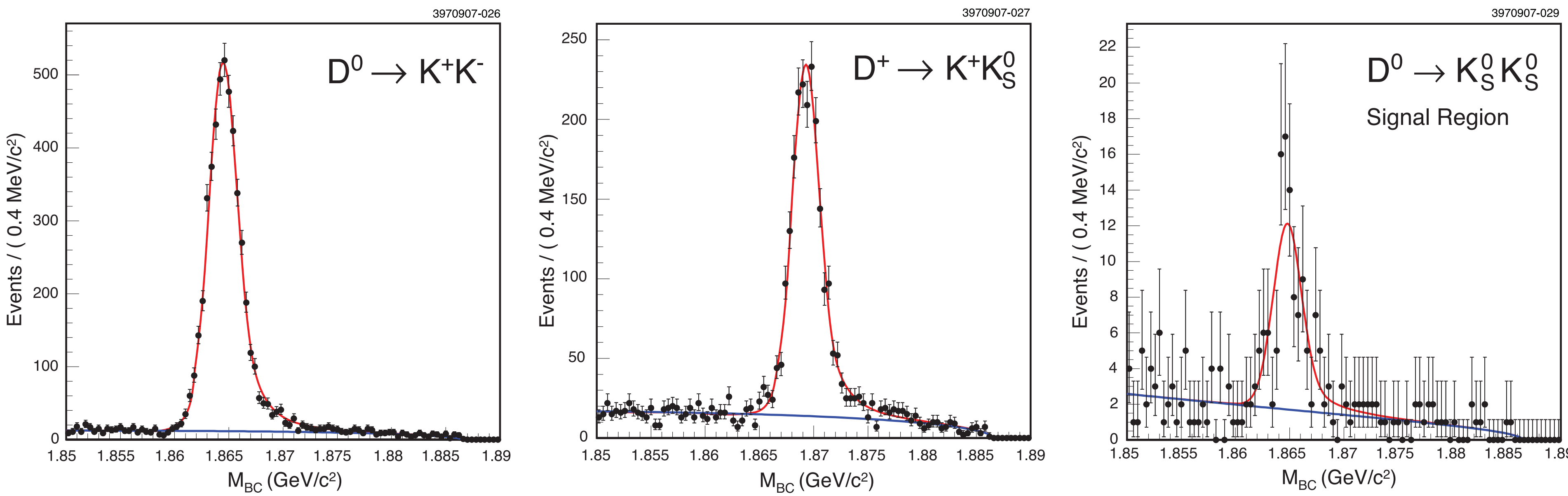
$D^0 \to X\pi^0$



$D \to KK$ Decays

$D \to KK$ **decays are Cabibbo suppressed**

- **Two W exchange diagrams for $D^0 \to K^0_S K^0_S$ interfere destructively**
- **We search for Single Tag $D \to KK$ decays and normalize to the reference mode branching fractions.**

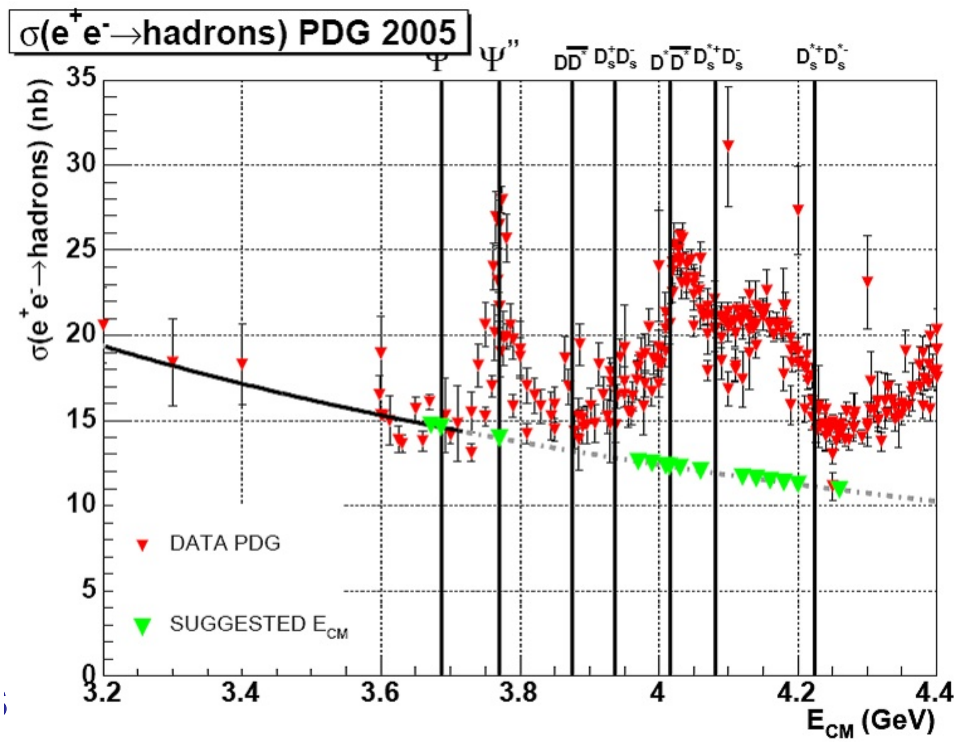


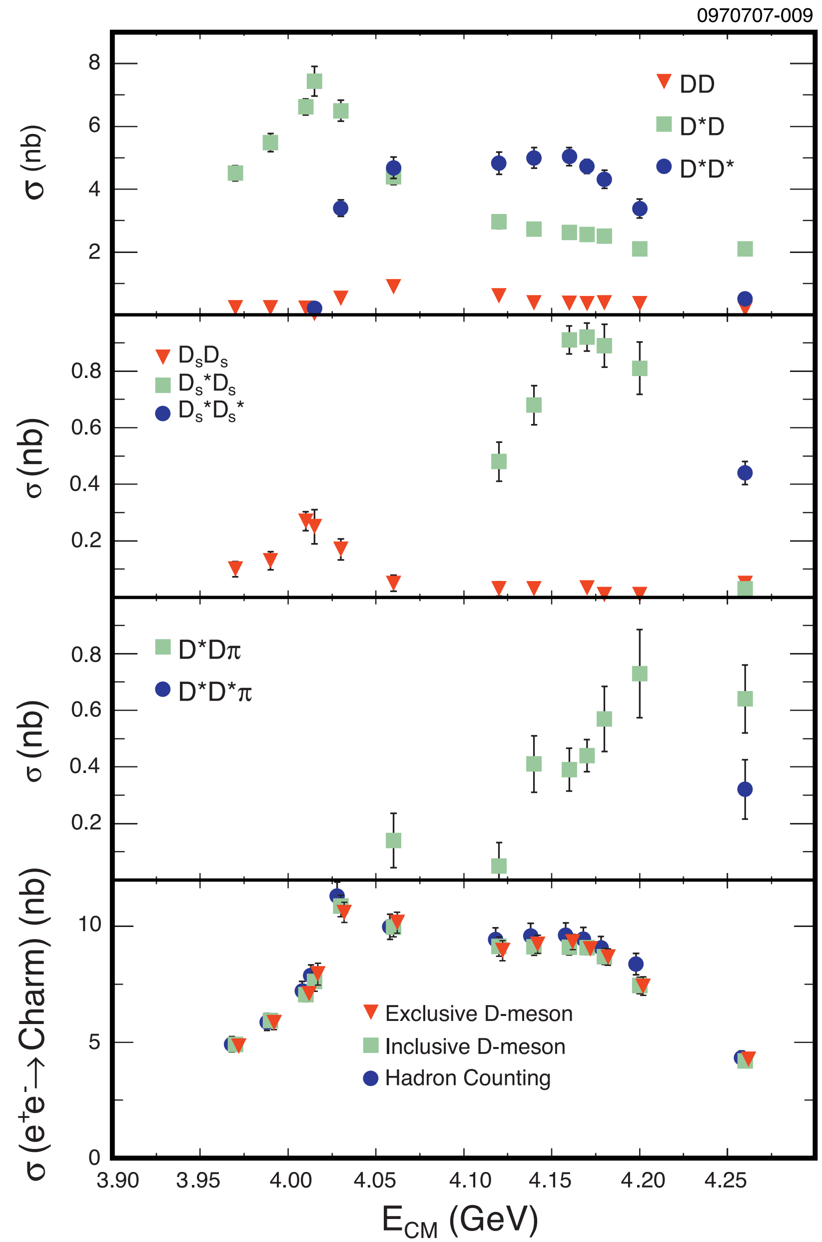
Preliminary

Mode	Our Result	PDG 2006
$\mathcal{B}(D^0 \to K^+K^-)$	$(4.08 \pm 0.08 \pm 0.09) \times 10^{-3}$	$(3.85 \pm 0.09) \times 10^{-3}$
$\mathcal{B}(D^0 \to K^0_S K^0_S)$	$(1.49 \pm 0.33 \pm 0.09) \times 10^{-4}$	$(3.6 \pm 0.7) \times 10^{-4}$
$\mathcal{B}(D^+ \to K^+ K^0_S)$	$(3.17 \pm 0.09 \pm 0.08) \times 10^{-3}$	$(2.95 \pm 0.19) \times 10^{-3}$

D_s Production Cross Section

- Little was know about the composition of $\sigma(e^+e^-)$ above $E_{cm} = 3.8$ GeV.
- CLEO scan with ~ 5 pb^{-1} per point with fast turnaround and feedback
- More luminosity in the region around $E_{cm} = 4.17$ GeV where $D_s^{\pm}D_s^{*\mp}$ peaks
  - $\sigma(e^+e^- \to D_s^{\pm}D_s^{*\mp}) \approx 0.9$ nb

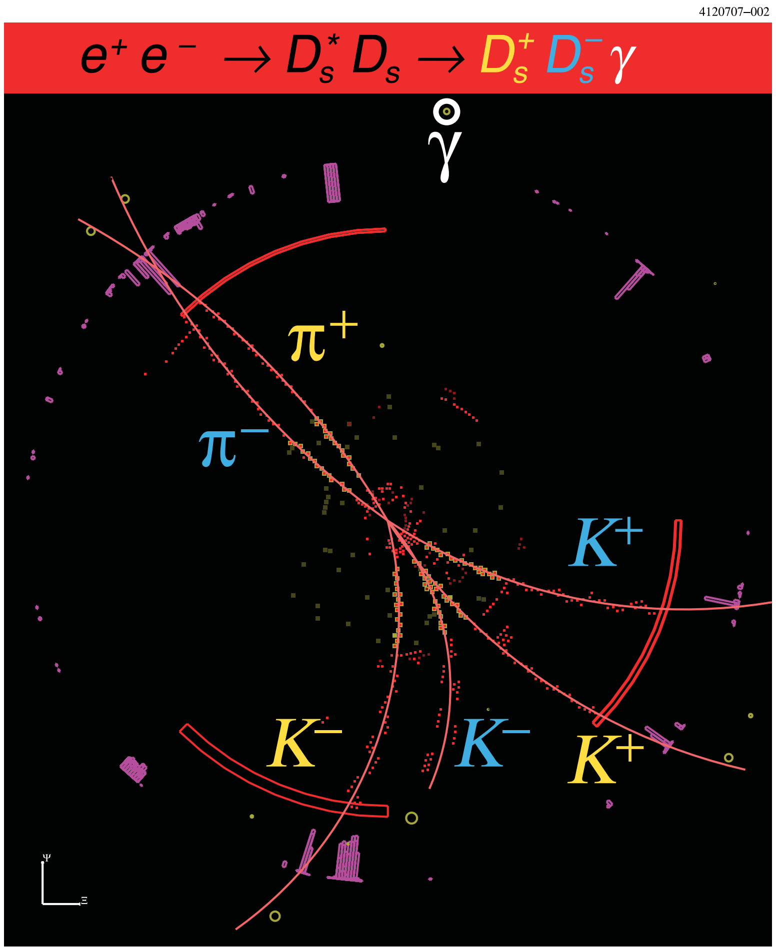




Selecting $D_s^{\pm} D_s^{*\mp}$ Events

DT event

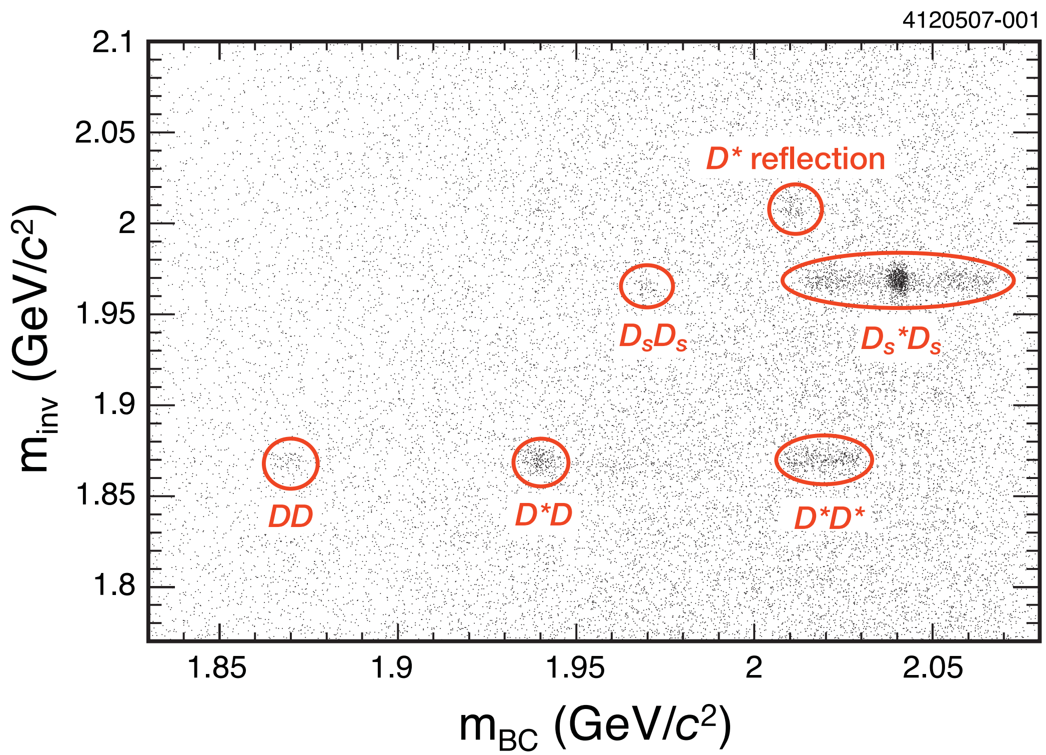
$D_s^+ \to K^+ K^- \pi^+ / D_s^- \to K^+ K^- \pi^-$



Ignore the γ or π^0 from D_s^* decay

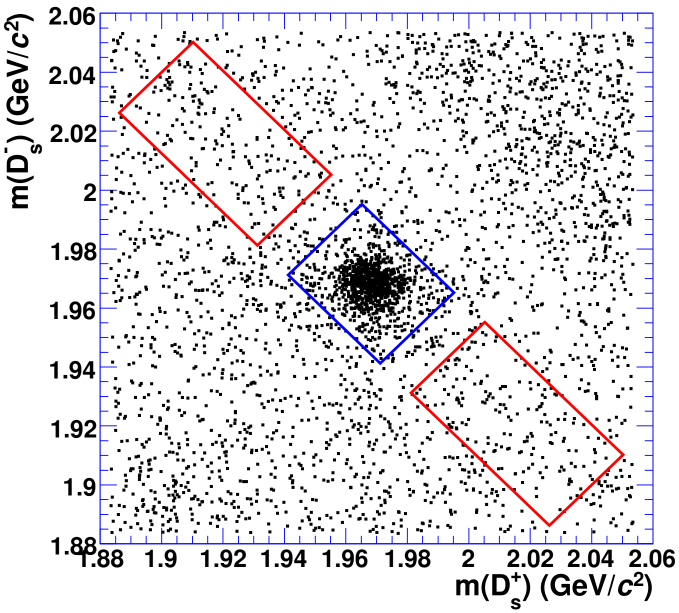
Select $D_s^{\pm} D_s^{*\mp}$ events using:

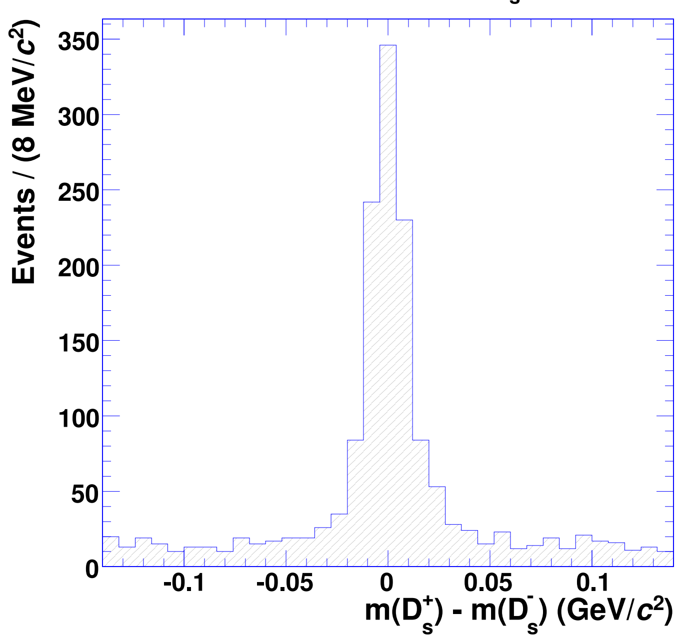
- m_{inv}, the candidate invariant mass
- $m_{BC} \equiv [E_{\text{beam}}^2 - p^2(D_s)]^{\frac{1}{2}}$
  - The m_{BC} distribution is:
    - narrow for direct D_s
    - wide for D_s from D_s^*



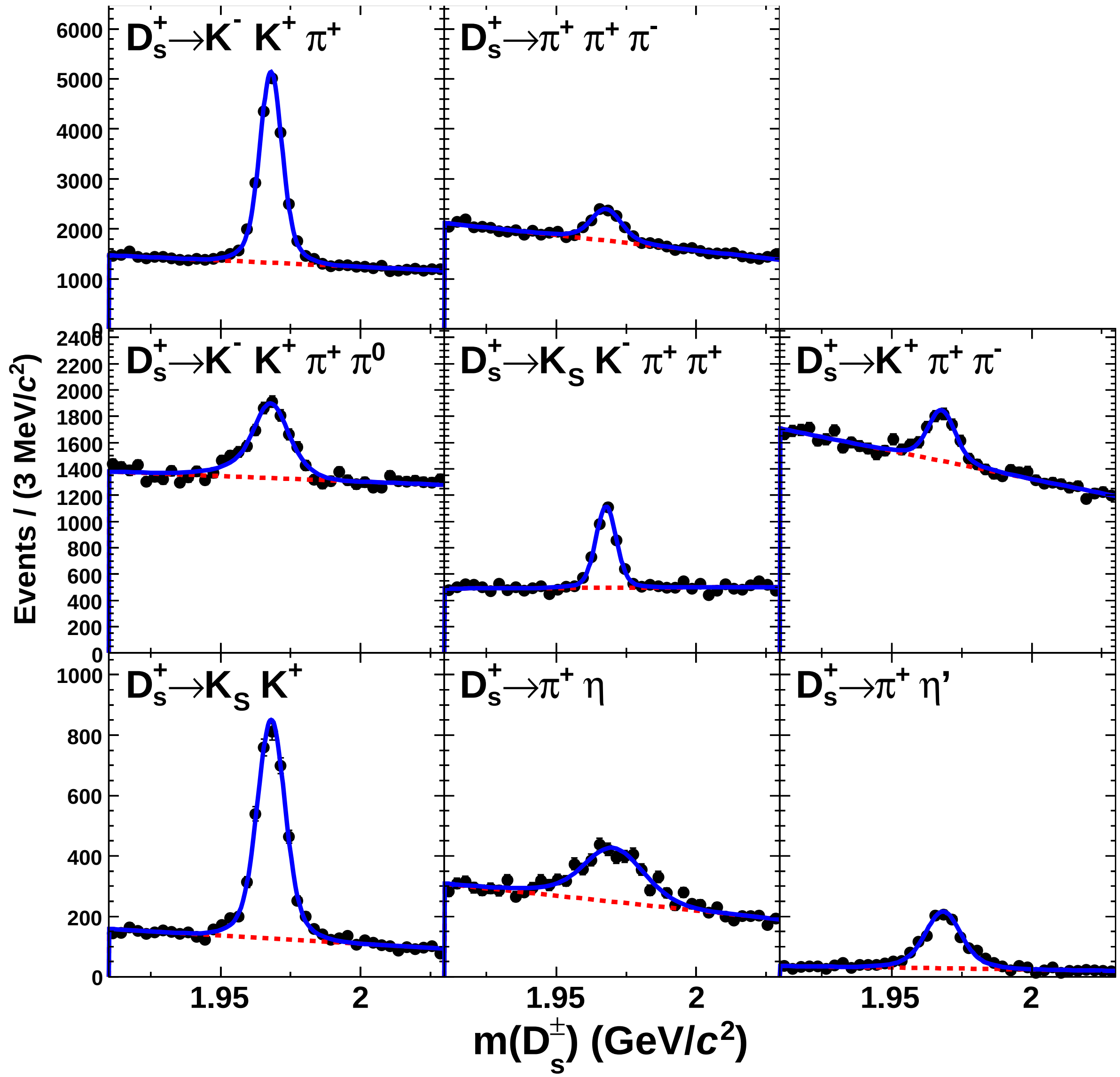
Analyzing $D_s^{\pm} D_s^{*\mp}$ Events

All D_s Double Tags





D_s Single Tags Square Root Scales

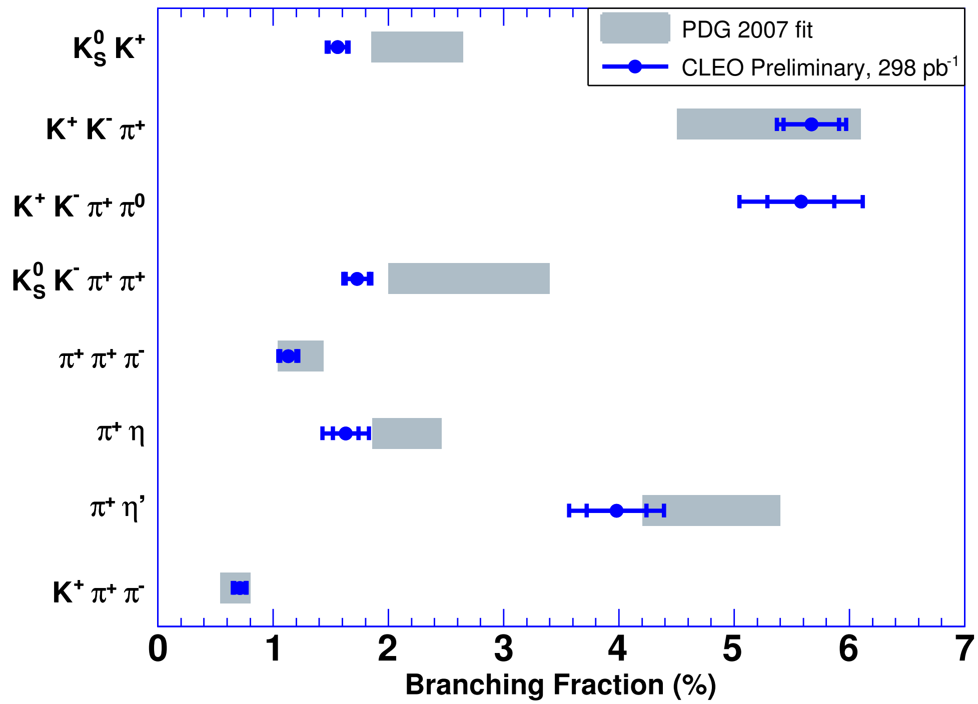


Absolute Hadronic D_s Branching Fractions

Preliminary from 298 pb^{-1} of data

D_s^+ Mode	$\mathcal{B}$ (%)
$K_S^0 K^+$	$1.56 \pm 0.08 \pm 0.05$
$K^- K^+ \pi^+$	$5.67 \pm 0.24 \pm 0.18$
$K^- K^+ \pi^+ \pi^0$	$5.58 \pm 0.29 \pm 0.45$
$K_S^0 K^- \pi^+ \pi^+$	$1.73 \pm 0.10 \pm 0.07$
$\pi^+ \pi^+ \pi^-$	$1.13 \pm 0.07 \pm 0.05$
$\pi^+ \eta$	$1.63 \pm 0.11 \pm 0.17$
$\pi^+ \eta'$	$3.98 \pm 0.26 \pm 0.32$
$K^+ \pi^+ \pi^-$	$0.71 \pm 0.05 \pm 0.03$

Comparison with PDG 2007



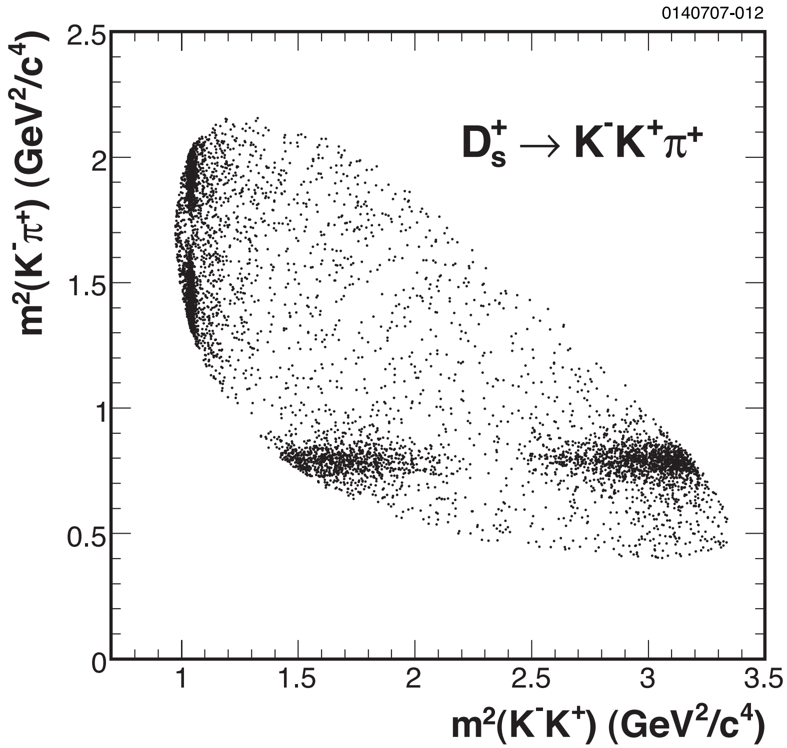
Belle measures $\mathcal{B}(D_s^+ \to K^- K^+ \pi^+)$ utilizing a partial reconstruction technique for $e^+e^- \to D_{s1} D_s^*$ events hep-ex/0701053

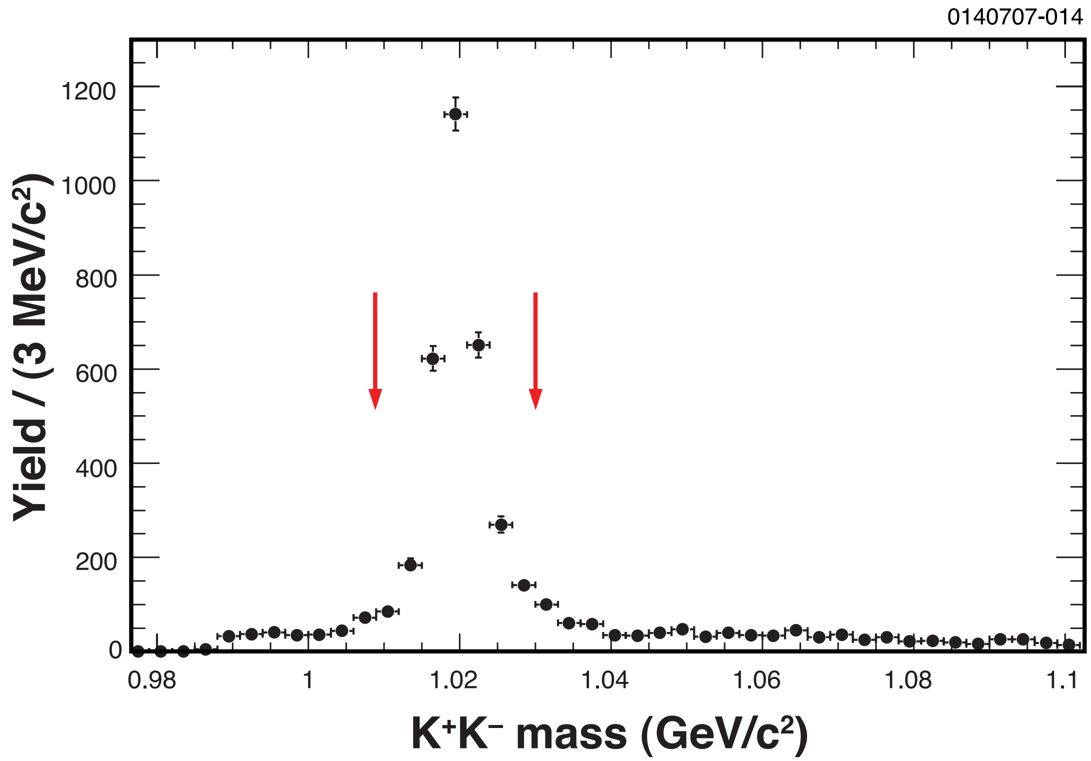
		$\mathcal{B}(D_s^+ \to K^- K^+ \pi^+)$ (%)
CLEO	Preliminary	$5.67 \pm 0.24 \pm 0.18$
Belle	Preliminary	$4.0 \pm 0.4 \pm 0.4$

Partial $D_s^+ \to K^- K^+ \pi^+$ Branching Fractions and $D_s^+ \to \phi\pi^+$

$\mathcal{B}(D_s^+ \to \phi\pi^+ \to K^- K^+ \pi^+)$ is one of the largest D_s branching fractions

- A branching fraction called $\mathcal{B}(D_s^+ \to \phi\pi^+)$ has often been used as a reference branching fraction for D_s decays.
  - Derived from a fairly narrow mass cut (typically near ± 10 MeV/c^2) around the ϕ peak in the $M(K^+K^-)$ distribution in $D_s^+ \to K^- K^+ \pi^+$ events.
- E687 and FOCUS report significant contributions from $f_0(980)$ (or $a_0(980)$) in the $\phi\pi$ region of the $D_s^+ \to K^- K^+ \pi^+$ Dalitz plot.





Partial $D_s^+ \to K^-K^+\pi^+$ Branching Fractions and $D_s^+ \to \phi\pi^+$

With a mass cut of approximately ± 10 MeV/c^2:

- The scalar contribution under the ϕ peak in $M(K^+K^-)$ is $\sim 6\%$.
  - Hence about 6% of the quoted $\mathcal{B}(D_s^+ \to \phi\pi^+)$ is due to other processes.
  - This contribution is comparable to current CLEO-c errors for partial $D_s^+ \to K^-K^+\pi^+$ branching fractions
  - CLEO now quotes $\mathcal{B}_{\Delta M} \equiv \mathcal{B}(D_s^+ \to K^-K^+\pi^+)$ with $|M(K^-K^+) - M_\phi| < \Delta M$ MeV/c^2.
  - This would be a better reference branching fraction for D_s^+ decays!

CLEO-c Preliminary

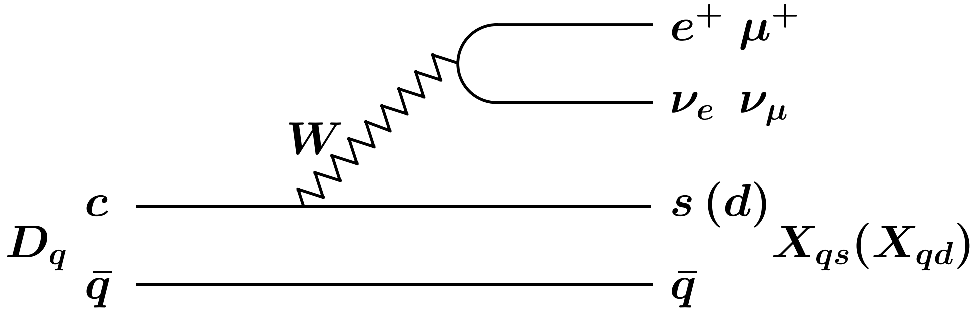
	$\mathcal{B}_{\Delta M}$ (%)
$\mathcal{B}_5$	$1.75 \pm 0.08 \pm 0.06$
$\mathcal{B}_{10}$	$2.07 \pm 0.10 \pm 0.05$
$\mathcal{B}_{15}$	$2.22 \pm 0.11 \pm 0.06$
$\mathcal{B}_{20}$	$2.32 \pm 0.11 \pm 0.06$
PDG 07	2.2 ± 0.2

$\mathcal{B}(D_s^+ \to \phi\pi^+)$ values from PDG 07

Experiment	$\mathcal{B}(D_s^+ \to \phi\pi^+)$ (%)	ΔM MeV/c^2
CLEO 96	$3.59 \pm 0.77 \pm 0.48$	± 8
BaBar 05	$4.81 \pm 0.52 \pm 0.38$	-11.5 $+15.5$
BaBar 06	$4.62 \pm 0.36 \pm 0.51$	± 15
PDG 07	4.5 ± 0.4	

The PDG 07 value of $\mathcal{B}_{\Delta M}$ is $\mathcal{B}(D_s^+ \to \phi\pi^+) \times \mathcal{B}(\phi \to K^-K^+)$

Exclusive Semileptonic D Decays



Final States X

$\bar{q}$	D_q	X_{qs} V_{cs}	X_{qd} V_{cd}
$\bar{u}$	D^0	$K^-, K^{*-}, \ldots$	π^- , $\rho^-, \ldots$
$\bar{d}$	D^+	$\bar{K}^0$, $\bar{K}^{*0}, \ldots$	π^0 , $\rho^0, \ldots$
$\bar{s}$	D_s	η , $\phi^0, \ldots$	$K^0, K^{*0}, \ldots$

- Semileptonic decay rates of D^0 or D^+ are proportional to V_{cs}^2 or V_{cd}^2

$$\Gamma(D_q \to X_{qs}\,\ell^+\nu_\ell) = \frac{\mathcal{B}(D_q \to X_{qs}\ell^+\nu_\ell)}{\tau_{D_q}} = \gamma_{qs}|V_{cs}|^2 \quad \text{(also } s \to d\text{)}$$

  - γ_{qs} and γ_{qd} must come from theory

- Exclusive decays depend on the mass-squared (q^2) of the virtual W through form factors $f_{qs}(q^2)$ and γ_{qs}, which are integrals over the form factors (also $s \to d$)
- Decay to a pseudoscalar meson P_s (K^- or $\bar{K}^0$) involves only one form factor

$$\frac{\Gamma(D_q \to P_s\,\ell^+\nu_\ell)}{dq^2} = \frac{p^3}{24\pi^3}\,|V_{cs}\ f_{qs}(q^2)|^2 \quad \text{(also } s \to d\text{)}$$

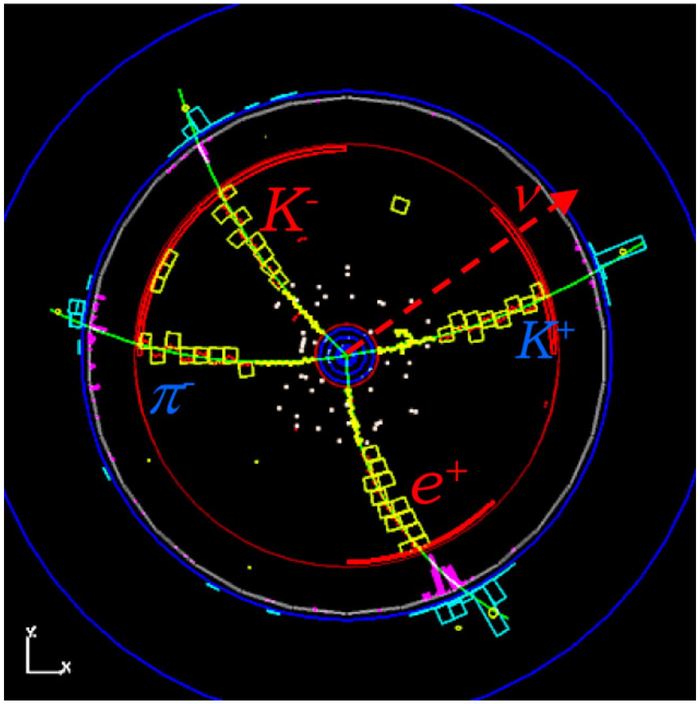
- CLEO-c measures $|V_{cs}f_{qs}(q^2)|$ and $|V_{cd}f_{qd}(q^2)|$ to test QCD theories of $f(q^2)$
  - Goal is to validate theories of $f(q^2)$ for application in the B meson sector
  - Most important for V_{ub} from $b \to u$ transitions where HQET does not apply

Semileptonic D^0 and D^+ Decays

- Find a hadronic decay tag and fully reconstruct it
- Find a semileptonic candidate in the event
- Fit the $U \equiv E_{\rm miss} - cP_{\rm miss}$ distribution for the signal

$e^+e^- \to \psi(3770) \to D^+D^-$

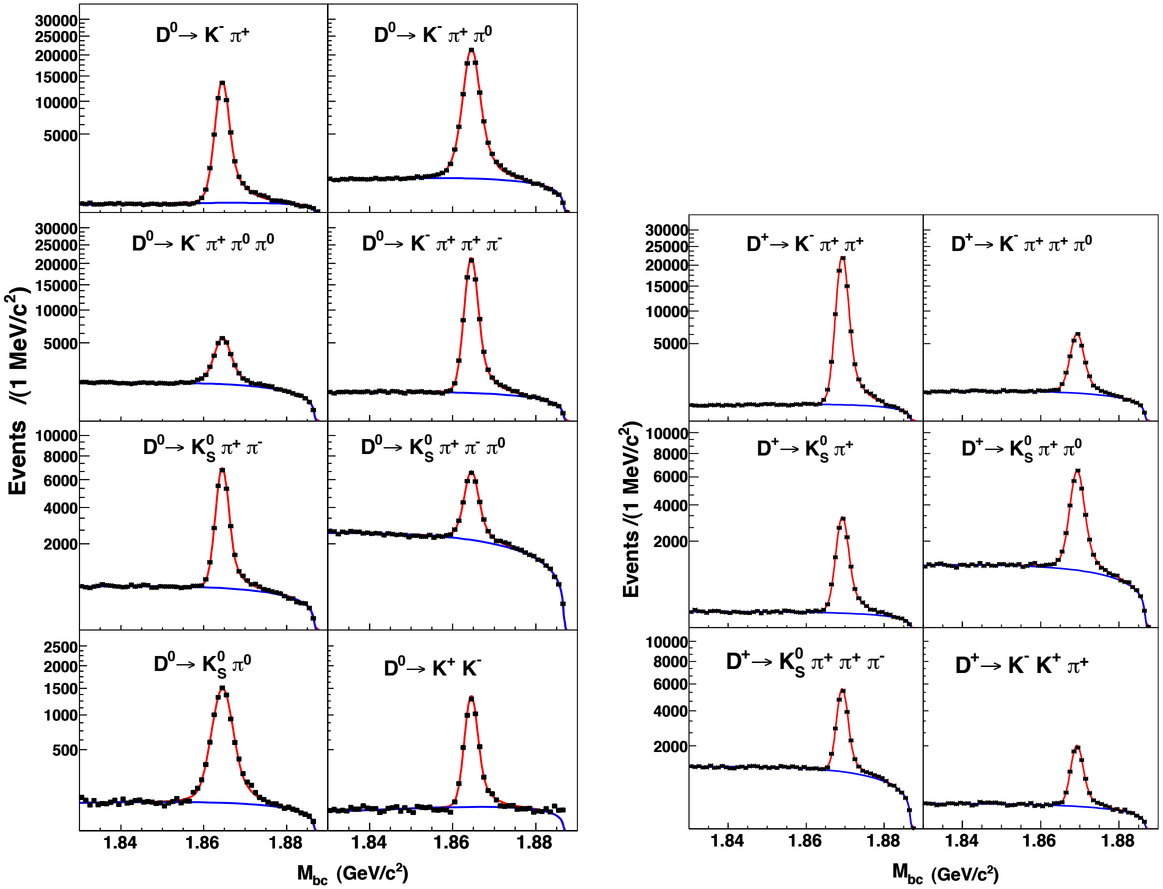
$\bar{D}^0 \to K^+\pi^-$ and $D^0 \to K^-e^+\nu$



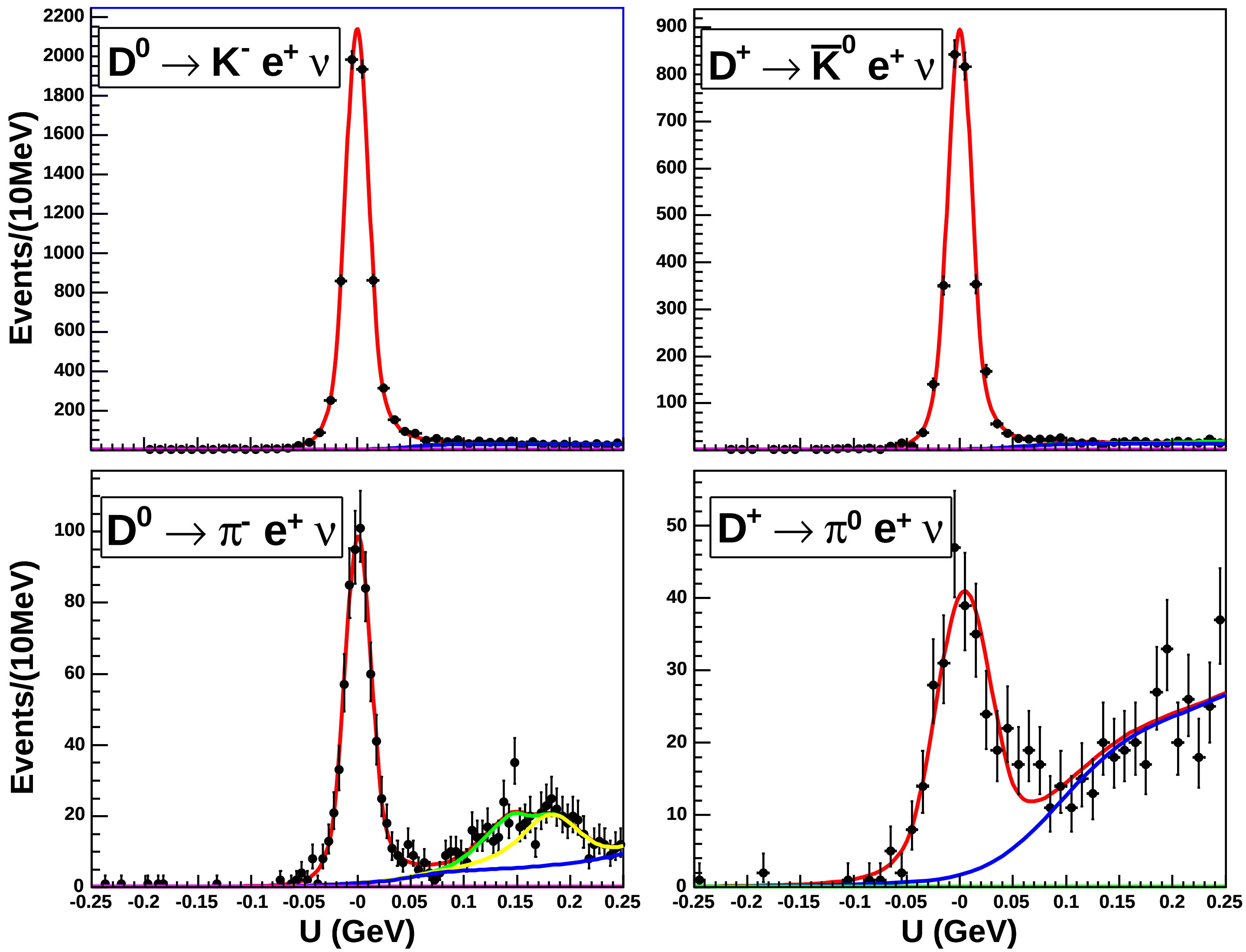
Square Root Scales

D^0 Tags

D^+ Tags



Semileptonic $D \to K e \nu$ and $D \to \pi e \nu$ Decays



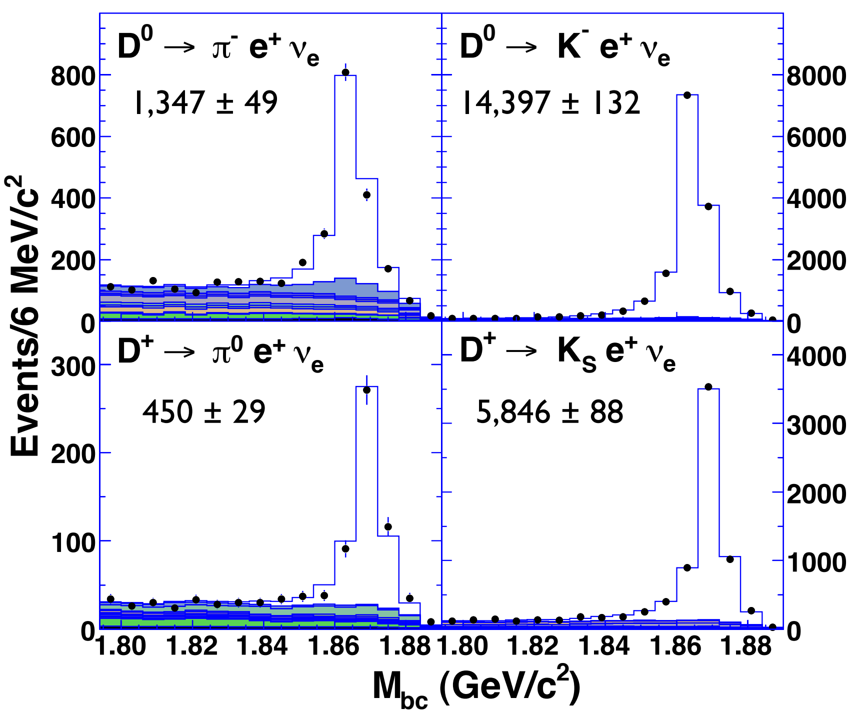
Preliminary yields for 281 pb^{-1}

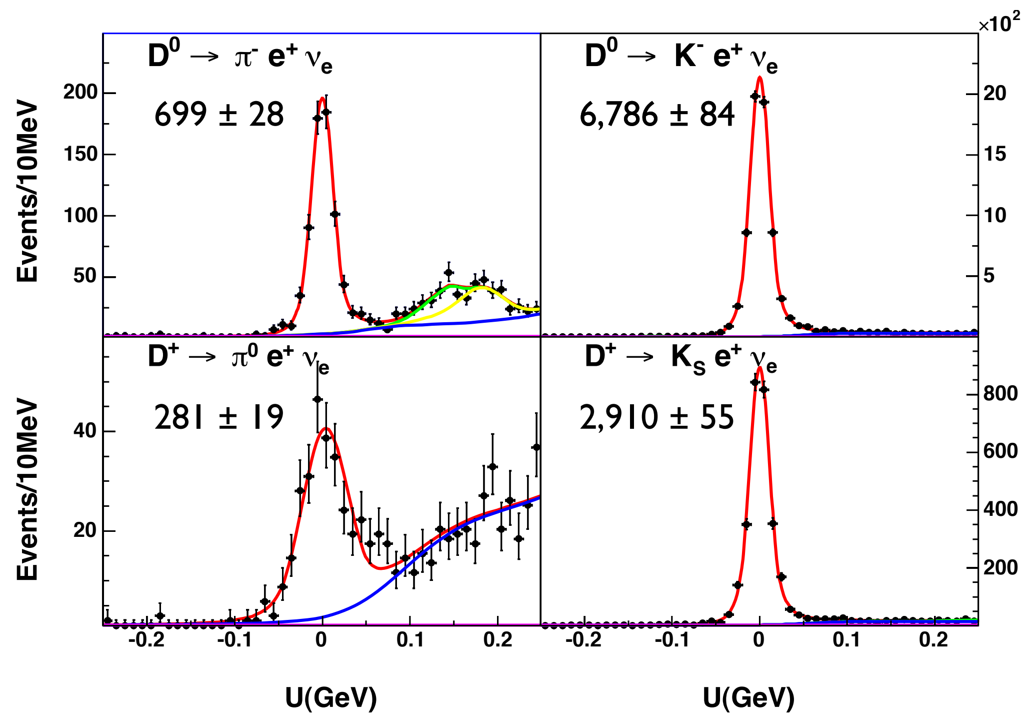
$6,786 \pm 84 \; D^0 \to K^- e^+ \nu$ $\quad 2,919 \pm 55 \; D^+ \to K^0_S e^+ \nu$

$699 \pm 28 \; D^0 \to \pi^- e^+ \nu$ $\quad 281 \pm 19 \; D^+ \to \pi^0 e^+ \nu$

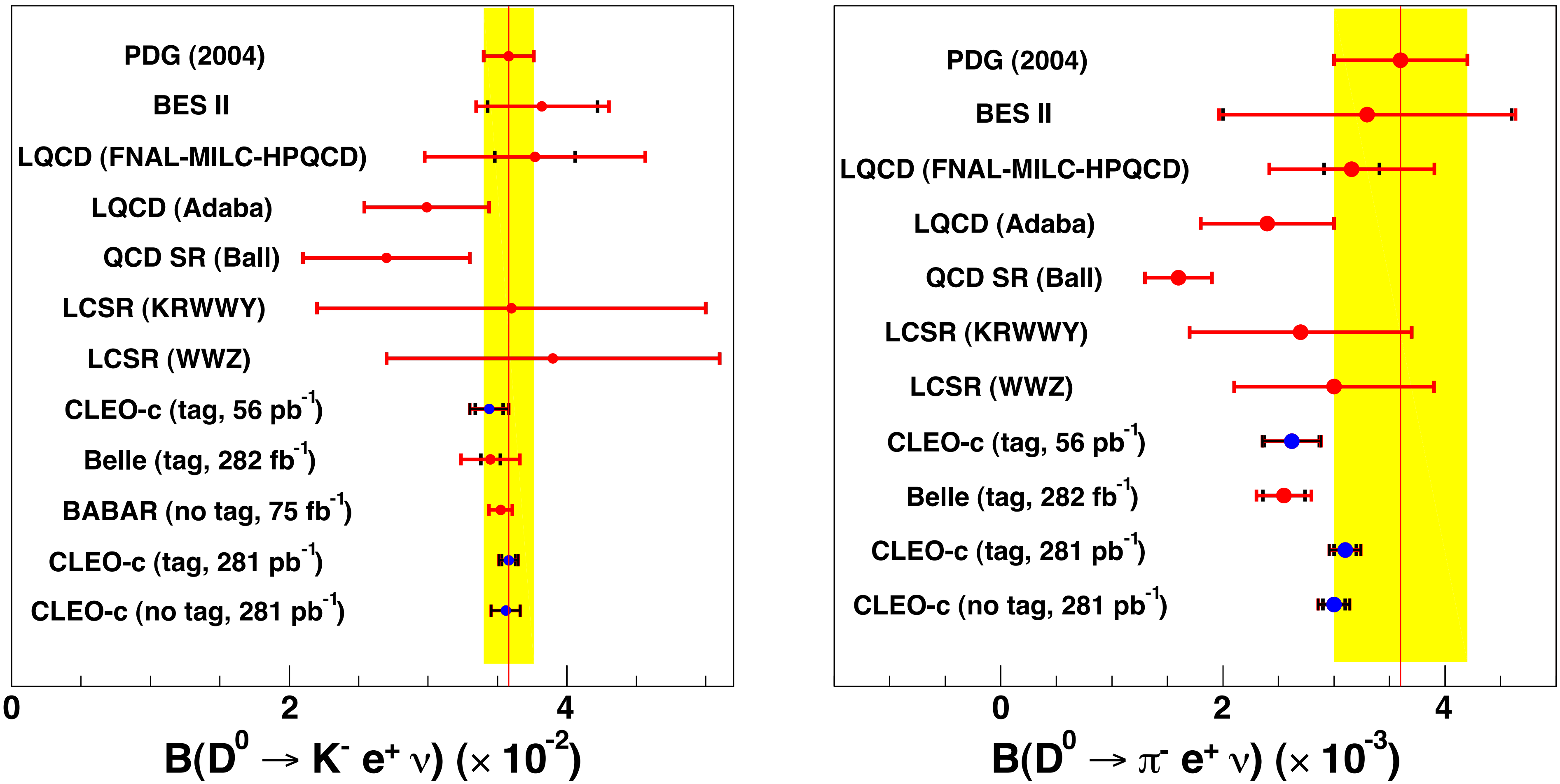
Semileptonic D^0 and D^+ Decays – Untagged Analysis

- Find an event with an electron
- Using $(E_i, \vec{p}_i)$ for all observed charged and neutral particles, calculate: $E_{\text{miss}} \equiv E_{cm} - \Sigma E_i$ and $\vec{p}_{\text{miss}} = -\Sigma \vec{p}_i$
- Require $M^2_{\text{miss}} = E^2_{\text{miss}} - \vec{p}^{\,2}_{\text{miss}}$ be consistent with a neutrino
- Calculate M_{bc} using all particles other than the electron
- Needs $N_{D^0\bar{D}^0}$ and $N_{D^+D^-}$ from the hadronic branching fraction measurement
- Gives larger yields, but with larger systematic uncertainties
- Approximately 40% overlap with the Tagged sample (averaging requires care)





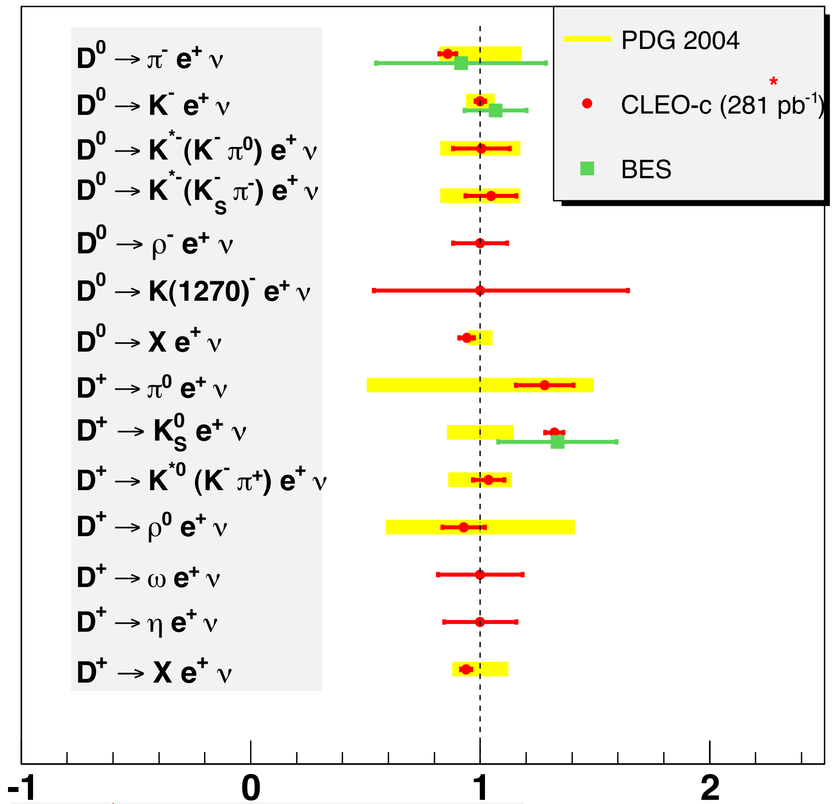
$D^0 \to K^- e^+ \nu$ and $D^0 \to \pi^- e^+ \nu$ Branching Fractions



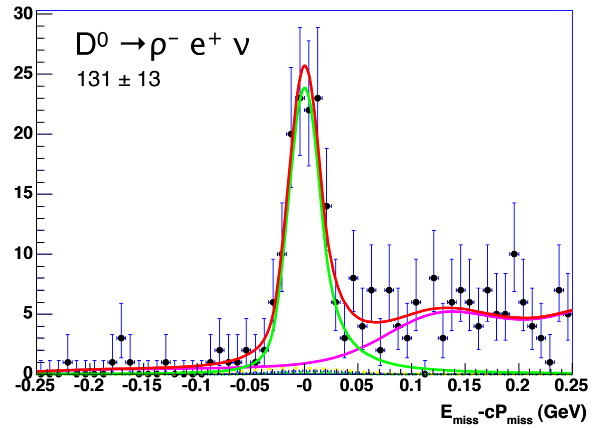
- CLEO-c 56 pb^{-1} results published, 281 pb^{-1} results Preliminary
- CLEO-c Tagged results absolute, CLEO-c Untagged results relative
- CLEO-c precision per pb^{-1} compared to BaBar and Belle demonstrates advantages of $\psi(3770)$

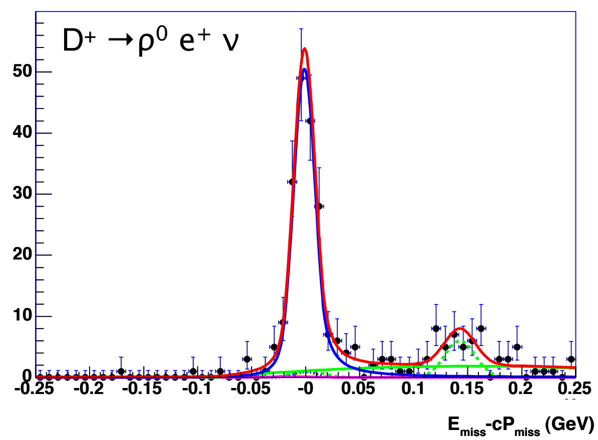
Branching Fraction Summary and Some First Observations

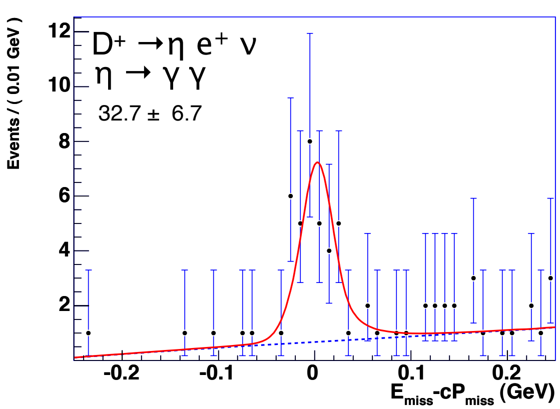
Preliminary Branching Fractions

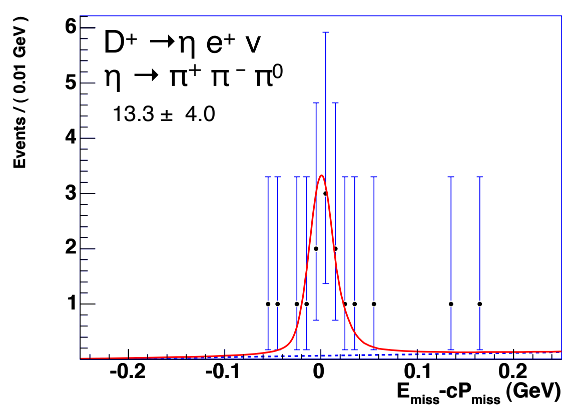


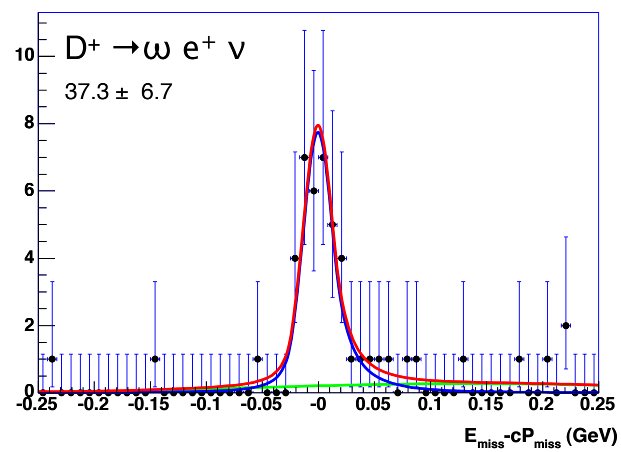
* $D \to K^* e^+ \nu$ branching fractions are for 56/pb





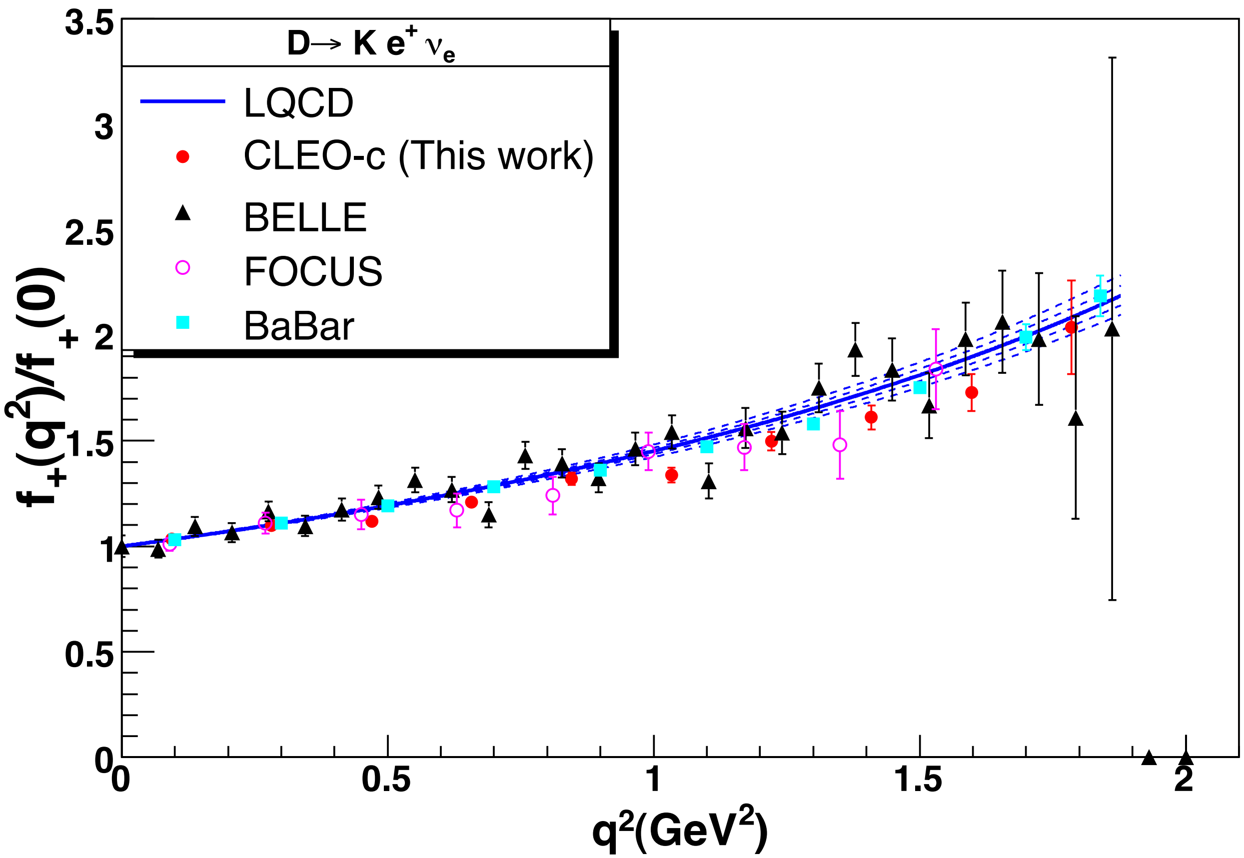


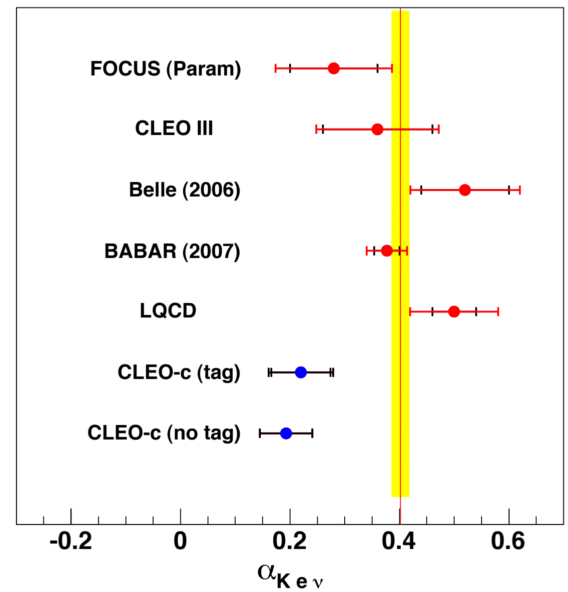


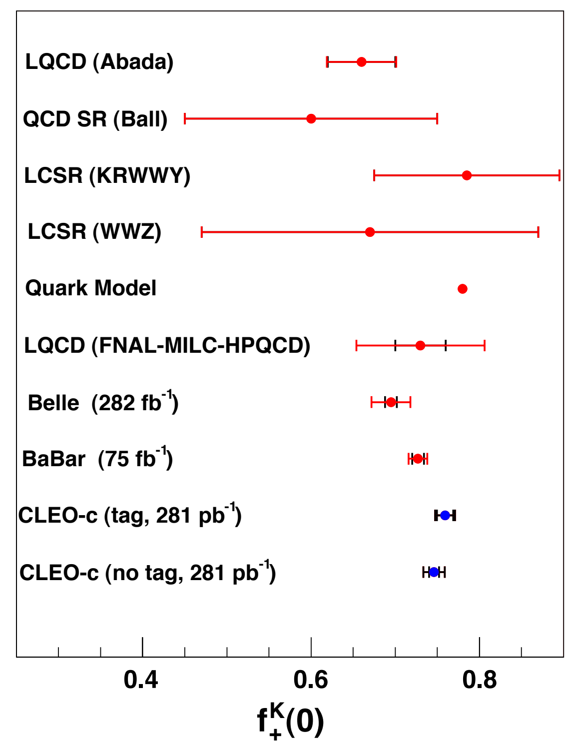


Semileptonic $D \to Ke\nu$ Form Factors

Preliminary Data and LQCD predictions







Use a modified pole form factor with

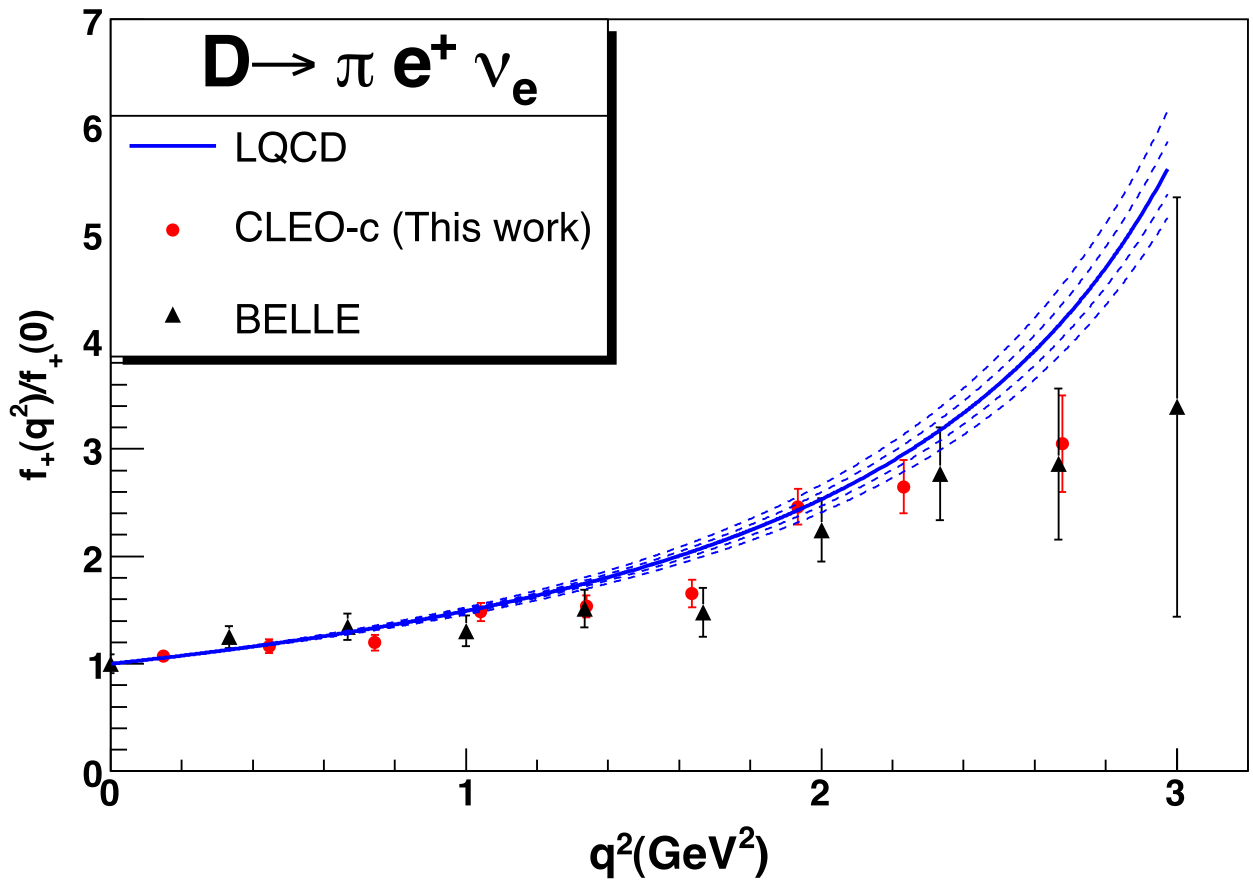
$M = M_{D_s^*}$ and V_{cs} from PDG07:

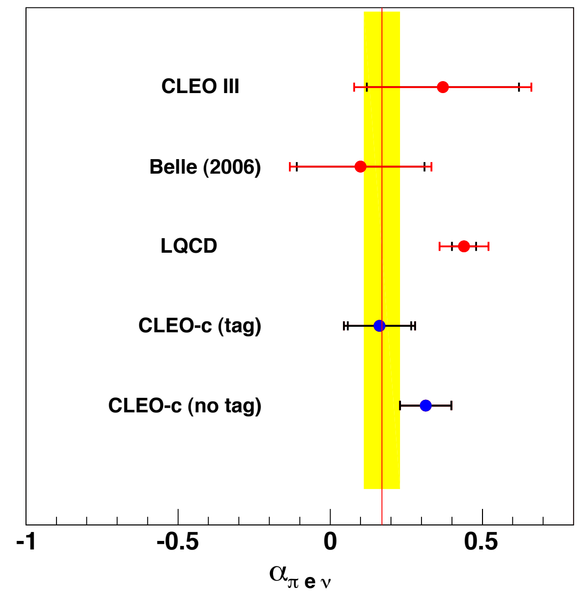
$$f_+(q^2) = \frac{f_+(0)}{(1 - q^2/M^2)(1 - \alpha\, q^2/M^2)}$$

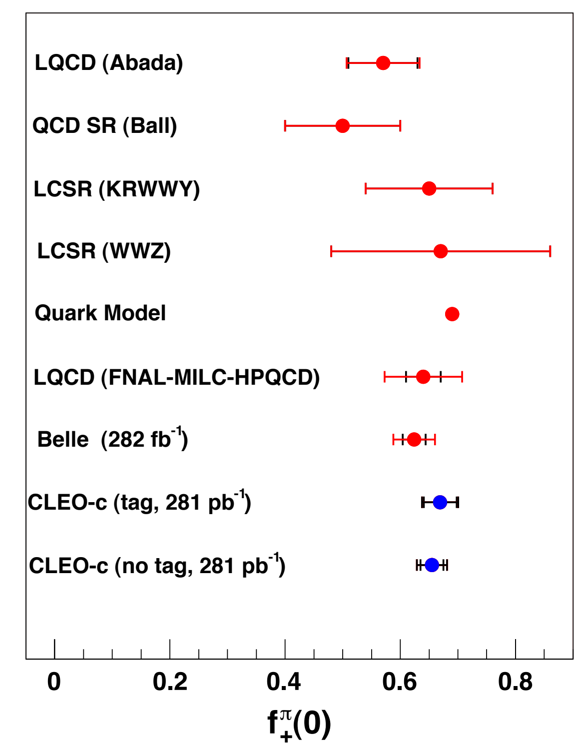
There are other important parameterizations in use

Semileptonic $D \to \pi e \nu$ Form Factors

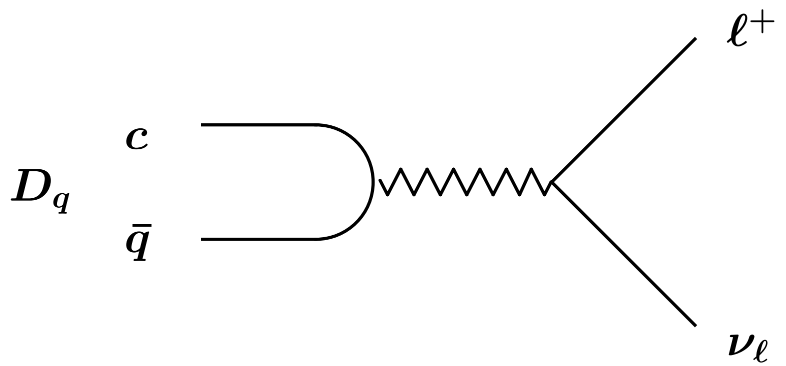
Preliminary Data and LQCD predictions







Leptonic D Decays and D Meson Decay Constants



The factor $f_{D_q} V_{cq}$ occurs in the decay amplitude for the $c\bar{q}W$ vertex

- The decay widths for leptonic D^+ and D_s^+ decays are:

$$\Gamma(D_q^+ \to \ell^+ \nu_\ell) = \frac{1}{8\pi} G_F^2 M_{D_q}\, m_\ell^2 \left(1 - \frac{m_\ell^2}{M_{D_q}^2}\right) |f_{D_q} V_{cq}|^2$$

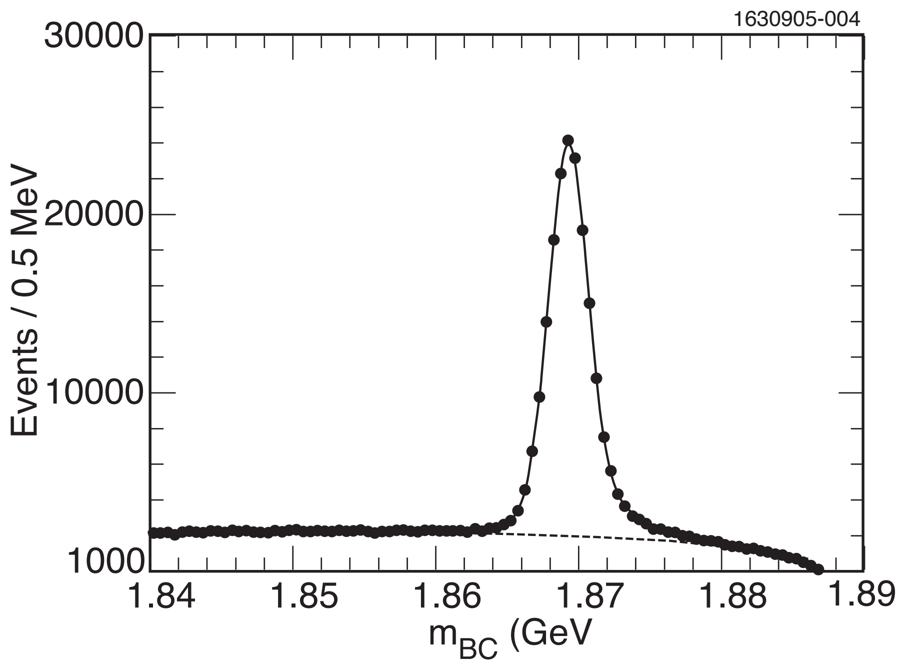
- Measurements of $\mathcal{B}(D^+ \to \ell^+ \nu_\ell)$ and $\mathcal{B}(D_s^+ \to \ell^+ \nu_\ell)$
  Determine $f_D V_{cd}$ and $f_{D_s} V_{cs}$
- We can measure $f_{D_q} V_{cq}$ and use values of V_{cq} to get f_{D_q}
  - f_D and f_{D_s} measurements can constrain and validate QCD calculations of f_B
  - Recall that the f_B uncertainty dominates the error in $|V_{td}|$ from measurements of Δm_d in $B^0 \bar{B}^0$ mixing
  - We also determine V_{cd} and V_{cs} from semileptonic D decays and QCD form factors

Leptonic D^+ Decays and f_D

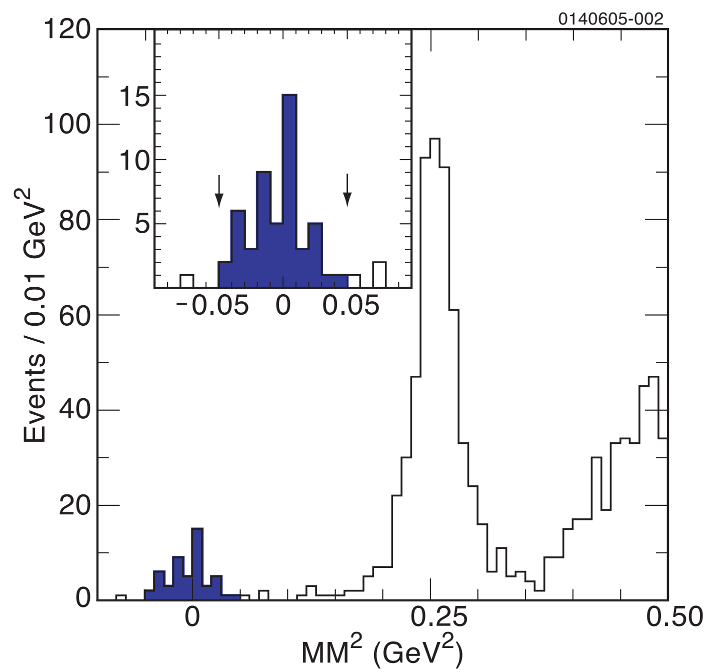
Reconstructing $D^+ \to \mu^+\nu$ decays:

- Find a hadronic D^- decay tag and fully reconstruct it
- Find a μ^+ candidate in the event and nothing else
- Calculate the square of the missing mass
  $MM^2 = (E_{cm} - E_{\text{Tag}} - E_\mu)^2 - (\vec{p}_{\text{Tag}} + \vec{p}_\mu)^2$
- Fit the MM^2 distribution for the signal

All D^- Tags



$D^+ \to \mu^+\nu$ Signal

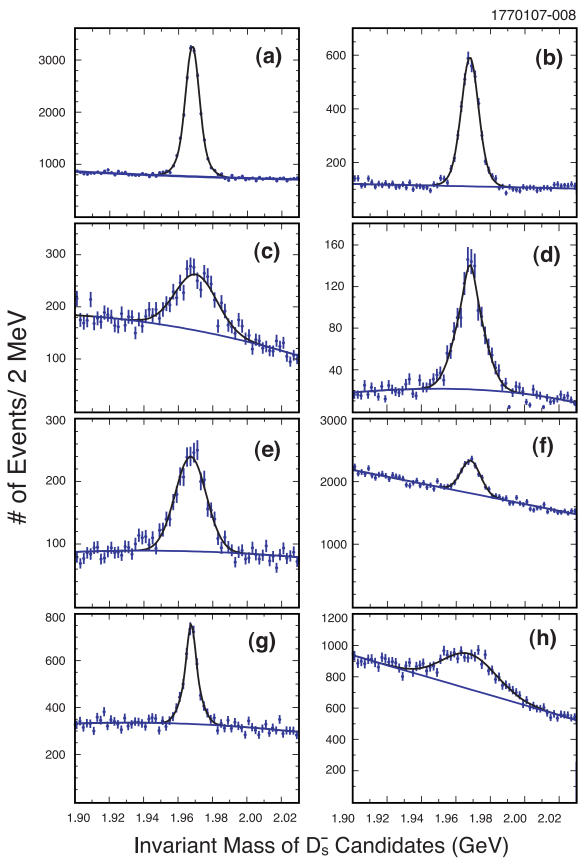


$\mathcal{B}(D^+ \to \mu^+\nu) = (4.40 \pm 0.66^{+0.09}_{-0.12}) \times 10^{-4}$ and $f_D = (222.6 \pm 16.7^{+2.8}_{-3.4})$ MeV

Leptonic D_s Decays and f_{D_s}

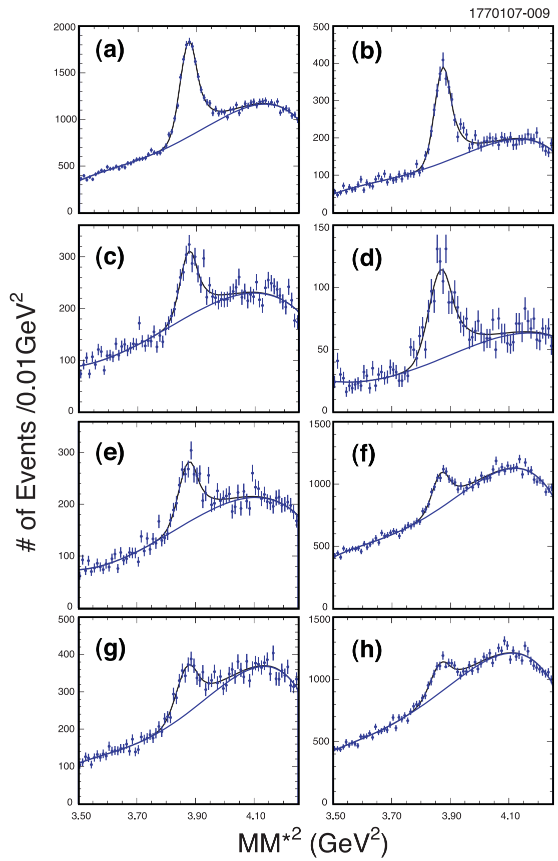
Cut on Tag Candidates Invariant Mass

$$\sqrt{E_{\rm Tag}^2 - p_{\rm Tag}^2}$$



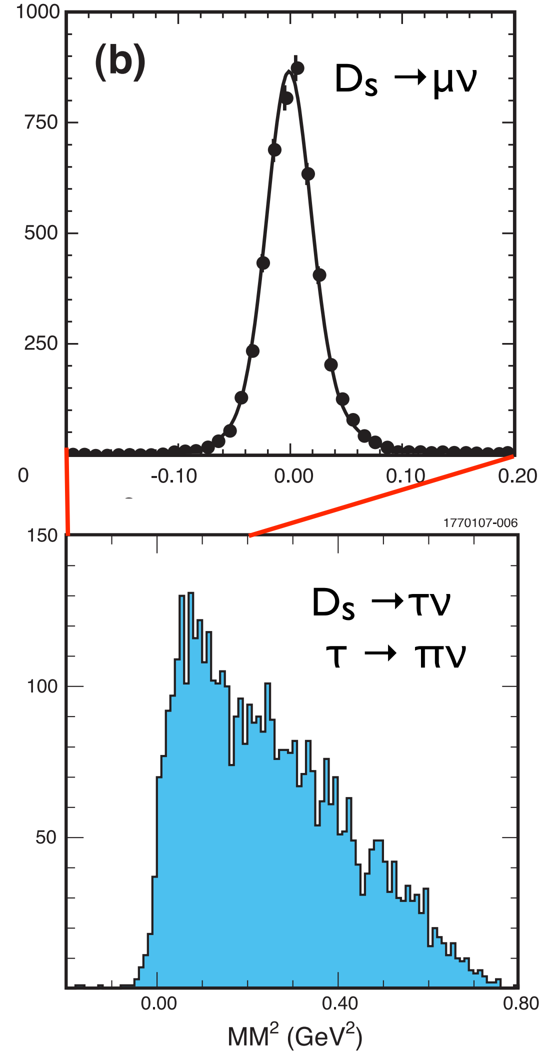
Fit Recoil Mass of $D_s \to \mu\nu$ Candidates

$$(E_{cm} - E_{\rm Tag} - E_\gamma)^2 - (\vec{p}_{\rm Tag} + \vec{p}_\gamma)^2$$



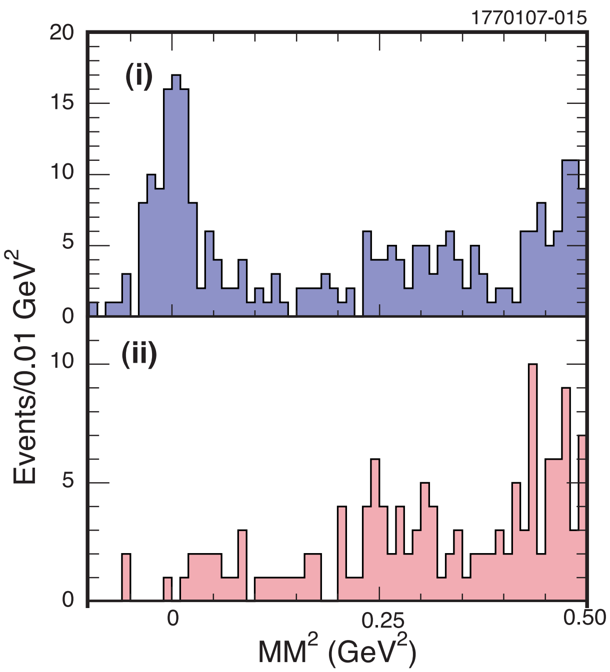
MC Missing Mass (MM^2)

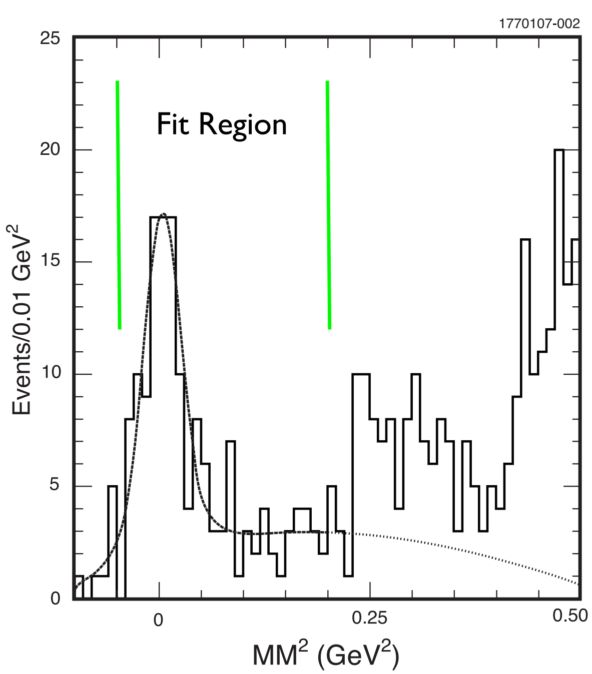
$$(E_{cm} - E_{\rm Tag} - E_\gamma - E_{\rm cand})^2 - (\vec{p}_{\rm Tag} + \vec{p}_\gamma + \vec{p}_{\rm cand})^2$$



(a) $D_s^- \to K^+K^-\pi^-$ (b) $D_s^- \to K_S^0 K^-$ (c) $D_s^- \to \eta\pi^-$
(d) $D_s^- \to \eta'\pi^-$ (e) $D_s^- \to \phi\rho^0$ (f) $D_s^- \to \pi^+\pi^-\pi^-$
(g) $D_s^- \to K^{*-}K^{*0}$ (h) $D_s^- \to \eta\rho_1$

Leptonic D_s Decays and f_{D_s}





Determining the number of $D_s \to \mu\nu$ candidates

- Need to distinguish between $D_s \to \mu\nu$ and $D_s \to \tau\nu$ $(\tau \to \pi\nu)$
- Measure the energy $E^{\rm CsI}_{\rm cand}$ of the candidate μ in the CsI colorimeter
- Generally pions loose more energy in the calorimeter than muons

(i) $E^{\rm CsI}_{\rm cand} < 300$ MeV with PID not e or K

- $-0.05 < MM^2 < 0.05$ — **92 Events**
  Like $D_s \to \mu\nu$ with $\epsilon \sim 99\%$
- $+0.05 < MM^2 < 0.20$ — **31 Events**
  Like $D_s \to \tau\nu$ $(\tau \to \pi\nu)$ with $\epsilon \sim 60\%$

(ii) $E^{\rm CsI}_{\rm cand} > 300$ MeV with PID not e or K

- $+0.05 < MM^2 < 0.20$ — **25 Events**
  Like $D_s \to \tau\nu$ $(\tau \to \pi\nu)$ with $\epsilon \sim 40\%$

(iii) Identified as an electron

- Used for background estimates

- Estimate 16.4 background events

Leptonic D^+ and D_s decays and f_D and f_{D_s}

Results:

- $\mathcal{B}(D_s \to \mu\nu) = (0.597 \pm 0.067 \pm 0.039)\%$
- $\mathcal{B}(D_s \to \tau\nu) = (8.0 \pm 1.3 \pm 0.4)\%$
- Combine $D_s \to \mu\nu$ and $D_s \to \tau\nu$ using lepton universality
  - $\mathcal{B}(D_s \to \widehat{\mu}\nu) = (0.638 \pm 0.050 \pm 0.033)\%$
  - $f_{D_s} = 274 \pm 13 \pm 7$ MeV

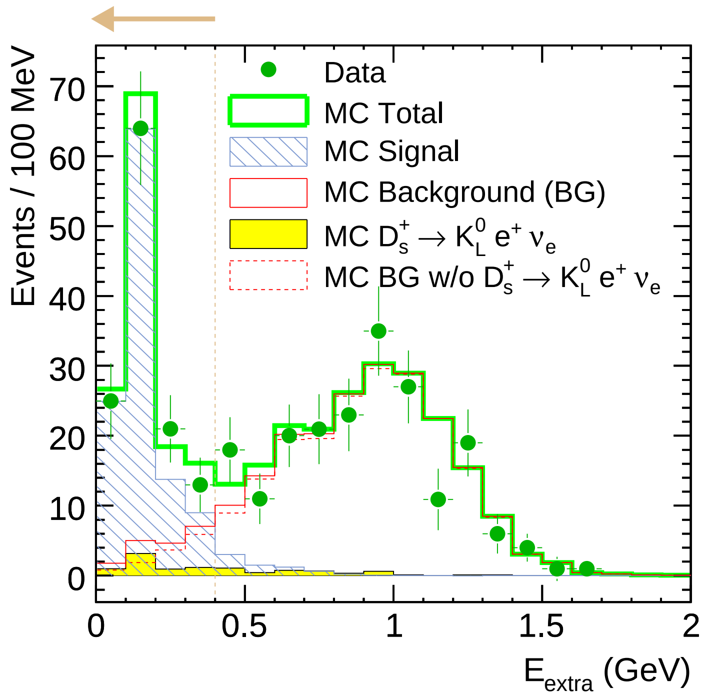
Preliminary result for $D_s \to \tau\nu$ and $\tau \to e\nu\nu$

- $\mathcal{B}(D_s \to \tau\nu) = (6.29 \pm 0.78 \pm 0.52)\%$
  - $f_{D_s} = 278 \pm 17 \pm 12$ MeV
- Preliminary weighted average
  - $f_{D_s} = 275 \pm 10 \pm 5$ MeV
    (systematic errors mostly uncorrelated)
- Using $f_D = 222.6 \pm 16.7^{+2.3}_{-3.4}$ MeV
  - $f_{D_s}/f_D = 1.24 \pm 0.10 \pm 0.03$

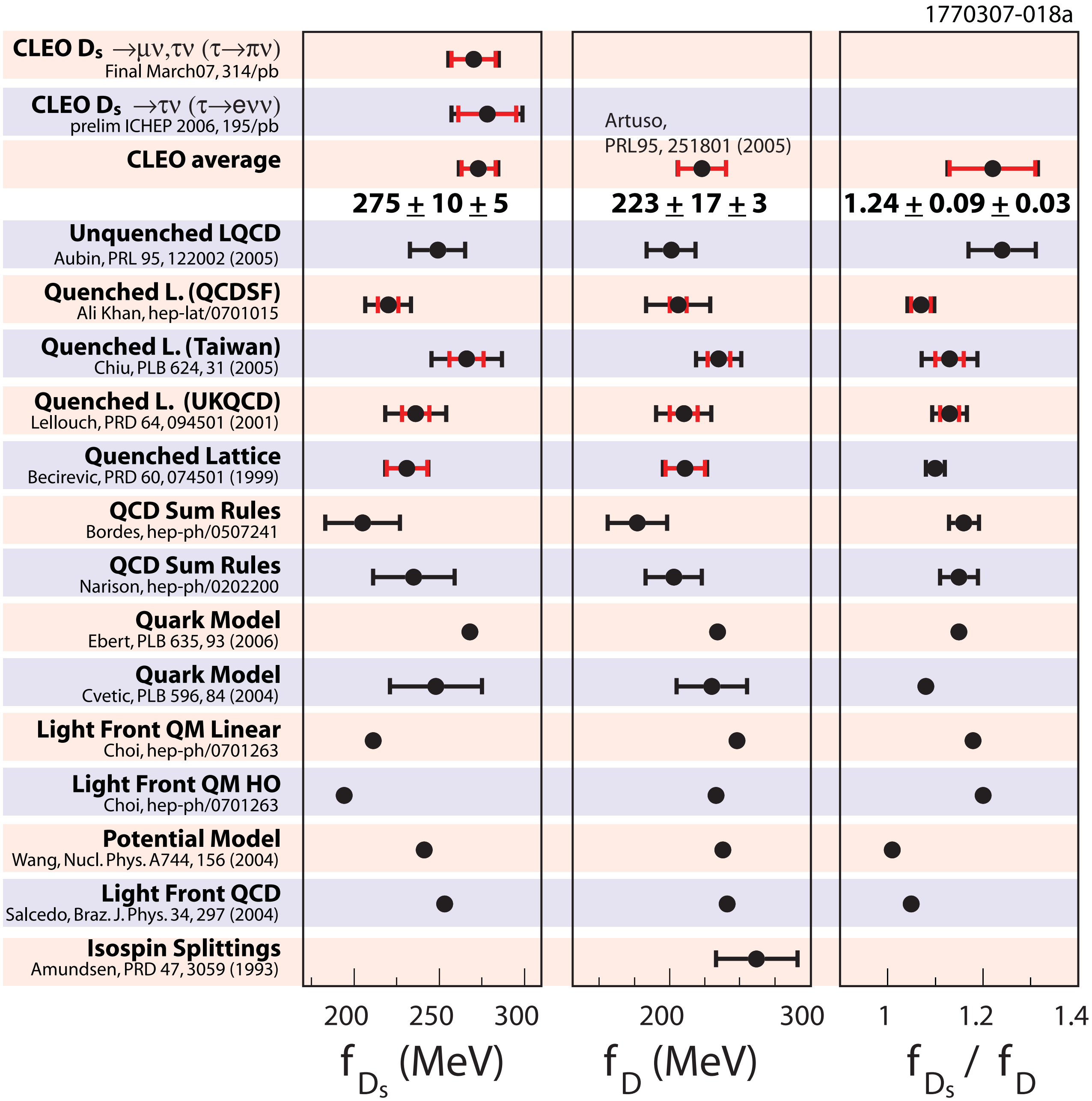
$D_s \to \tau\nu$ and $\tau \to e\nu\nu$

Analysis:

- Reconstruct a D_s tag
- Require one extra electron and no other tracks
- $E_{CC}^{extra} < 400$ MeV
  CsI calorimeter energy after all track showers are removed.



Comparing f_D and f_{D_s} with Theoretical Estimates

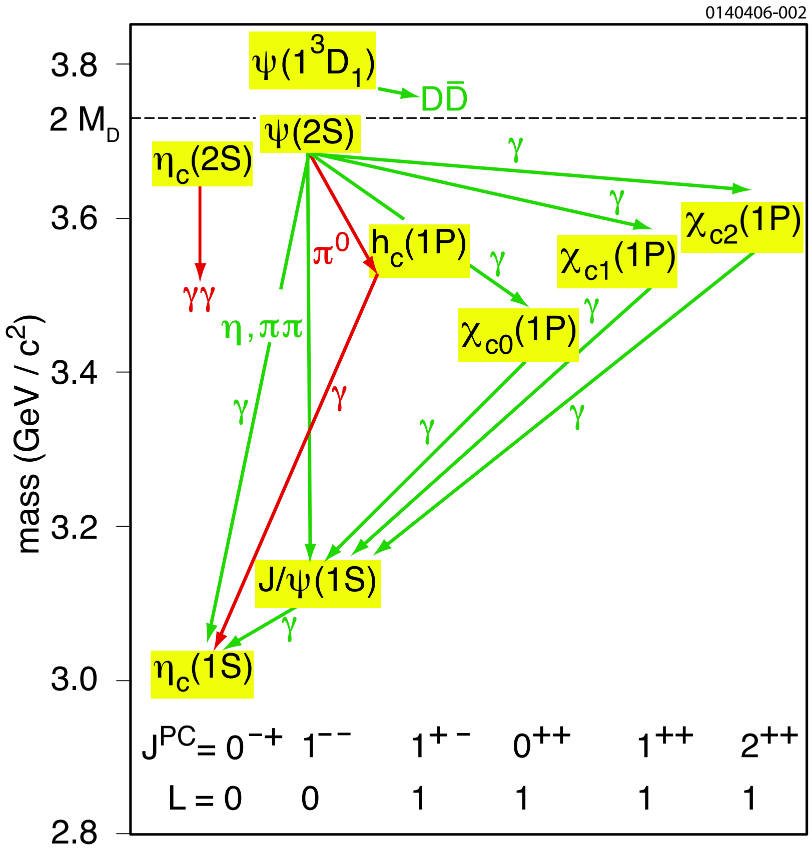


The Unquenched LQCD calculation for f_D was a *prediction* rather than a *postdiction* like most QCD calculations.

The CLEO-c and LQCD groups kept their results secret prior to the LP2005 conference and announced them together at the conference.

Charmonium Below the $D\bar{D}$ Threshold and $\psi(3770)$

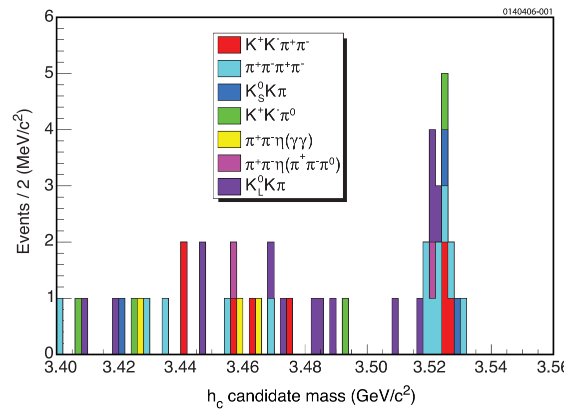
Spectroscopy



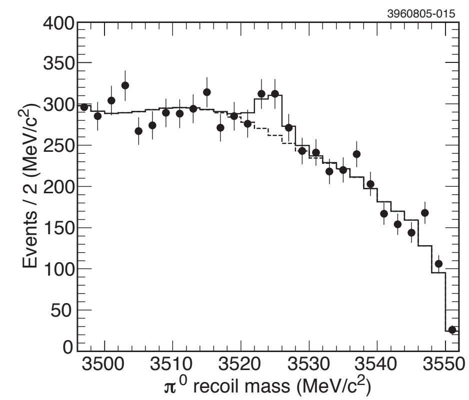
h_c discovery using $\psi(2S) \rightarrow \pi^0 h_c$ & $h_c \rightarrow \eta_c \gamma$

$M(h_c)$ from π^0 recoil

η_c reconstruction



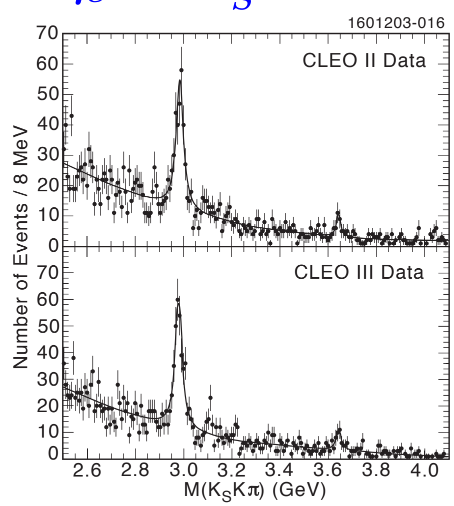
E_γ cut



$\eta_c(2S)$ Confirmation

$\psi(2S) \rightarrow \gamma \eta_c$

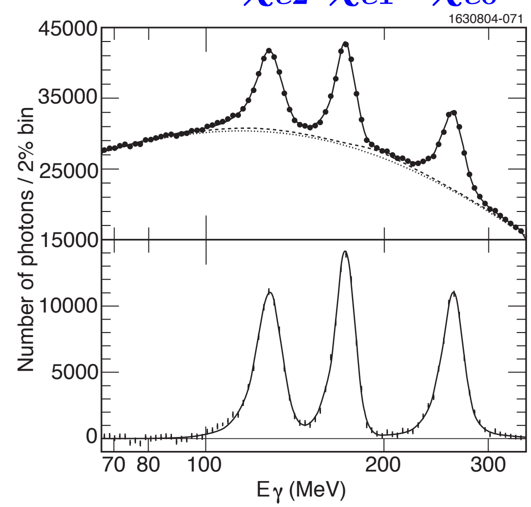
$\eta_c \rightarrow K^0_S K^{\pm} \pi^{\mp}$



χ_{cJ} Spectroscopy

$\psi(2S) \rightarrow \gamma \chi_{cJ}$

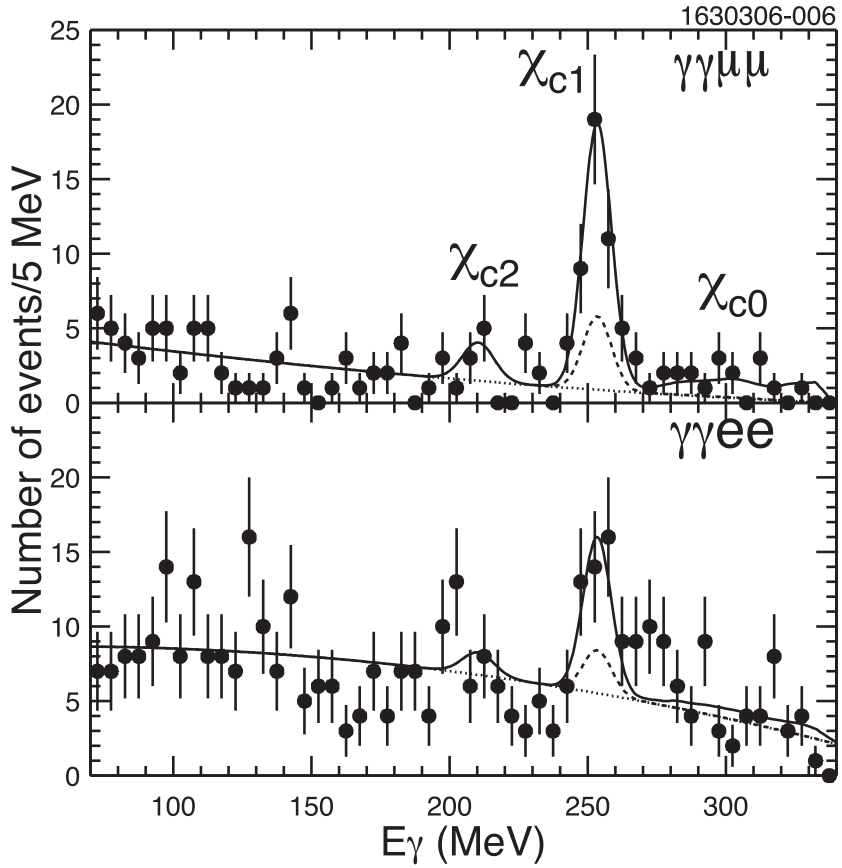
χ_{c2} χ_{c1} χ_{c0}



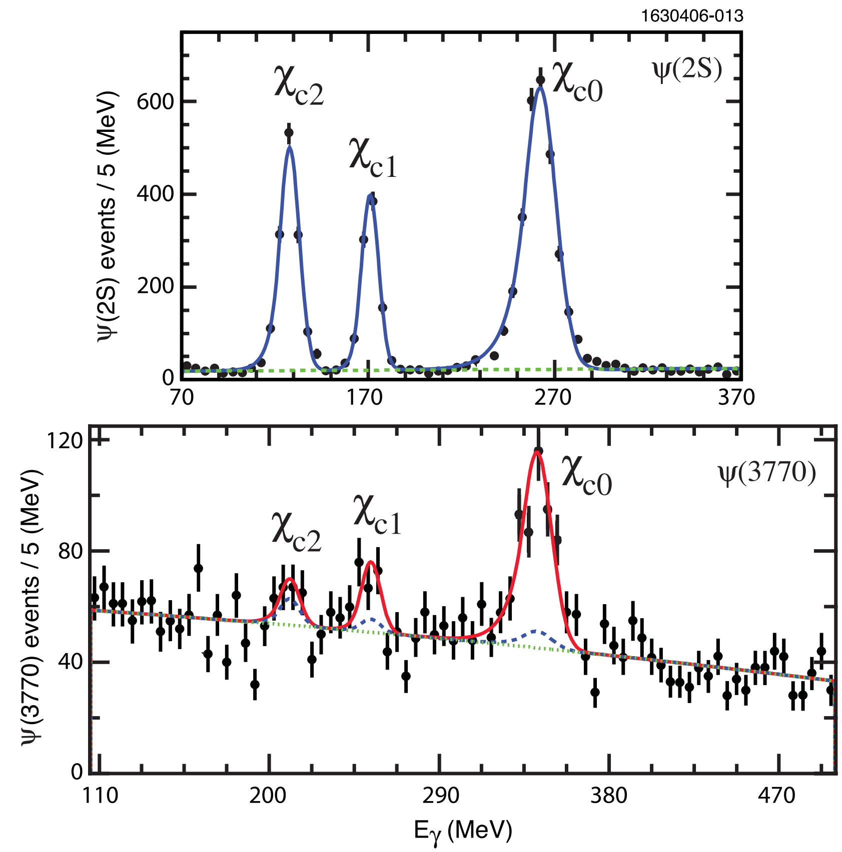
$\psi(3770) \to \gamma\chi_{cJ}$

CLEO observed $\psi(3770) \to \gamma\chi_{cJ}$ decays in two independent analyses

$\psi(3770) \to \gamma\chi_{cJ} \to \gamma\ell^+\ell^-$



$\psi(3770) \to \gamma\chi_{cJ}$ & $\chi_{cJ} \to$ hadrons



Pattern of branching fractions agrees with *relativistic* calculations

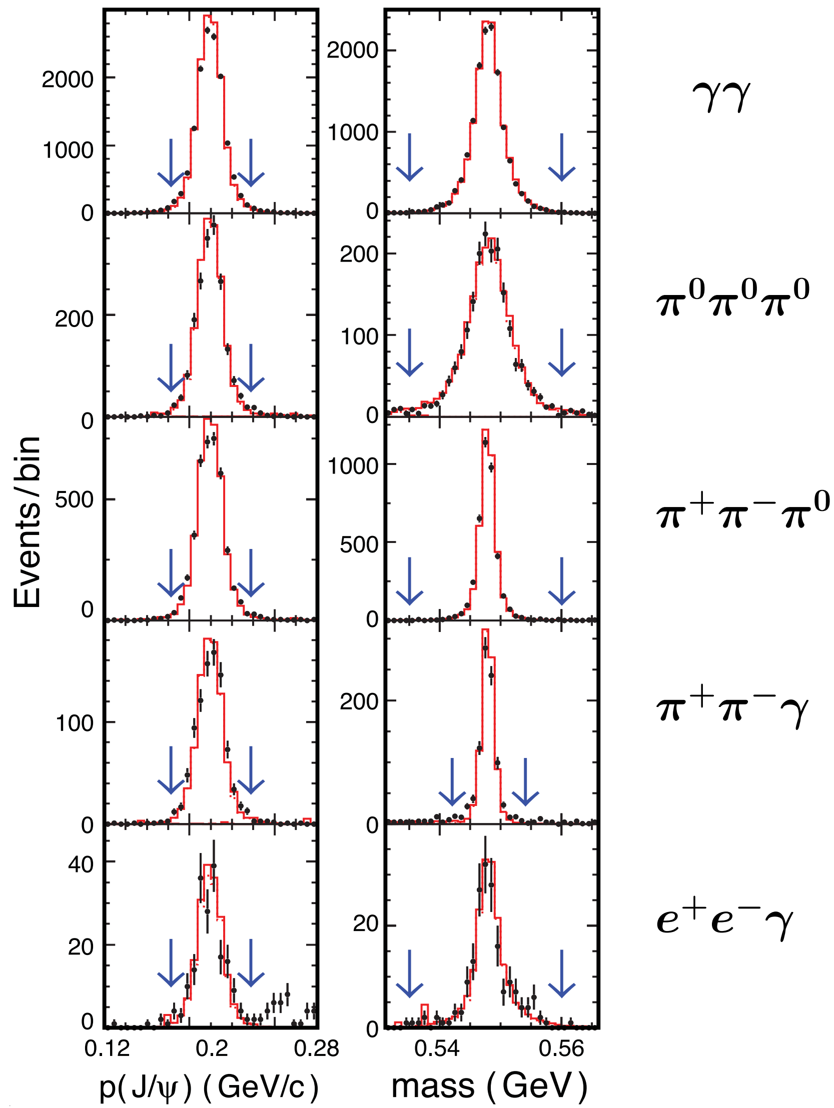
Reinforces interpretation of $\psi(3770)$ as primarily a $^3D_1$ $c\bar{c}$ state

Measuring Key η Branching Fractions

PDG 06 gets η branching fractions from 43 measurements from many experiments

- CLEO measures the most important branching fractions using $\psi(2S) \to \eta J/\psi$
- 27 M $\psi(2S)$ events
  - CLEO fully reconstructs η decays to $\gamma\gamma$, $3\pi^0$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\gamma$, and $e^+e^-\gamma$
  - Covers 99.88% of the PDG 07 total
  - Includes all branching fractions of $\mathcal{O}(0.1\%)$ or more
  - Consistent measurement of branching ratios in one experiment!
  - Very clean signals
  - Reconstruct $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$
  - Kinematically constrain $J/\psi \to \ell^+\ell^-$ and $\psi(2S) \to \eta J/\psi$
    - Do not constrain to the η mass

Kinematic Cuts | Mode



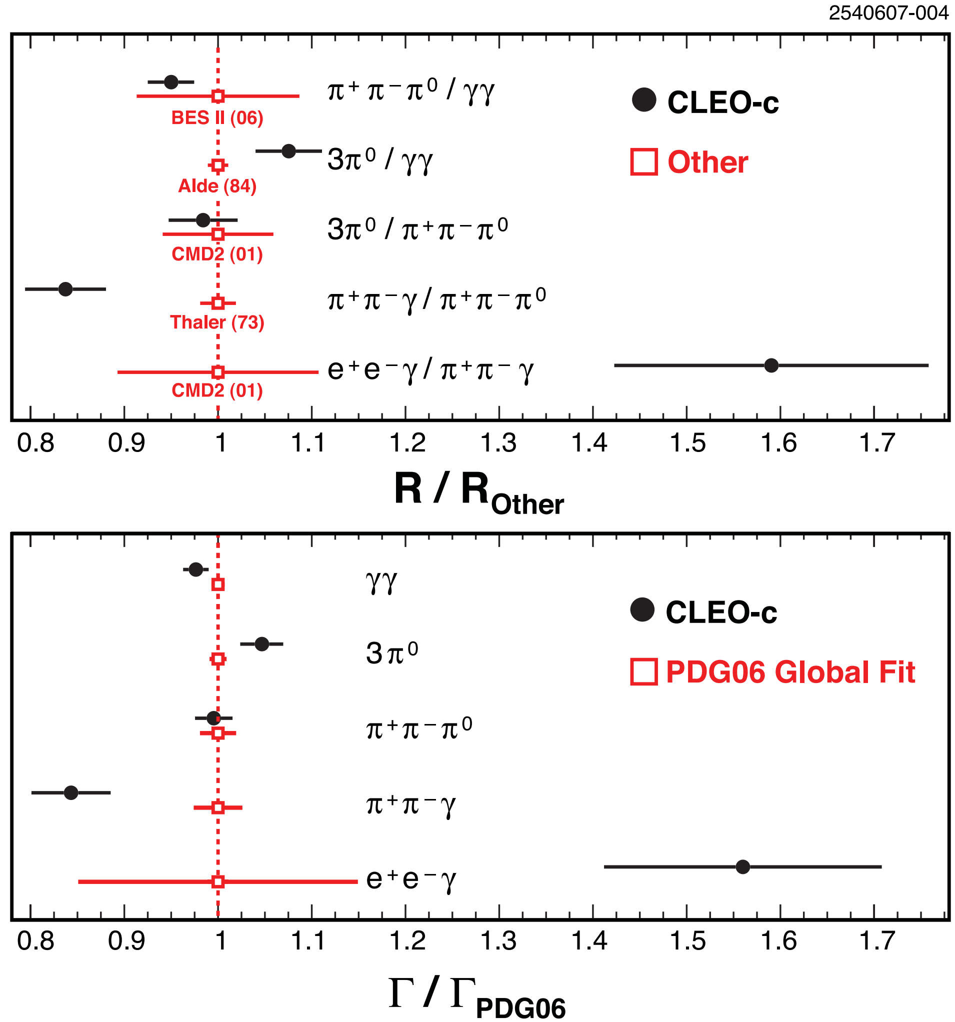
Measuring Key η Branching Fractions

Procedure

- Determine 8 branching ratios:
  - $\mathcal{B}(\pi^0\pi^0\pi^0)/\mathcal{B}(\gamma\gamma)$
    $\mathcal{B}(\pi^+\pi^-\pi^0)/\mathcal{B}(\gamma\gamma)$
    $\mathcal{B}(\pi^+\pi^-\gamma)/\mathcal{B}(\gamma\gamma)$
    $\mathcal{B}(e^+e^-\gamma)/\mathcal{B}(\gamma\gamma)$
    $\mathcal{B}(\pi^0\pi^0\pi^0)/\mathcal{B}(\pi^+\pi^-\pi^0)$
    $\mathcal{B}(\pi^+\pi^-\gamma)/\mathcal{B}(\pi^+\pi^-\pi^0)$
    $\mathcal{B}(e^+e^-\gamma)/\mathcal{B}(\pi^+\pi^-\pi^0)$
    $\mathcal{B}(e^+e^-\gamma)/\mathcal{B}(\pi^+\pi^-\gamma)$
  - Many systematic errors cancel
- Find individual branching fractions assuming that these 5 branching fractions add to 100%

Phys. Rev. Lett. 99, 122001 (2007)

Comparison to other measurements

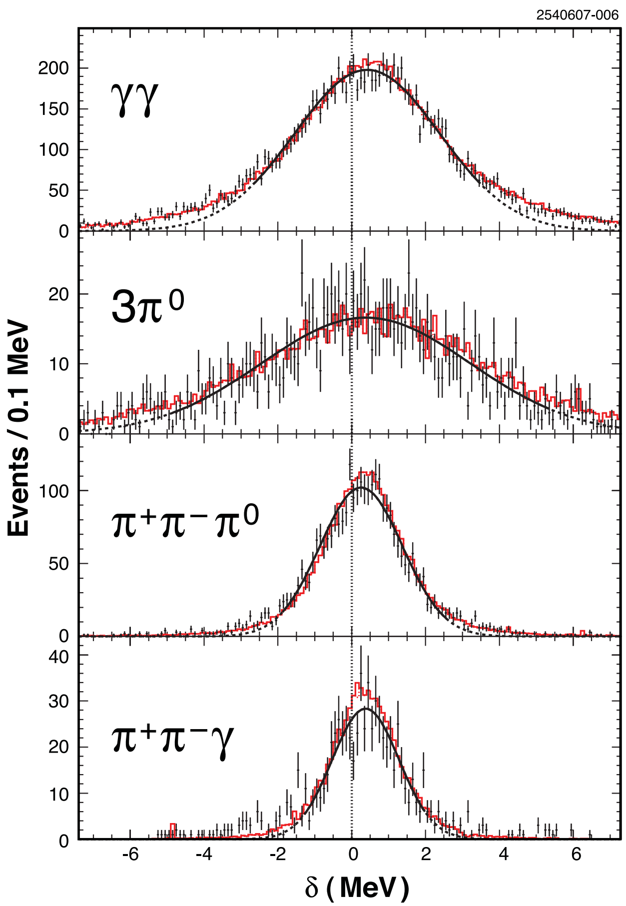


Measurement of the η Mass Using $\psi(2S) \rightarrow \eta J/\psi$

Prompted by disagreement: GEM (2005) differs from NA48 (2002) & KLOE (2006)
All three measurements have small quoted errors

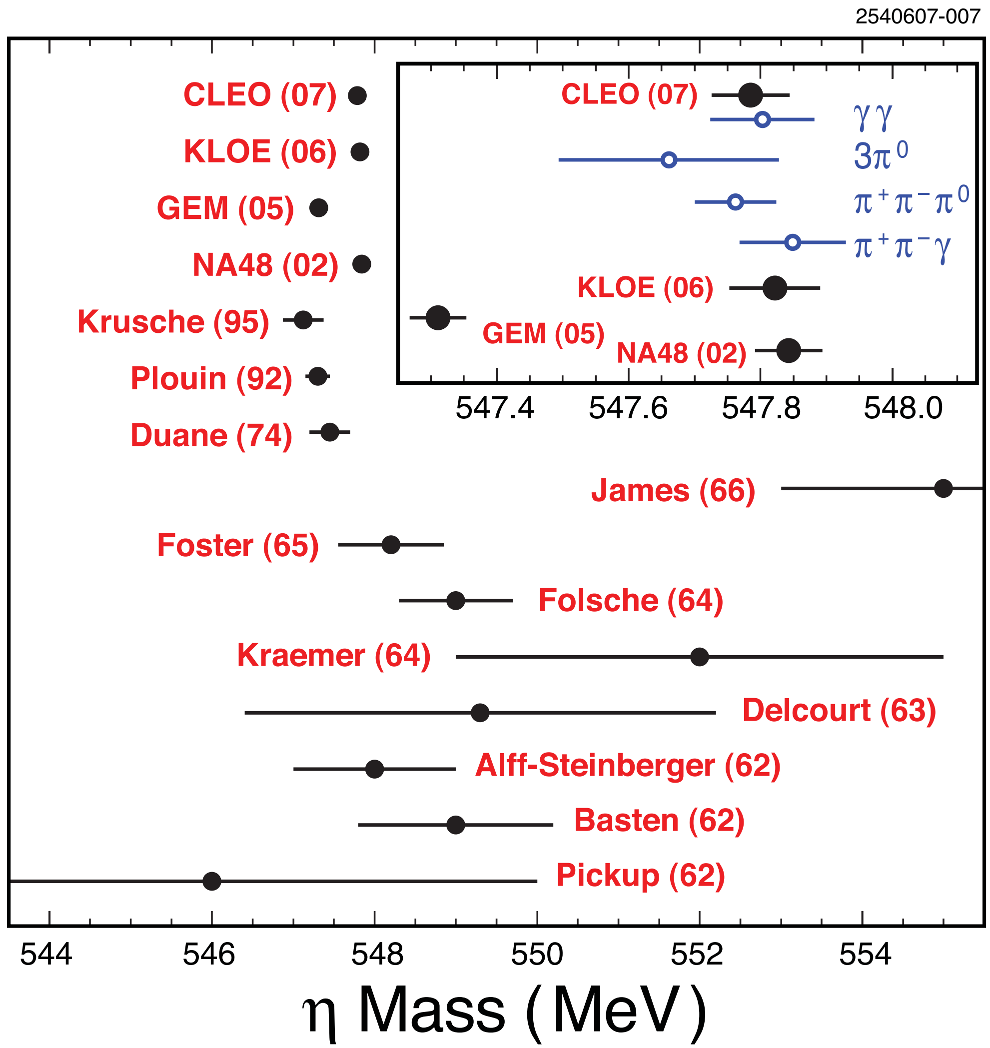
- CLEO: $M_\eta = 557.785 \pm 0.017 \pm 0.057$ MeV$/c^2$

$\delta \equiv M(CLEO) - M(PDG\ 06)$



Phys. Rev. Lett. 99, 122002 (2007)

Comparison to other measurements



$X(3872)$ and the Mass of the D^0

$X(3872)$ discovered by Belle may be a loosely bound $D^0\bar{D}^{*0}$ state

- Binding energy from PDG 06
  $E_B = M(D^0) + M(\bar{D}^{*0}) - M(X(3872)) = -0.9 \pm 2.1$ MeV ($E_B < 0$ means bound)
- Clearly more precision required
- $M(D^0)$ error significant

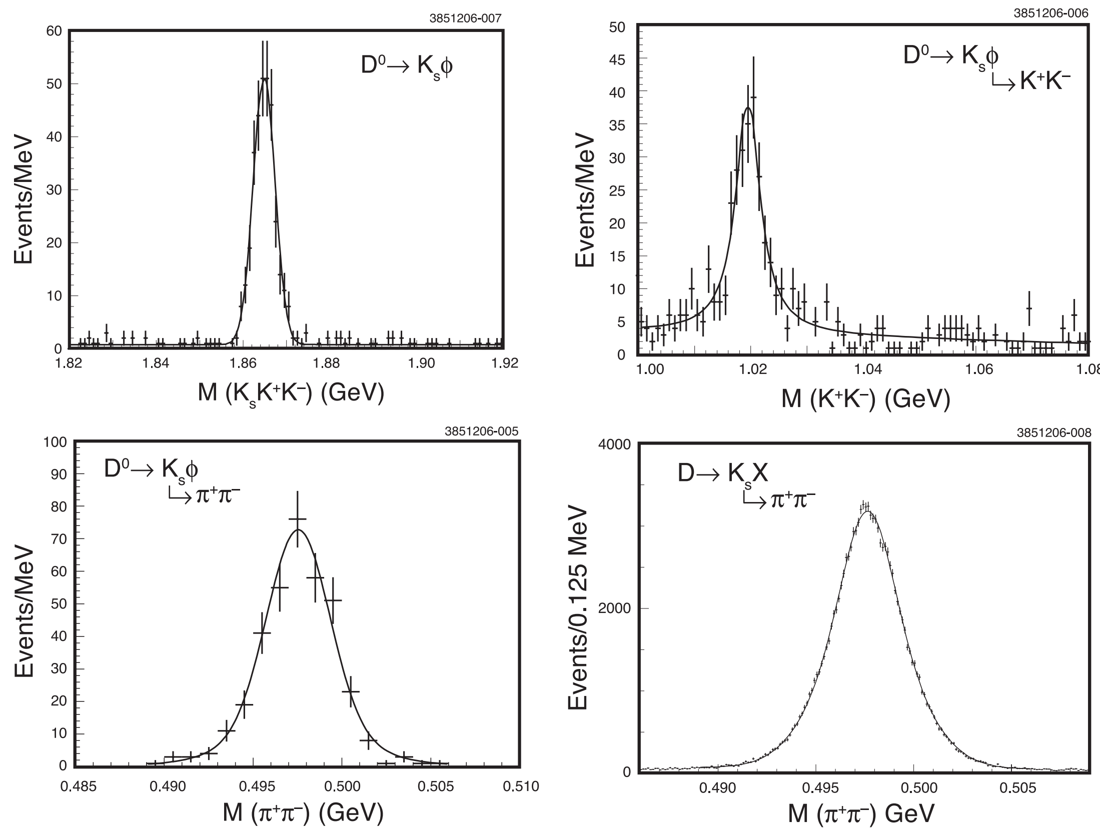
Measure $M(D^0)$ using
$D^0 \to K_S^0\phi$
Advantages:

- $M(K_S^0)$ and $M(\phi)$ well measured
- Beam energy not important
- Daughter momenta small
- Kinematic constraints
- Large $D^0\bar{D}^0$ data sample

$M(D^0) =$
$1864.847 \pm 0.150 \pm 0.095$ MeV$/c^2$

$X(3872)$: $E_B = 0.6 \pm 0.6$ MeV
Need more precise value of
$M_{X(3872)}$

$D^0 \to K_S^0\phi$ data



Summary and Conclusions

CLEO-c is changing the precision and sensitivity landscape of charm measurements
$\psi(3770) \to D\bar{D}$ events are very clean with little background

- 281 pb^{-1} results for D^0 and D^+ hadronic branching fractions limited by systematic errors
  - Cabibbo Favored decay errors $\lesssim 3\%$
  - Some improvement with more data may be possible
  - Final State Radiation must be considered carefully – effects $\sim 1\% - 3\%$
- 281 pb^{-1} Preliminary results $\mathcal{B}(D \to K(\pi)e\nu)$ and form factors
  - Beginning to challenge QCD form-factor calculations
- 281 pb^{-1} results for f_D from $D^+ \to e^+\nu$ decays are challenging QCD calculations

Absolute measurements of D_s branching fractions using $D_s\bar{D}_s^*$ events at $E_{cm} = 4170$ MeV

- 298 pb^{-1} Preliminary results for D_s hadronic branching fractions limited by statistical errors
  - Cabibbo Favored decay errors as low as small as 6%
  - Conventional $\mathcal{B}(D_s \to \phi\pi^+)$ is not well defined due to a significant scalar contribution under the ϕ peak in $M(K^+K^-)$
- 298 pb^{-1} results for f_{D_s} from $D_s \to e^+\nu$ decays are challenging QCD calculations

Expect to double data sample sizes!

Future of the Laboratory for Elementary-Particle Physics

Future – Elementary Particle Physics:

- CESR running for CLEO-c will end March 31, 2008 (as originally proposed)
  - Propose maintaining computing resources and staff for three years to complete and publish CLEO-c physics analyses
- The Cornell elementary particle physics group joined CMS as a single group
  - At varying rates and levels, Cornell faculty and research associates are shifting their principal research effort to CMS
- There is a TPC R&D effort for the ILC

Future – Accelerator Physics:

- Continue R&D on superconducting RF for the ILC
- Ongoing studies of ILC accelerator dynamics
- Propose to use CESR for ILC damping ring studies
- R&D is underway for an Energy Recovery Linac (ERL) as a fourth-generation synchrotron radiation source
  - NSF funds for R&D for the low emittance source
    most challenging component
  - NYS funds for construction design studies

Energy Recovery Linac Concept

Fourth Generation Synchrotron Radiation Facility