CLNS 01/1742
Revised 10/01

**CLEO-c and CESR-c:
A New Frontier of
Weak and Strong Interactions**

**CESR-c Taskforce** **CLEO-c Taskforce**

**CLEO-c Collaboration**

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Ph.D. Edinburgh 1986
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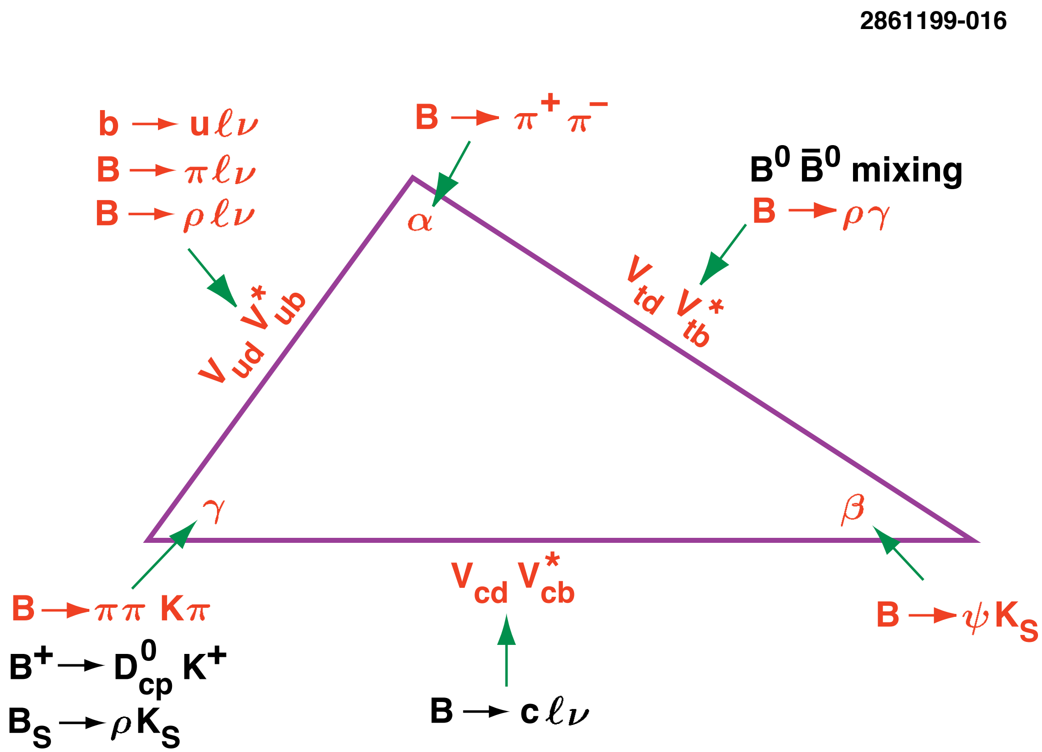
Survived a Terrible Cancer 1989
Profoundly Deaf Since 1989
Cochlear Implant 2002
CLEO-c Taskforce Co-Cordinator 2001
CLEO-c Co-Spokesperson 2001–2004

- Primary goal in Heavy Flavor Physics is understanding $CP$ violation in $b$ quarks and beyond.
- $CP$ violation in the $b$ quark system is described by the unitarity triangle.
- In principle the CKM matrix elements of the unitarity triangle can be determined by measurements of $B$ meson decays and $B^0\bar{B}^0$ mixing.
  - However theoretical uncertainties limit the ability to relate CKM matrix elements to $B$ physics measurements.



# The CESR and CLEO Program

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From 1979 to 2000 the CESR $e^+e^-$ collider and CLEO detectors enabled a highly productive program of $\Upsilon$ and $B$ research at the frontier of heavy quark physics.

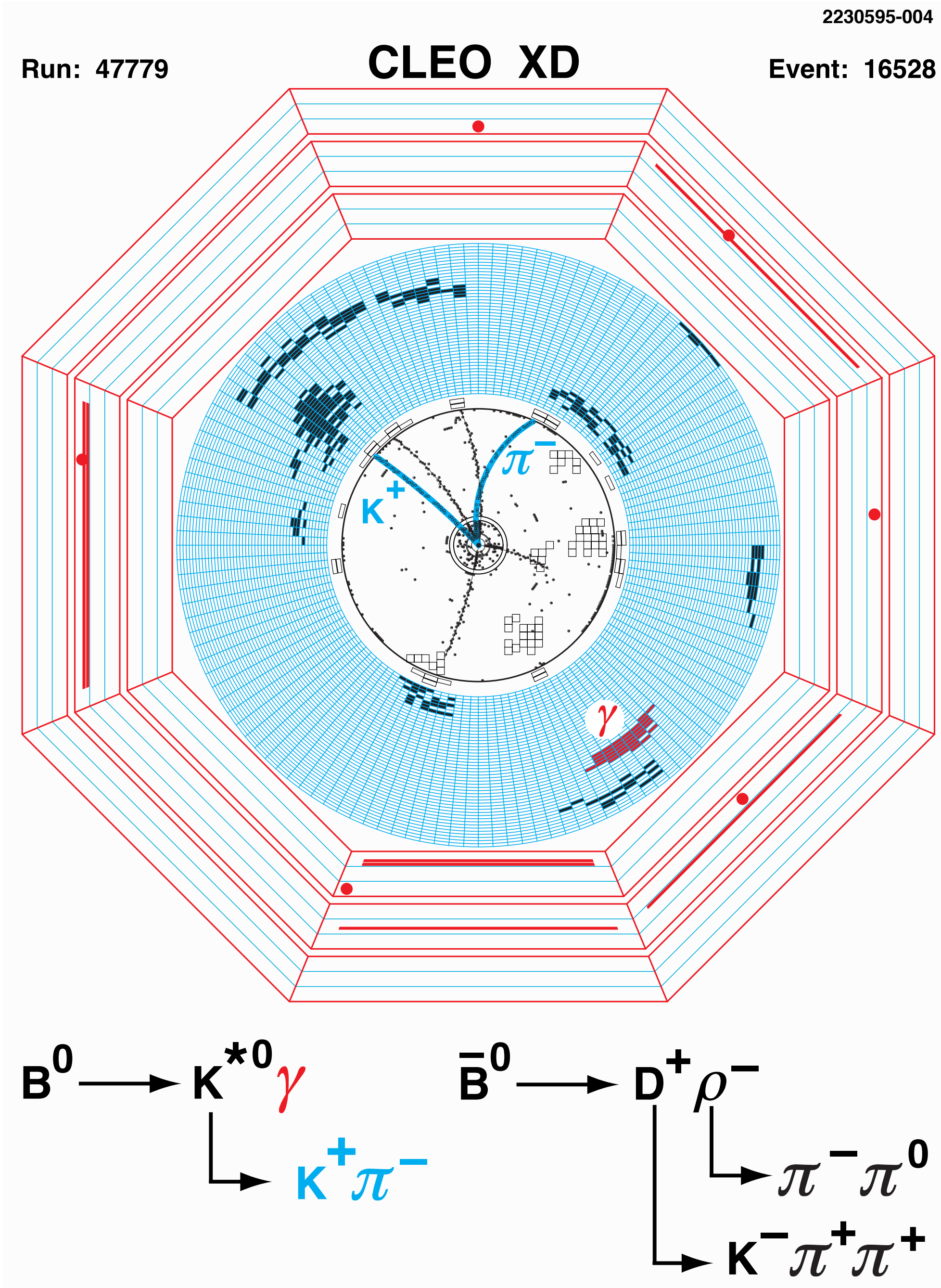
- Successive CESR upgrades improved luminosity from $10^{30}$ cm$^{-2}$s$^{-1}$ to $10^{33}$ cm$^{-2}$s$^{-1}$
  - Many $e^+e^-$ collider luminosity records during that period
- A sequence of CLEO detectors, CLEO I, CLEO II, CLEO II.V, and CLEO III were built with successive improvements resulting in excellent: charged particle tracking, charged particle identification, photon detection, and muon tracking.

## Some Highlights of the CESR/CLEO Program

- Confirm that the $\Upsilon(3S)$ is narrow *
- $\Upsilon(4S)$ discovery *
- Increase of $e$ and $\mu$ rates at the $\Upsilon(4S)$ *
  Implied new $b$ quark flavor and $B$ mesons
- Discovery of $\Upsilon(5S)$ and $\Upsilon(6S)$ *
- $b \to c\ell\nu$ decays discovery and measurements
  Exclusive $b \to c\ell\nu$ decays
- $b \to u\ell\nu$ decays discovery and measurements **
  Exclusive $b \to u\ell\nu$ decays
- Discovery of $B \to K^*\gamma$ photon penguin decays
- Discovery of $B \to K\pi$ & $B \to \pi\pi$ gluon penguins
- Measurement of inclusive $b \to s$ decays
- $D_s$ discovery
- Discovery and measurement of many $B$ meson decays
- Discovery of $B^0 \to J/\psi K^0$ decays
- Discovery of 11 charm baryons
- Discovery of the $\Upsilon(1D)$
- Discovery of $\pi\pi$ transitions among $\Upsilon$s
- Discovery of $\chi_{b\,1\&2} \to \omega\Upsilon(1S)$ and $\Upsilon(2S) \to \eta\Upsilon(1S)$
- Confirmed the ARGUS discovery of $B^0\bar{B}^0$ mixing
- $D_{s1}(2460)$ discovery and $D^*_{s0}(2317)$ confirmation
- Resolved discrepancies between inclusive and exclusive $\tau$ decay measurements

Independently observed by CUSP * or ARGUS **

$B^0 \to K^{*0}\gamma$ Event



# The CESR and CLEO Program

- By 2000 the luminosity of the PEP-II and KEKB asymmetric $e^+e^-$ colliders had overtaken that of CESR, so reconsideration of the CESR and CLEO programs was necessary.
- It was widely understood that physics of the charm sector had essentially been abandoned in the race to build higher-energy colliders.
  - Known exclusive $D$ decays were a fraction of the totals.
  - Branching fraction uncertainties were significant.
  - Accurate $B$ decay measurements were often limited by $D$ decay measurements.
  - This realization led to thoughts of a CESR/CLEO program in the charm region, but a sufficient physics motivation was missing.
- Two events provided the physics motivation:
  - Word came from Peter Lapage that a workshop he was hosting at Cornell concluded that calculations of $D$ meson decay parameters were on the verge of enough precision that meaningful comparisons between theory and experiment would be possible. However substantial progress in experimental precision was necessary. That had an immediate and positive impact on our thinking about the value of an experimental program in the charm threshold region.
  - Marina Artuso produced an internal CLEO report that described the potential for a productive charm physics program with the CLEO III detector and high luminosity produced from CESR.

These motivations led to the creation of:

- A CLEO-c Task Force coordinated by Marina Artuso and Ian Shipsey
  - Report author list included Peter Lepage and Aida El-Khadra who provided theoretical insight
- A CLEO-c Task Force coordinated by David Rice
  - Cornell CESR physicists

Taskforce studies led to 6 areas of research with significant opportunities and goals:

- Leptonic Charm Decays: $D^+ \to \ell^+\nu$ and $D_s^+ \to \ell^+\nu$
  - Comparing precision measurements of $f_D$ and $f_{D_s}$ to LQCD calculations, can constrain or validate the LQCD calculations of $f_B$ and $f_{B_s}$ required to extract $|V_{td}|$ and $|V_{ts}|$ from $B\bar{B}$ mixing measurements
- Semileptonic Decays of Charmed Mesons: $D \to (K, K^*)\ell\nu$, $D \to (\pi, \rho)\ell\nu$ ...
  - Semileptonic decays are the primary source of information for the CKM matrix elements $|V_{ub}|$, $|V_{cb}|$, $|V_{cd}|$, and $|V_{cs}|$. Measurements of form factors in $D$ decays can constrain or validate models (such as HQET) for these form factors in $B$ decay.
- Hadronic Decays of Charmed Mesons: $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to K^+K^-\pi^+$ ...
  - Many important $B$ meson decays involve decays to $D$ mesons, so accurate $B$ branching fraction measurements require precise absolute measurements of the branching fractions of intermediate $D$ decay modes.

Proposed Physics for the CESR-c and CLEO-c Program

- Rare Decays, $D\bar{D}$ Mixing, and CP Violating Decays
  - The proposed program includes data and detector capability for precision measurements of $D^0\bar{D}^0$ mixing parameters, searches for rare decays with branching fractions of order $10^{-6}$ and searches for violations of $CP$ of order 1% in $D$ decays.
- Quarkonia and QCD
  - $\psi(2S)$ data will provide precision measurements of bound $c\bar{c}$ states for comparison with LQCD and other theoretical calculations.
- Spotchecks of $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$
  - These measurements with precision of a few %, will supplement the BES measurements and find the optimal energy for production of $D_s^+D_s^-$ events.

Realization of this CESR-c and CLEO-c Program required:

- For CLEO-c, an upgrade of the CLEO III detector to optimize it for detection and measurement of decay products of $c$ quark decay, whose momenta are lower than those from $b$ quark decay.
- For CESR-c, operation of CESR with beam energies between about 1.5 GeV and 2 GeV, *i.e.*, center-of-mass energies between about 3 GeV and 4 GeV.

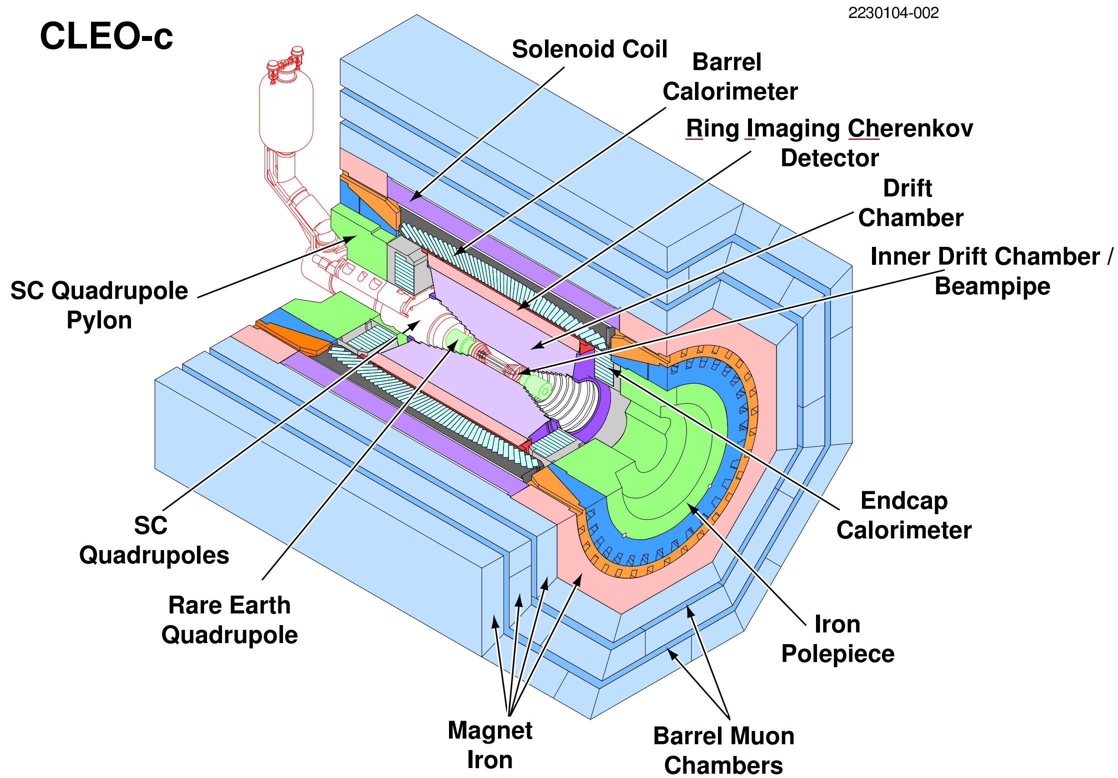
# The CLEO-c Detector

Principal modifications of the CLEO III detctor:

- Reduced the magnetic field from 1.5 T to 1 T
- Replaced the inner silicon vertex detector with a low-mass 6-layer drift chamber for $z$ measurements near the vertex

Performance:

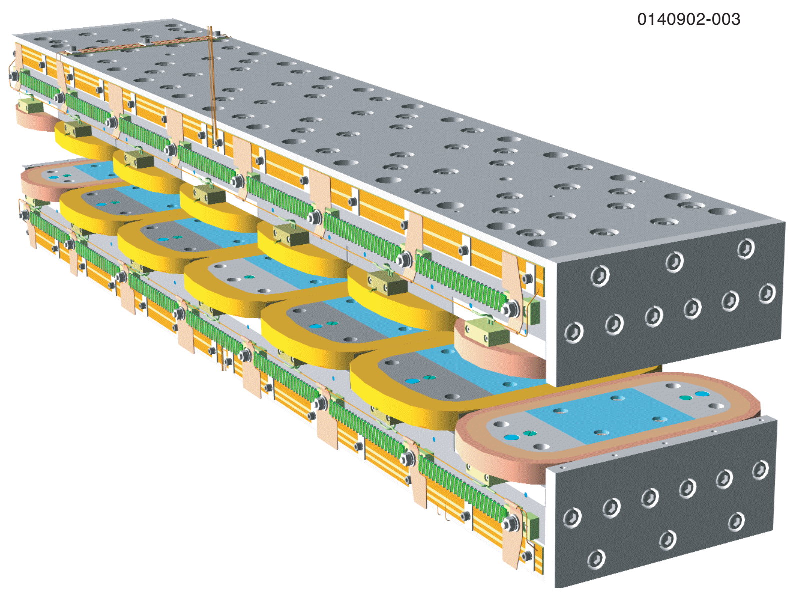
- Excellent Particle Identification ($dE/dx$ and RICH): $p < 1$ GeV$/c$ over 83% of $4\pi$
- Tracking: $\sigma_p/p = 0.6\%$ at $p = 1$ GeV$/c$
- CsI Calorimeter: $\sigma_E/E = 6\%$ at $E_\gamma = 100$ MeV and 2.2% at 1 GeV



# The CESR-c Upgrade

Serious CESR upgrades were required for high performance at charm energies.

- Synchrotron radiation provides essential beam damping.
  - At lower energies, synchrotron radiation would be reduced leading to damping times for beams after injection that would be far too long.
  - This was mitigated by the installation of 12 multipole damping magnets.
- Additional beam dynamics issues had to be addressed.
- Energies of synchrotron radiation x-rays were too low to be useful for CHESS experiments.
  - Dedicated beam time at 5.3 GeV for the CHESS program was required, which reduced total CLEO-c luminosity by at least a factor of 2.
  - Additional instrumentation facilitated transitions between the two energies.



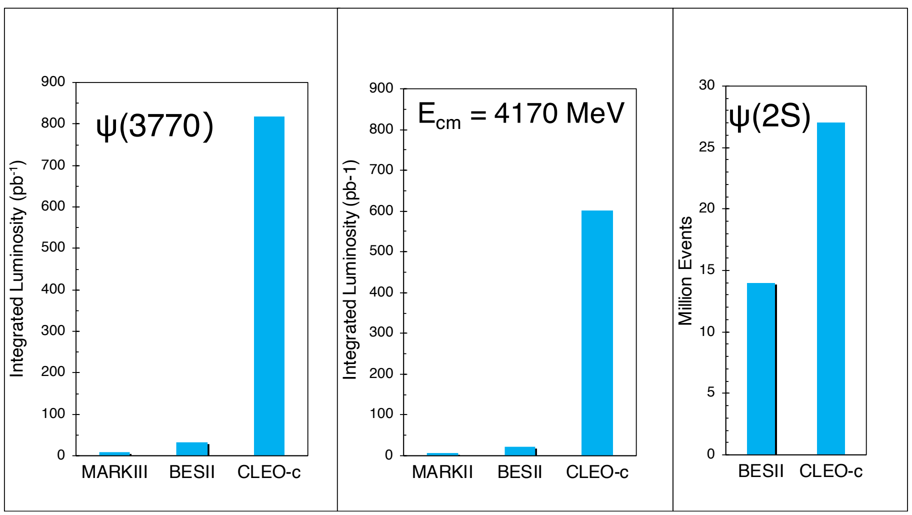
# CLEO-c Data Samples

Most CLEO-c data were taken at:

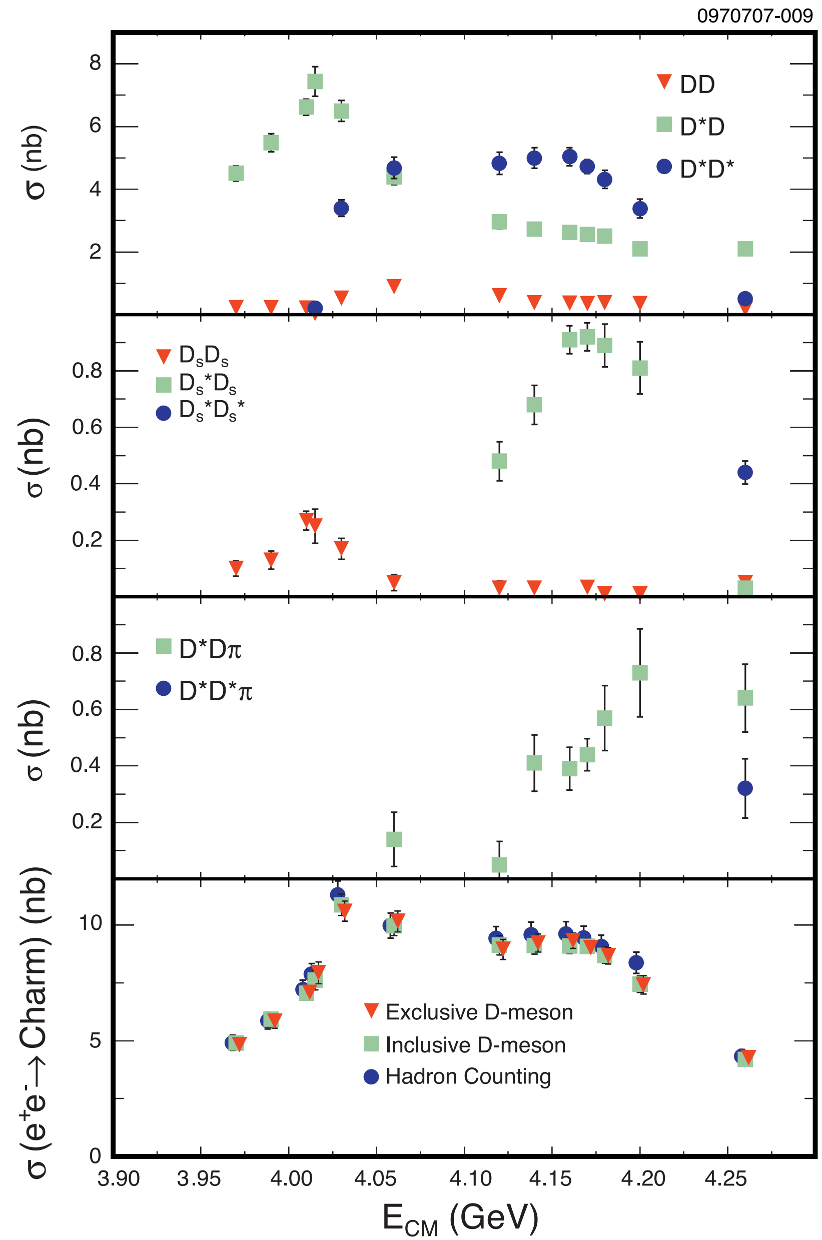
- $\psi(3770)$ that decays primarily to $D\bar{D}$
- $E_{cm} = 4170$ MeV, for $D_s\bar{D}_s^*$ events
- $\psi(2S)$

Additional data were take in energy scans

Some key $D$ measuremnts were published multiple times utilizing successively 56 $\text{pb}^{-1}$, 281 $\text{pb}^{-1}$, and 818 $\text{pb}^{-1}$ data samples



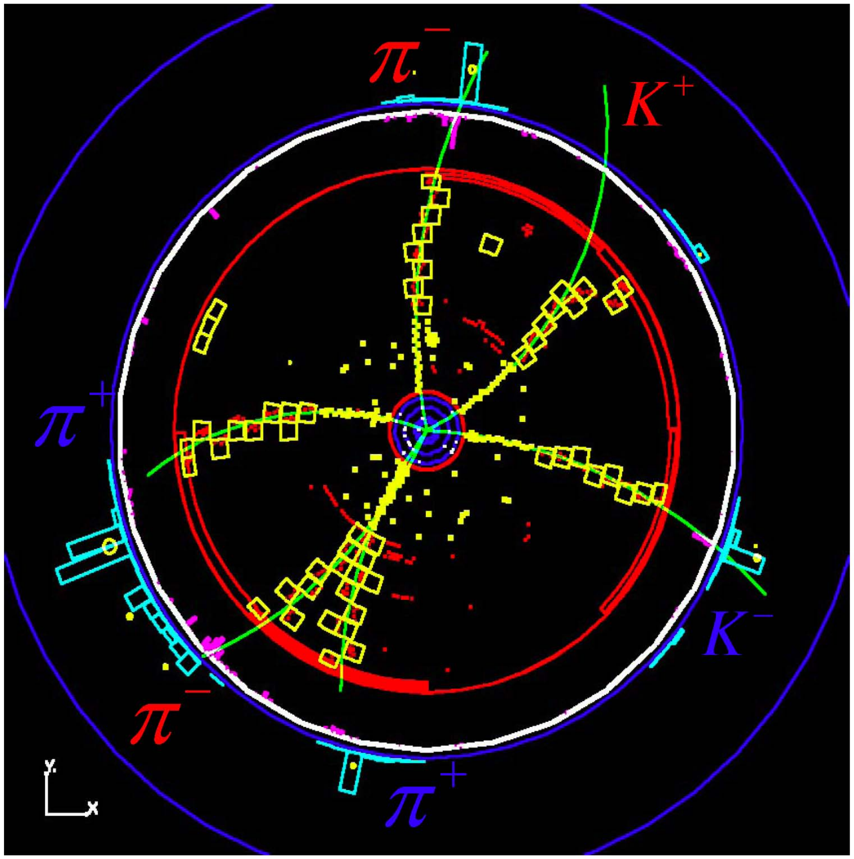

## Energy Scans



# $e^+e^- \to \psi(3770) \to D\bar{D}$ 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 measured leptonic, semileptonic, and key hadronic branching fractions with a double tagging technique
  - Other branching fractions were usually measured relative to a reference mode, generally $D^0 \to K^-\pi^+$ or $D^+ \to K^-\pi^+\pi^+$

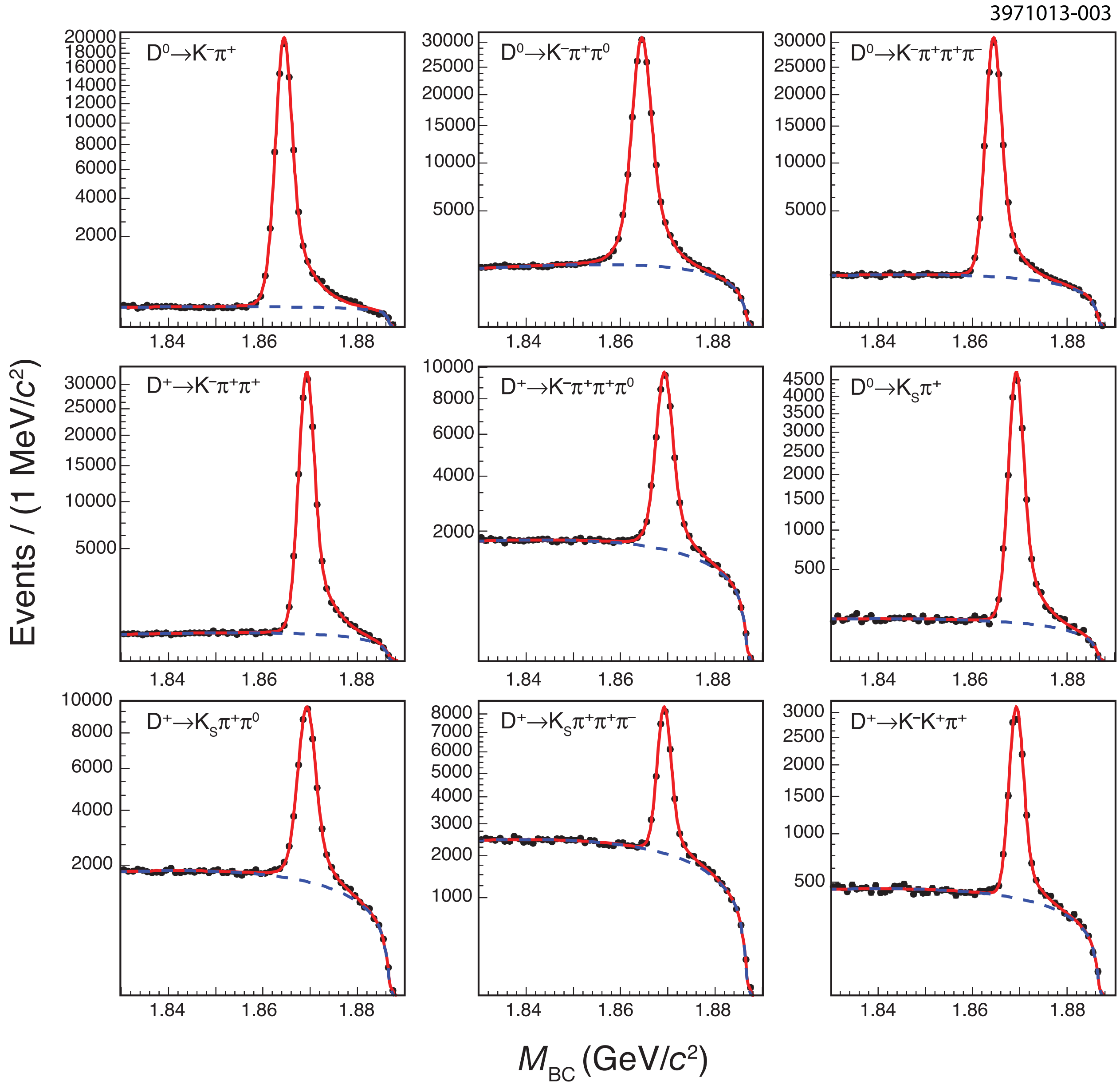
# Absolute $D^0$ and $D^+$ Hadronic Branching Fractions

We utilized 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 $N_{D\bar{D}}$
    $\mathcal{B}_i = \frac{y_{i\bar{j}}}{y_{\bar{j}}}\frac{\epsilon_{\bar{j}}}{\epsilon_{i\bar{j}}}$ and $N_{D\bar{D}} = \frac{y_i y_{\bar{j}}}{y_{i\bar{j}}}\frac{\epsilon_{i\bar{j}}}{\epsilon_i\epsilon_{\bar{j}}}$
  - $\epsilon_{i\bar{j}} \approx \epsilon_i\epsilon_{\bar{j}}$ so $\mathcal{B}_i$ is nearly independent of efficiencies for $\bar{j}$.
  - Branching fraction values independent of luminosity or $N_{D\bar{D}}$ measurements.
  - Did a $\chi^2$ 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)

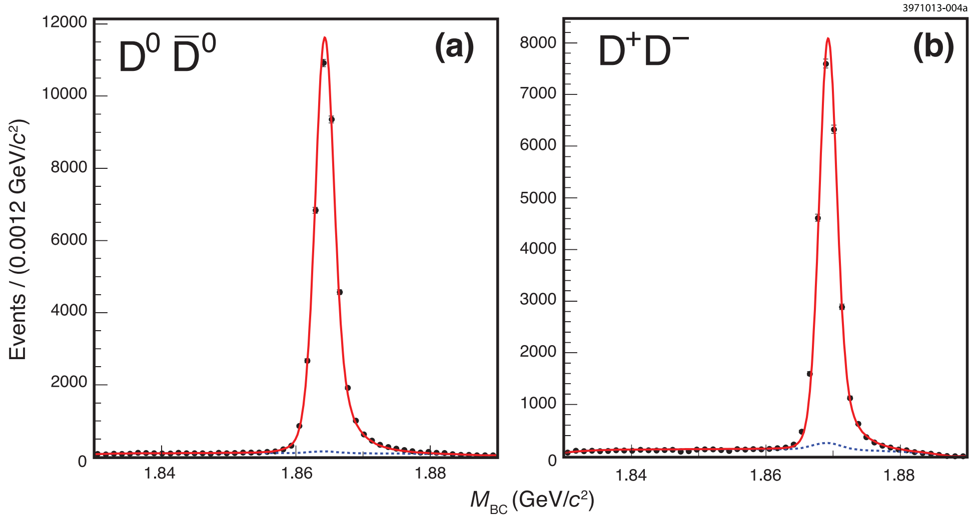
# Single Tag $D^0$ and $D^+$ Data

## All Single Tags: Square Root Scales



# Double Tag $D^0$ and $D^+$ Data

## All Double Tags




| Branching Fraction | Fitted value | Fractional error Stat.(%) | Syst.(%) |
|---|---|---|---|
| $\mathcal{B}(D^0 \to K^-\pi^+)$ | $(3.934 \pm 0.021 \pm 0.061)\%$ | 0.5 | 1.5 |
| $\mathcal{B}(D^0 \to K^-\pi^+\pi^0)$ | $(14.956 \pm 0.074 \pm 0.335)\%$ | 0.5 | 2.2 |
| $\mathcal{B}(D^0 \to K^-\pi^+\pi^+\pi^-)$ | $(8.287 \pm 0.043 \pm 0.200)\%$ | 0.5 | 2.4 |
| $\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$ | $(9.224 \pm 0.059 \pm 0.157)\%$ | 0.6 | 1.7 |
| $\mathcal{B}(D^+ \to K^-\pi^+\pi^+\pi^0)$ | $(6.142 \pm 0.045 \pm 0.154)\%$ | 0.7 | 2.5 |
| $\mathcal{B}(D^+ \to K^0_S\pi^+)$ | $(1.578 \pm 0.013 \pm 0.025)\%$ | 0.8 | 1.6 |
| $\mathcal{B}(D^+ \to K^0_S\pi^+\pi^0)$ | $(7.244 \pm 0.053 \pm 0.166)\%$ | 0.7 | 2.3 |
| $\mathcal{B}(D^+ \to K^0_S\pi^+\pi^+\pi^-)$ | $(3.051 \pm 0.027 \pm 0.082)\%$ | 0.9 | 2.7 |

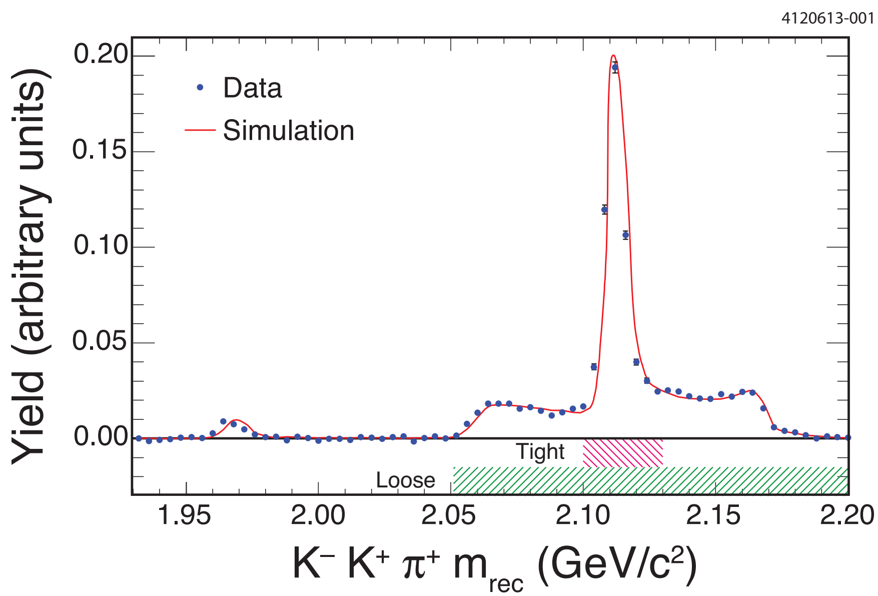
$$\sigma(e^+e^- \to D^0\bar{D}^0) = (3.607 \pm 0.017 \pm 0.056)\ \text{nb}$$
$$\sigma(e^+e^- \to D^+D^-) = (2.882 \pm 0.018 \pm 0.042)\ \text{nb}$$

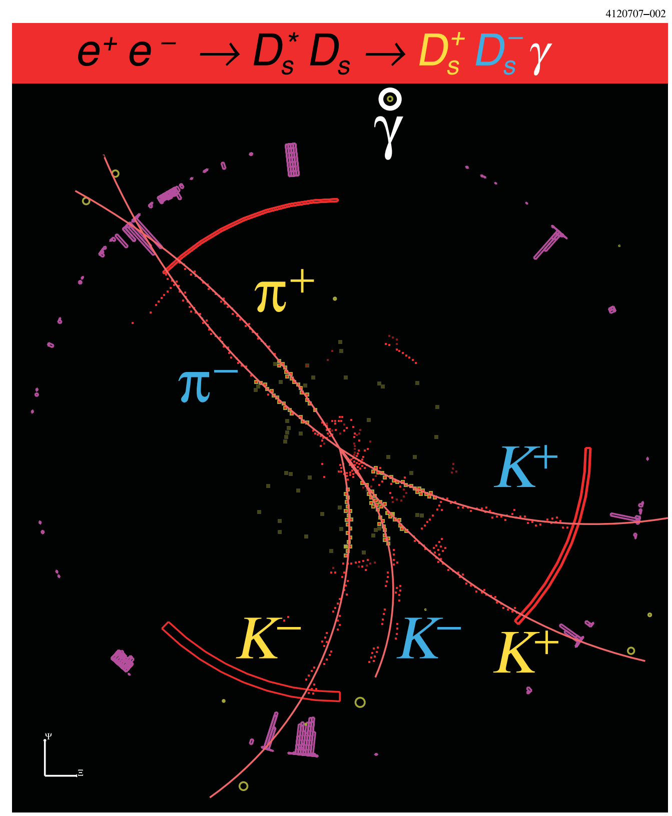
# Absolute $D_s$ Branching Fractions

Data for measuring absolute $D_s$ branching fractions were collected at $E_{cm} = 4.17$ Gev.

- 4.17 GeV is above the threshold for $D_s^+ D_s^-$ but below the threshold for $D_s^{\pm} D K$
    - So all events with a $D_s^{\pm}$ must contain a $D_s^{\mp}$ enabling use of the double tag technique

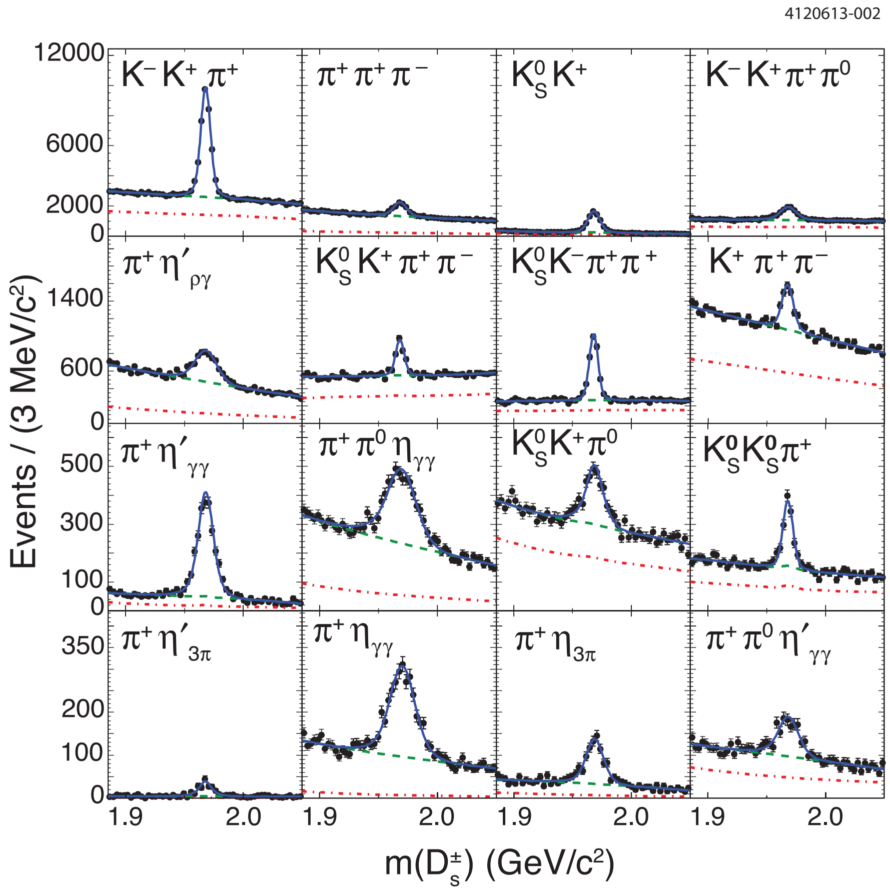
- 4.17 GeV is above the threshold for $D_s^{\pm} D_s^{*\mp}$
    - So $D_s$ events must be either $D_s^+ D_s^-$ or $D_s^{\pm} D_s^{*\mp}$
    - $D_s^{\pm} D_s^{*\mp}$ dominates so most $D_s$ events are $D_s^{\pm} D_s^{\mp}(\gamma, \pi^0)$
        - Wide $m_{\text{rec}}$ peak for $D_s^{\pm}$ from $D_s^{*\pm}$
        - Narrow $m_{\text{rec}}$ peak for $D_s^{\pm}$ not from $D_s^{*\pm}$
        - Both peaks are well understood



# Absolute $D_s$ Branching Fractions

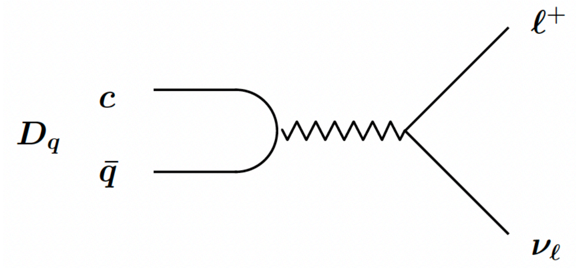
## Double Tag $D_s^{\pm} D_s^{\mp}$ Mass Distributions




## $D_s^{\pm}$ Branching Fractions

| Mode | This result $\mathcal{B}$ (%) | PDG 2012 fit $\mathcal{B}$ (%) |
|---|---|---|
| $K_S^0 K^+$ | $1.52 \pm 0.05 \pm 0.03$ | $1.48 \pm 0.08$ |
| $K^- K^+ \pi^+$ | $5.55 \pm 0.14 \pm 0.13$ | $5.49 \pm 0.27$ |
| $K_S^0 K^+ \pi^0$ | $1.52 \pm 0.09 \pm 0.20$ | — |
| $K_S^0 K_S^0 \pi^+$ | $0.77 \pm 0.05 \pm 0.03$ | — |
| $K^- K^+ \pi^+ \pi^0$ | $6.37 \pm 0.21 \pm 0.56$ | $5.6 \pm 0.5$ |
| $K_S^0 K^+ \pi^+ \pi^-$ | $1.03 \pm 0.06 \pm 0.08$ | $0.96 \pm 0.13$ |
| $K_S^0 K^- \pi^+ \pi^+$ | $1.69 \pm 0.07 \pm 0.08$ | $1.64 \pm 0.12$ |
| $\pi^+ \pi^+ \pi^-$ | $1.11 \pm 0.04 \pm 0.04$ | $1.10 \pm 0.06$ |
| $\pi^+ \eta$ combined | $1.67 \pm 0.08 \pm 0.06$ | $1.83 \pm 0.15$ |
| $\pi^+ \eta_{\gamma\gamma}$ | $1.75 \pm 0.08 \pm 0.16$ | — |
| $\pi^+ \eta_{3\pi}$ | $1.63 \pm 0.12 \pm 0.06$ | — |
| $\pi^+ \pi^0 \eta$ | $9.2 \pm 0.4 \pm 1.1$ | $8.9 \pm 0.8$ † |
| $\pi^+ \eta'$ combined | $3.94 \pm 0.15 \pm 0.20$ | $3.94 \pm 0.33$ |
| $\pi^+ \eta'_{\gamma\gamma}$ | $4.07 \pm 0.17 \pm 0.30$ | — |
| $\pi^+ \eta'_{3\pi}$ | $3.7 \pm 0.5 \pm 0.2$ | — |
| $\pi^+ \eta'_{\rho\gamma}$ | $3.91 \pm 0.17 \pm 0.33$ | — |
| $\pi^+ \pi^0 \eta'$ | $5.6 \pm 0.5 \pm 0.6$ | $12.5 \pm 2.2$ † |
| $K^+ \pi^+ \pi^-$ | $0.654 \pm 0.033 \pm 0.025$ | $0.69 \pm 0.05$ |

# Leptonic $D$ Decays and $D$ Meson Decay Constants




A factor $f_{D_q}|V_{cq}|^2$ occurs in the decay amplitude for the $c\bar{q}W$ vertex

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

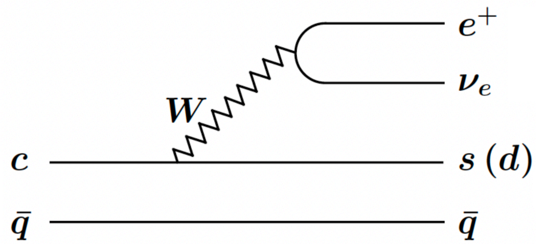
$$\Gamma(D_q^+ \to \ell^+\nu_\ell) = \frac{1}{8\pi} G_F^2 M_{D_q}\, m_\ell^2 \left(1 - \frac{m_\ell^2}{M_{D_q}^2}\right) |f_{D_q}|\ |V_{cq}|^2$$

- Measurements of $\mathcal{B}(D^+ \to \ell^+\nu_\ell)$ and $\mathcal{B}(D_s^+ \to \ell^+\nu_\ell)$
  Determine $f_D|V_{cd}|^2$ and $f_{D_s}|V_{cs}|^2$
- We can measure $f_{D_q}|V_{cq}|^2$ and use values of $|V_{cq}|$ from unitarity to get $f_{D_q}$
  - $f_D$ and $f_{D_s}$ measurements can constrain and validate LQCD calculations of $f_B$

CLEO-c results:

- $f_D = (205.8 \pm 8.5 \pm 2.5)$ MeV
- $f_{D_s} = (263.3 \pm 8.2 \pm 3.9)$ MeV

# Exclusive Semileptonic $D$ Decays

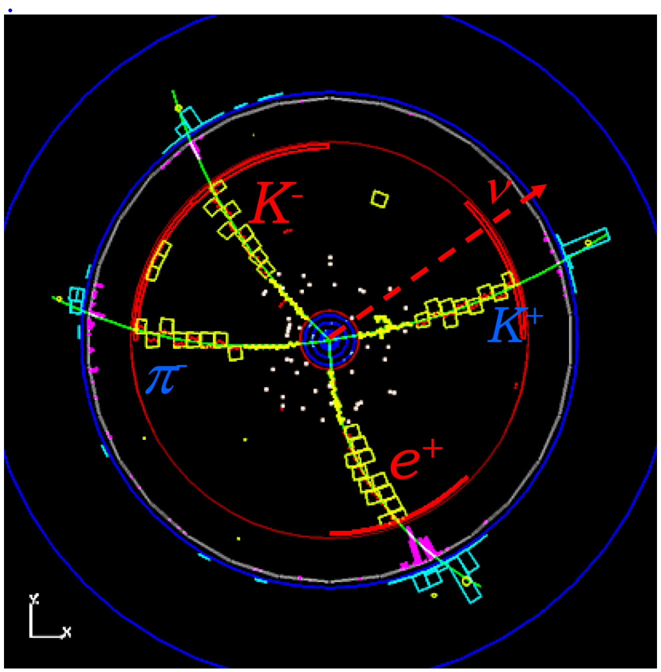



CLEO-c Measured:
$\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)$
$\mathcal{B}(D^0 \to K^- e^+ \nu_e)$
$\mathcal{B}(D^+ \to \pi^0 e^+ \nu_e)$
$\mathcal{B}(D^+ \to K^0 e^+ \nu_e)$

- Exclusive semileptonic decay to a pseudoscalar meson $P_s$ depends on the mass-squared ($q^2$) of the virtual $W$ through a single form factor $f_{qs(d)}(q^2)$

$$\frac{\Gamma(D_q \to P_s\, \ell^+ \nu_\ell)}{dq^2} = G_F^2 \frac{p^3}{24\pi^3} |V_{cs(d)}\ f_{qs(d)}(q^2)|^2 \qquad (\times 1/2 \text{ for } \pi^0)$$

- CLEO-c measures $|V_{cs(d)} f_{qs(d)}(q^2)|$ and uses $|V_{cs(d)}|$ from unitarity to determine $|f_{qs(d)}(q^2)|$
  - Goal is to validate theories of $f_D(q^2)$ for application in the $B$ meson sector



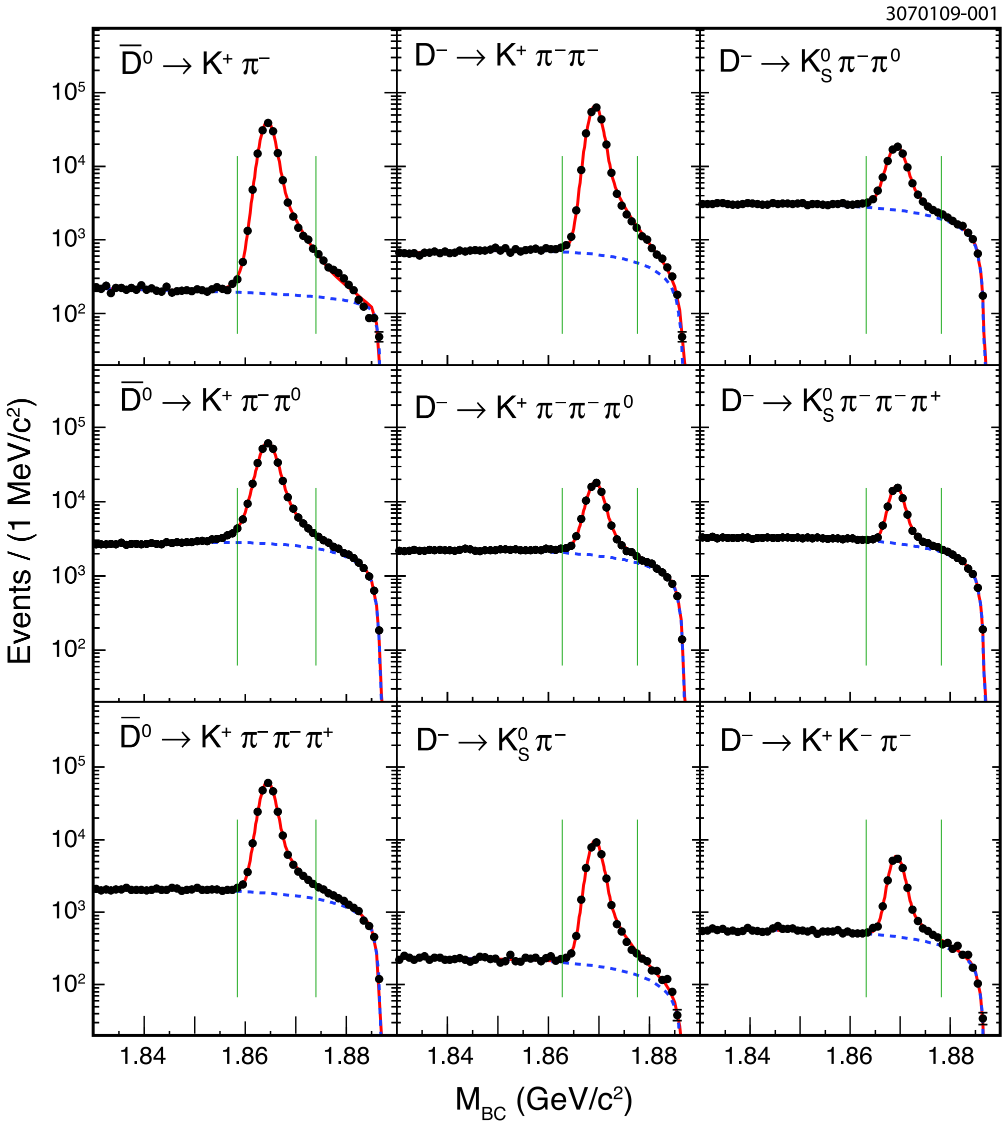

Tagged Reconstruction

- Reconstruct a hadronic decay
- Measure hadrons from semileptonic decay candidate
- Calculate $E_{\text{miss}}$ and $P_{\text{miss}}$ from $E_{cm}$, $e^\pm$, and hadrons
- Subtract background using $U \equiv E_{\text{miss}} - P_{\text{miss}}$ distribution

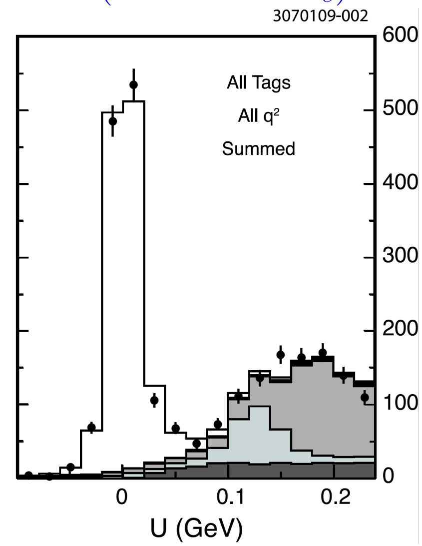
Typical Event
$\bar{D}^0 \to K^+ \pi^-$
$D^- \to K^- e^+ \nu_e$

# Exclusive Semileptonic Decay Data

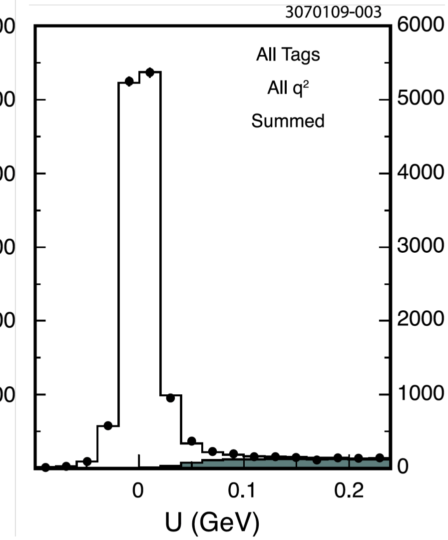
## Hadronic Tag Modes



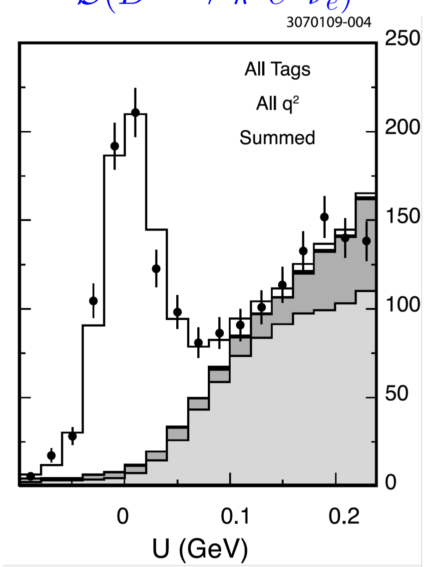

## $\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)$



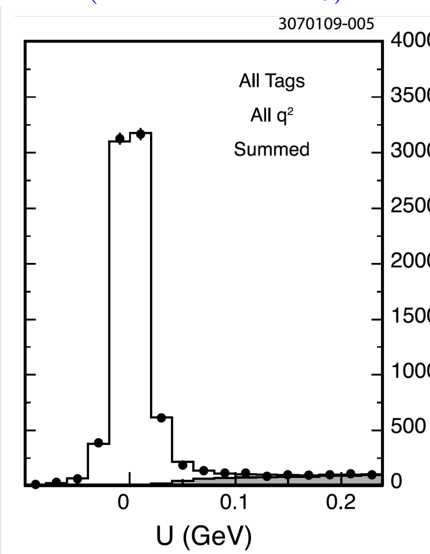

## $\mathcal{B}(D^0 \to K^- e^+ \nu_e)$




## $\mathcal{B}(D^+ \to \pi^0 e^+ \nu_e)$

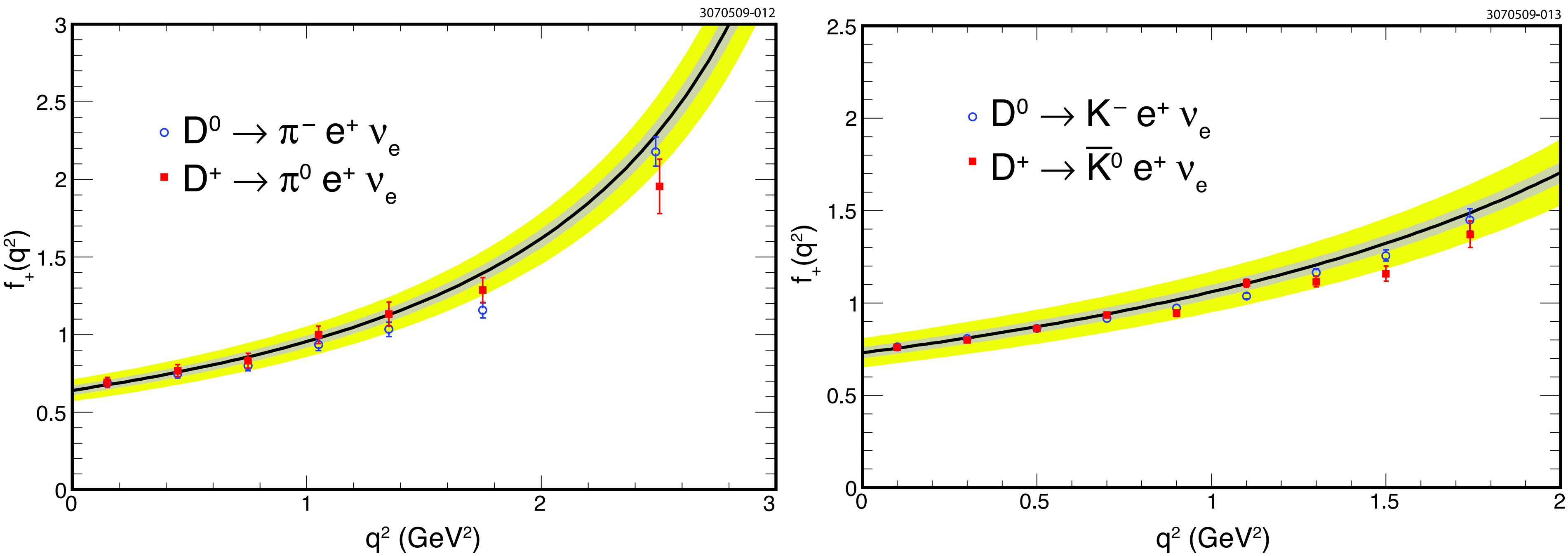



## $\mathcal{B}(D^+ \to K^0 e^+ \nu_e)$



# Exclusive Semileptonic Decay Results

$$\begin{aligned}
\mathcal{B}(D^0 \to \pi^- e^+ \nu_e) &= (0.288 \pm 0.008 \pm 0.003)\% \\
\mathcal{B}(D^0 \to K^- e^+ \nu_e) &= (3.50 \pm 0.03 \pm 0.04)\% \\
\mathcal{B}(D^+ \to \pi^0 e^+ \nu_e) &= (0.405 \pm 0.016 \pm 0.009)\% \\
\mathcal{B}(D^+ \to K^0 e^+ \nu_e) &= (8.83 \pm 0.10 \pm 0.20)\%
\end{aligned}$$




Using LQCD values of $f_D(0)$ we find

$$\begin{aligned}
|V_{cd}| &= 0.234 \pm 0.007 \pm 0.002 \pm 0.025 \\
|V_{cs}| &= 0.985 \pm 0.009 \pm 0.006 \pm 0.103
\end{aligned}$$

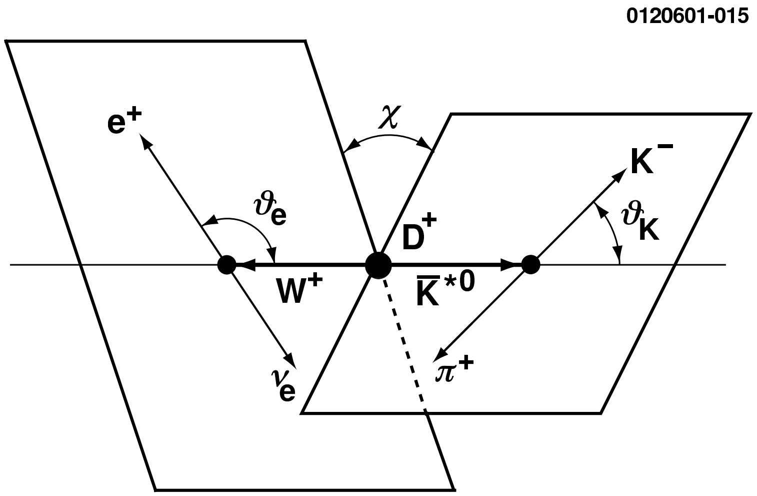
in agreement with PDG values of $|V_{cd}|$ and $|V_{cs}|$ determined from CKM unitarity.

# First Measurement of $D \to \rho\, e^+ \nu_e$ Form Factors

Decay width expressions for P to V semileptonic decays such as $D^0 \to \rho^-\, e^+\nu_e$ and $D^+ \to \rho^0\, e^+\nu_e$ involve 3 form factors:

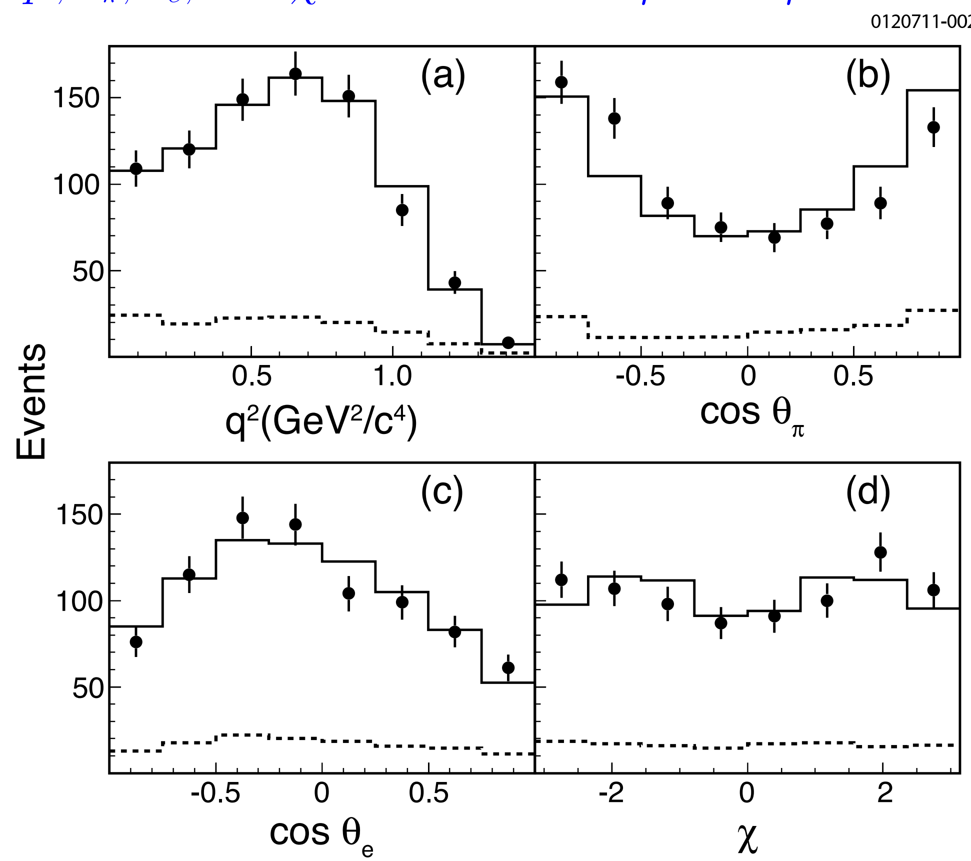
- One vector $V(q^2)$ and two axial vector $A_1(q^2)$ and $A_2(q^2)$
- These form factors contribute to helicity amplitudes, which can be determined from distributions of angles $\theta_e$, $\theta_\pi$, and $\chi$.

For $D^+ \to \rho^0\, e^+\nu_e$ decay, substitue $\rho^0$ for $\bar{K}^{*0}$, $\pi^-$ for $K^-$, and $\theta_\pi$ for $\theta_K$

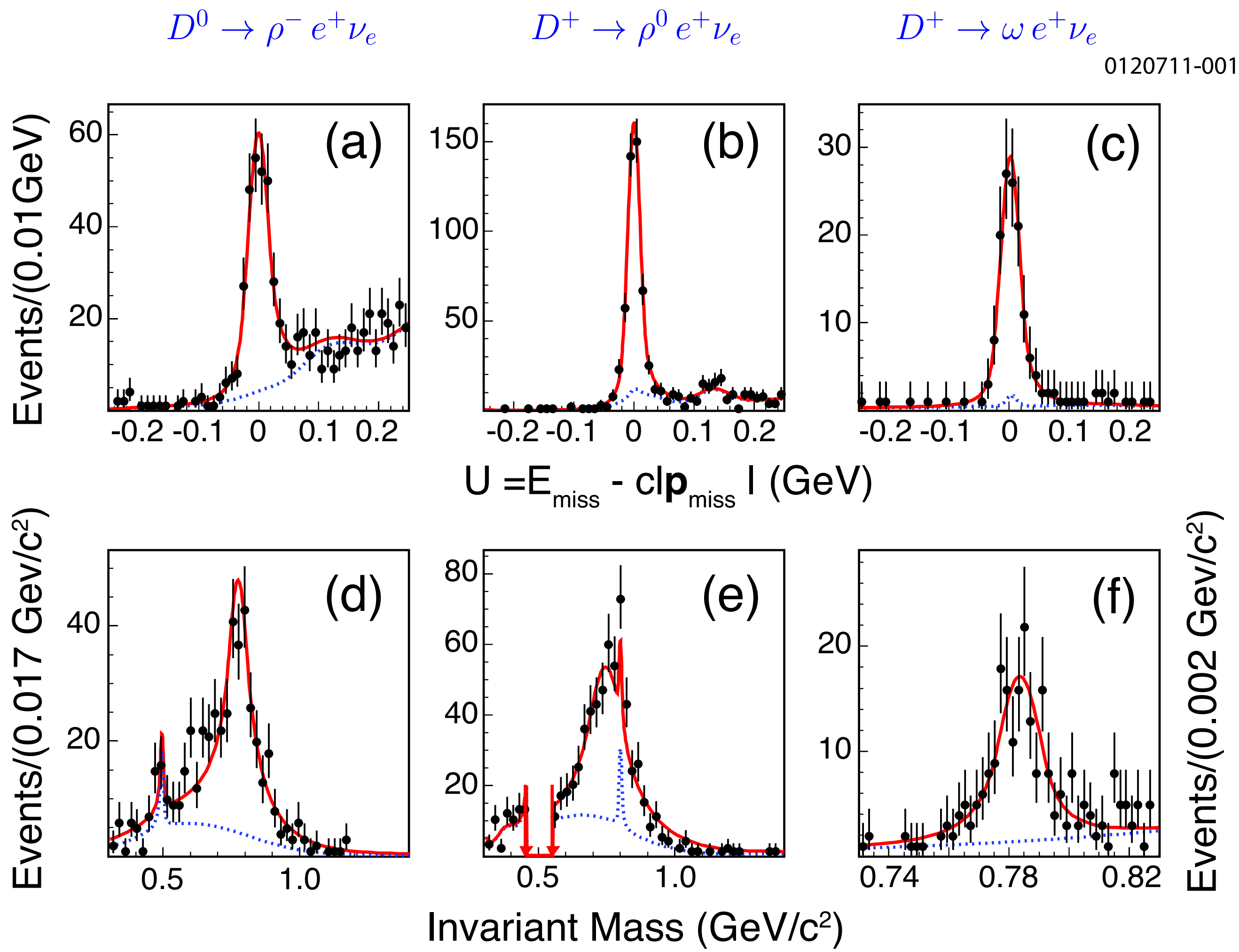



$D^+ \to \omega\, e^+\nu_e$ was detected and the branching fraction was measured, but form factors were not measured

$q^2$, $\theta_\pi$, $\theta_e$, and $\chi$ distributions for $\rho^-$ and $\rho^0$ combined



## First Measurement of $D \to \rho\, e^+\nu_e$ Form Factors




From our measured branching fractions, measured form factors, $|V_{cd}|$ obtained from CKM unitary by the PDG, and values of the $D^0$ and $D^+$ lifetimes, we obtained

$A_1(0) = 0.56 \pm 0.01^{+0.02}_{-0.03}$, $A_2(0) = 0.47 \pm 0.06 \pm 0.04$, and $V(0) = 0.84 \pm 0.09^{+0.05}_{-0.06}$,

One HQET-based model predicted: $A_1(0) = 0.61$, $A_2(0) = 0.31$, and $V(0) = 1.0$.

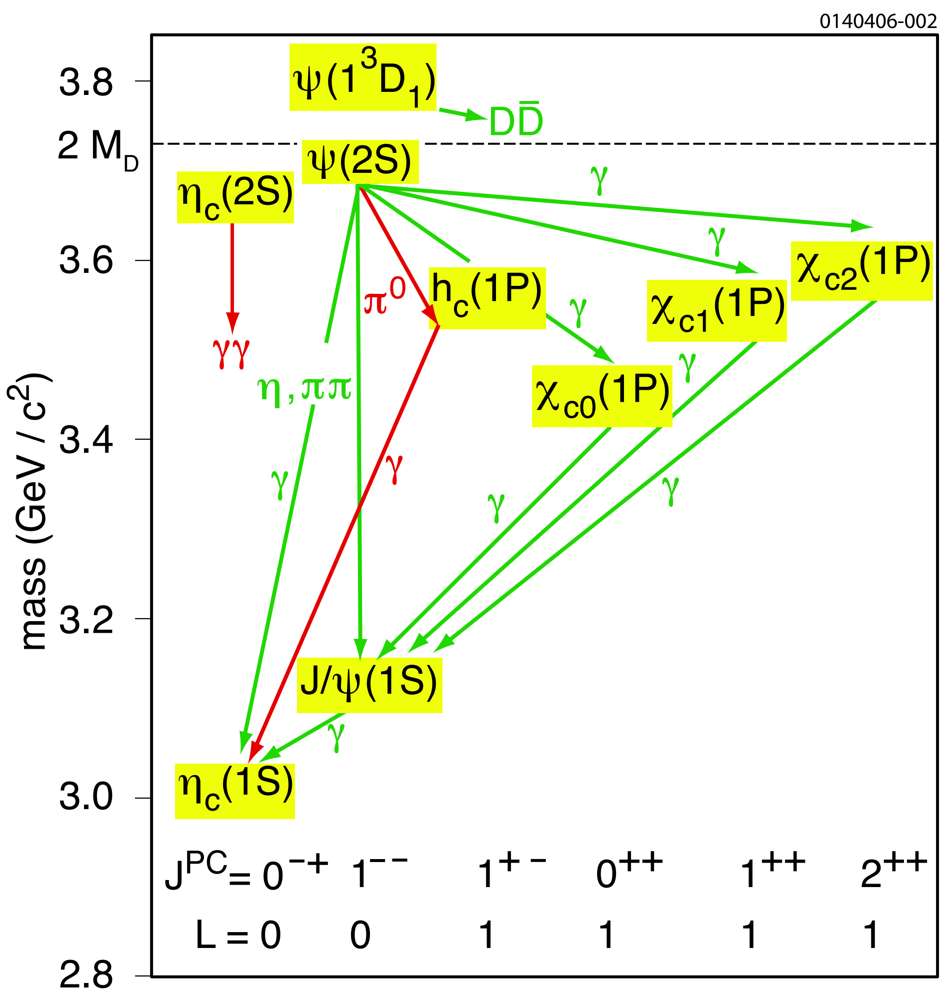
# Observation of the $c\bar{c}(1P)$ state $h_c$

Reconstructed $h_c$ using $\psi(2S) \to \pi^0 h_c$, $h_c \to \eta_c \gamma$, $\eta_c \to \mathit{hadrons}$

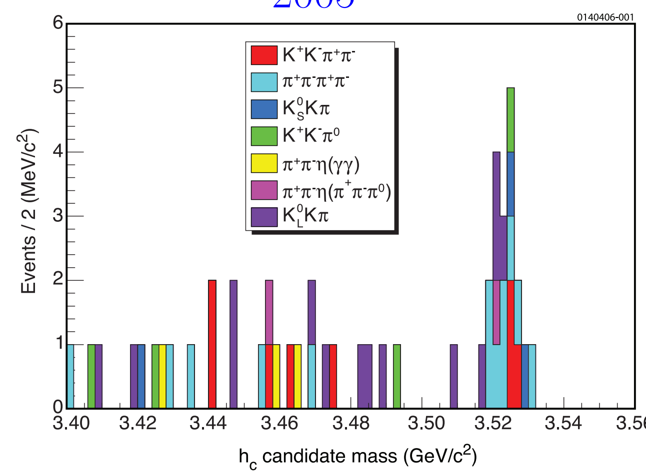
Completed bound-state $c\bar{c}$ spectroscopy and provided an essential validation of charmonium theory

Hyperfine splitting: Expected $M(h_c)$ equal to the spin average of $M(\chi_{cJ})$

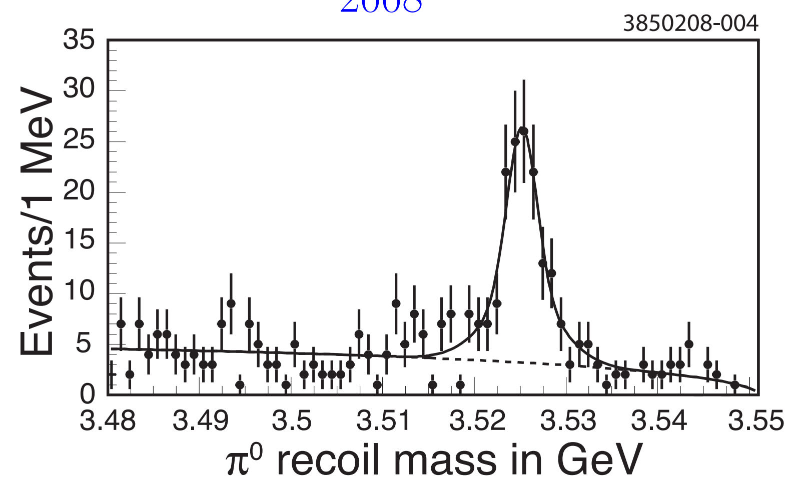
Found $\langle M(\chi_{cJ}) \rangle - M(h_c) = +0.02 \pm 0.19 \pm 0.13$ MeV




2005



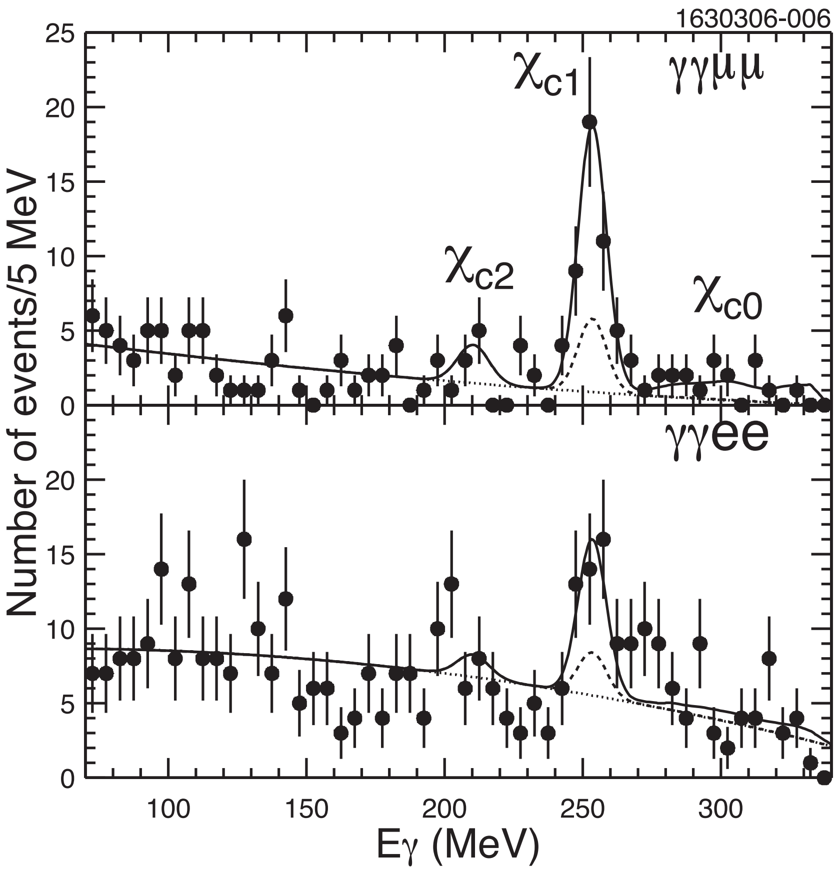

2008



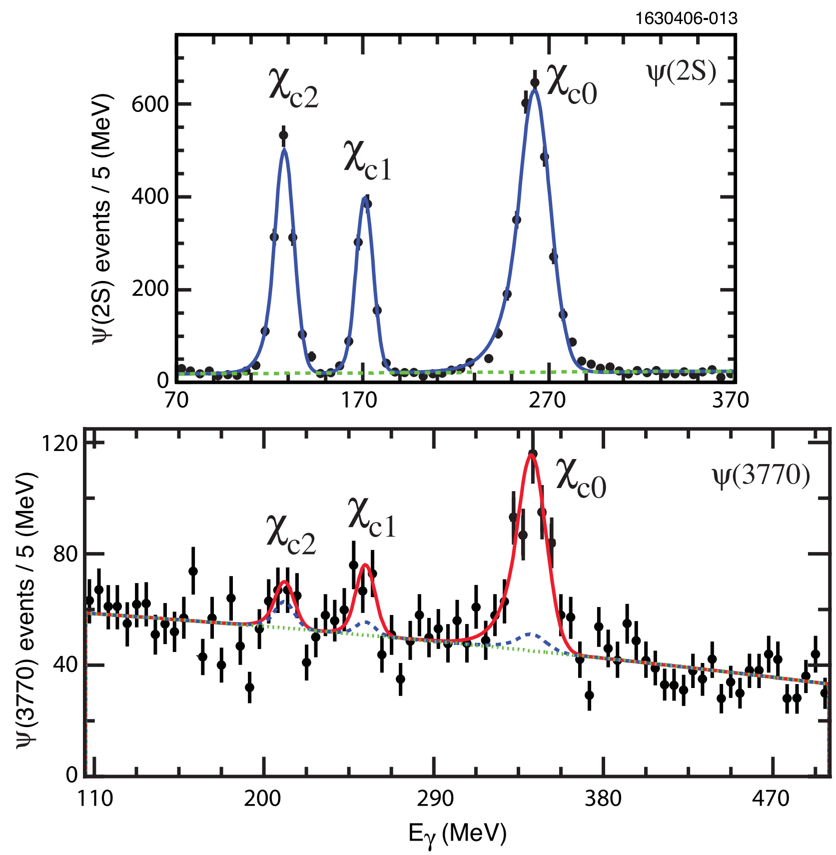
# $\psi(3770) \to \gamma\chi_{cJ}$

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

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




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



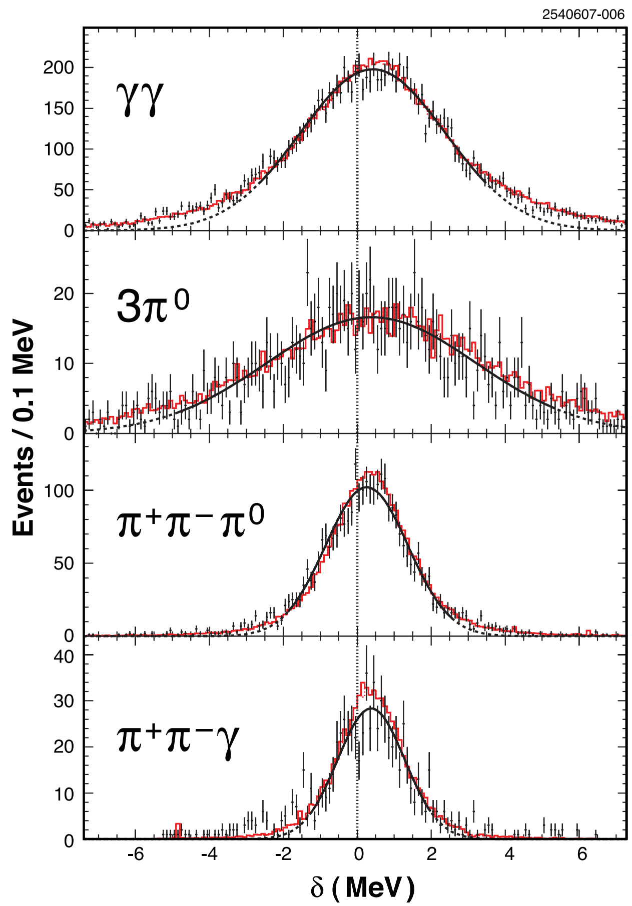

- Pattern of branching fractions agrees with *relativistic* calculations
- Reinforces interpretation of $\psi(3770)$ as primarily a $^3D_1$ $c\bar{c}$ state

# Measurement of the $\eta$ Mass Using $\psi(2S) \to \eta J/\psi$

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

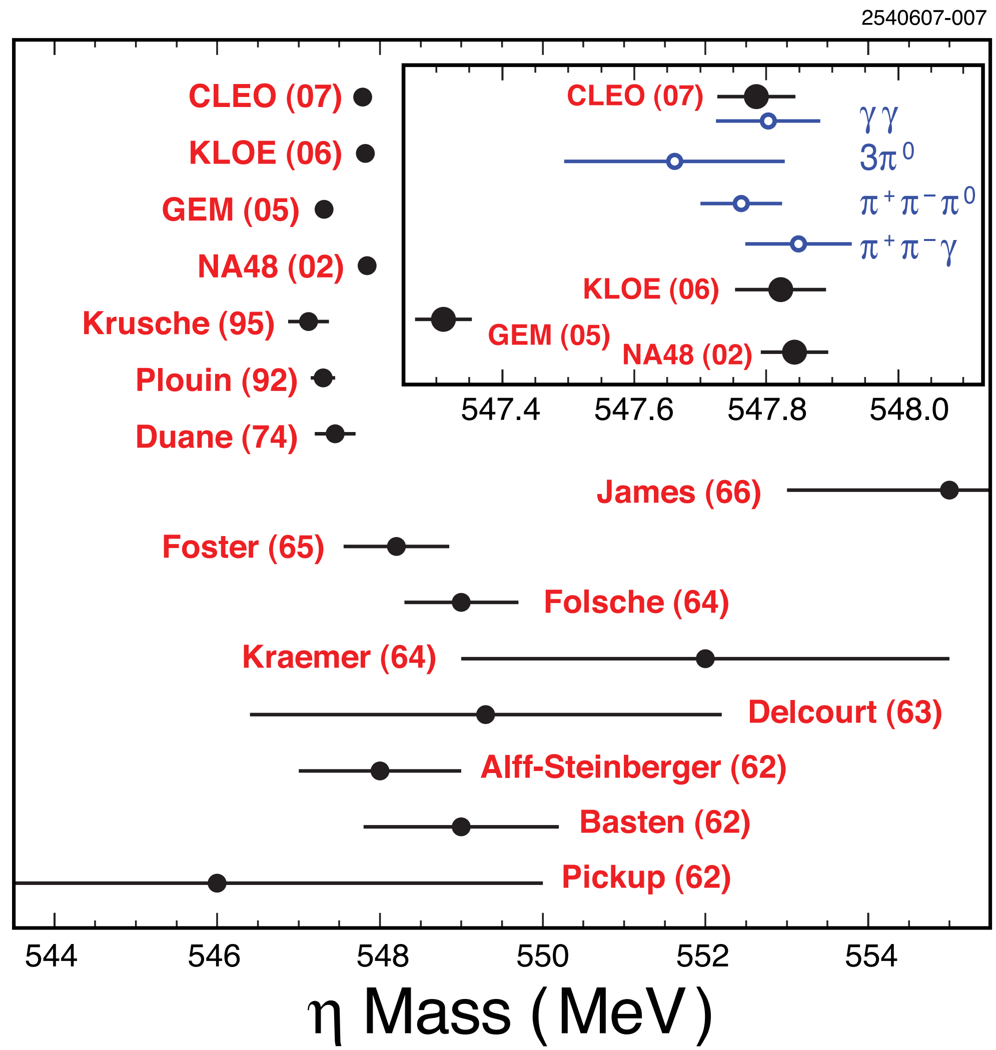
- CLEO: $M_\eta = 557.785 \pm 0.017 \pm 0.057$ MeV$/c^2$

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




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

Comparison to other measurements



## Some Additional Highlights of CLEO-c

By my count there are 118 CLEO-c publications among the 530 CLEO publications.

- Measurements of quantum correlations and phases in $D^0\bar{D}^0$ mixing
- Measurements of strong phases in $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to \pi^+\pi^+\pi^-$ needed for model independent measurements of the CP-violating angle $\gamma$
- Measurement of strong phases in $D^0 \to K_S^0 K^-\pi^+$ and $D^0 \to K^+K^-\pi^+\pi^-$ providing additional modes for measurements of the CP-violating angle $\gamma$
- Discovery of $D_s \to p\bar{n}$ decays, the only possible baryon-antibaryon decay of $D$ mesons
- Consistent accurate measurement of $\eta$ branching fractions accounting for 99.9% of all $\eta$ decays
- First observation of $J/\psi \to \gamma\gamma\gamma$ an analogue of ortho-positronium decays, which provides important tests of QCD theories of charmonium decay
  It was awarded the rare distinction "Editors Choice" by the editors of Physical Review Letters.
- Observation of $e^+e^- \to h_c(1P)\,\pi^+\pi^-$ confirming the original observation of that state
  It stimulated CLEO-c members who were also members of Belle to use the same technique to discover the elusive $h_b(1P)$ and $h_b(2P)$ states.
- First observation of higher (M2) multipoles in $\psi(2S) \to J/\psi\gamma\gamma$, which resolved long-standing discrepancies between theory and experiment and confirmed early theoretical calculations
- Observation of the Dalitz decay $D_s^{*\pm} \to D_s^{\pm}e^+e^-$, the only Dalitz decay observed in the $c$ or $b$ sectors

# Conclusions

- The CLEO-c program was stimulated by the progress of LQCD groups in being able to calculate $D$ meson decay parameters with enough precision that comparisons between theory and precise experiments would be meaningful.
- Throughout the program, CLEO-c measurements challenged LQCD calculations and vice versa.
- These challenges were only part of the CLEO-c program because talented physicists will have original ideas for what to do with excellent data.
- For this exciting program I owe special thanks to:
  - Peter Lapage for stimulating the program and participating in the CLEO-c Taskforce
  - LQCD colleagues for their challenges to CLEO-c results
  - CESR colleagues whose heroic efforts adapted CESR to run successfully in the charm threshold region and who worked so hard to ensure that CLEO-c received the maximum possible data at a wide variety of energies and acceleration conditions
  - CLEO-c colleagues who built and maintained the detector, took and processed the data, and derived so much good physics from the data
  - Ian Shipsey whose contributions, vitality, and good cheer constantly encouraged the rest of us