# D and $D_s$ Semileptonic Decays at CLEO


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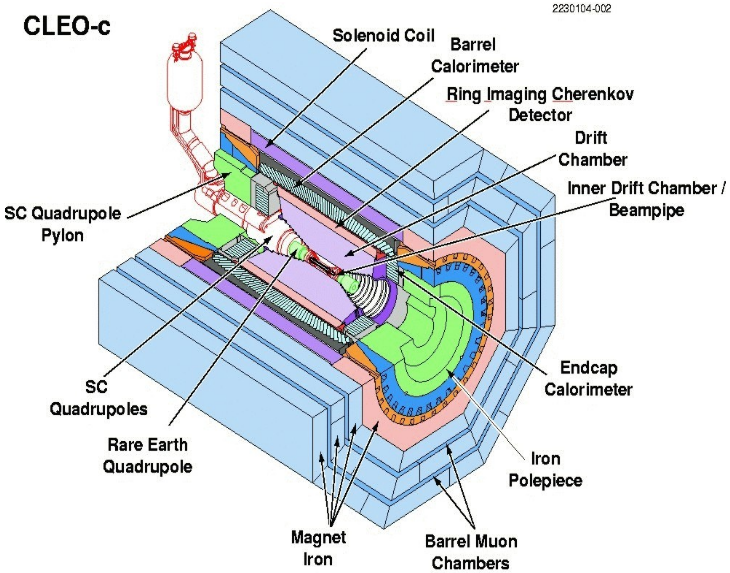
on behalf of the CLEO Collaboration


# Charm (aka Weak Interaction) Physics

Study of semileptonic charm decays is an excellent environment to provide validation and calibration for theory, especially Lattice QCD (LQCD), so it can be applied with confidence to B physics ($V_{ub}$).

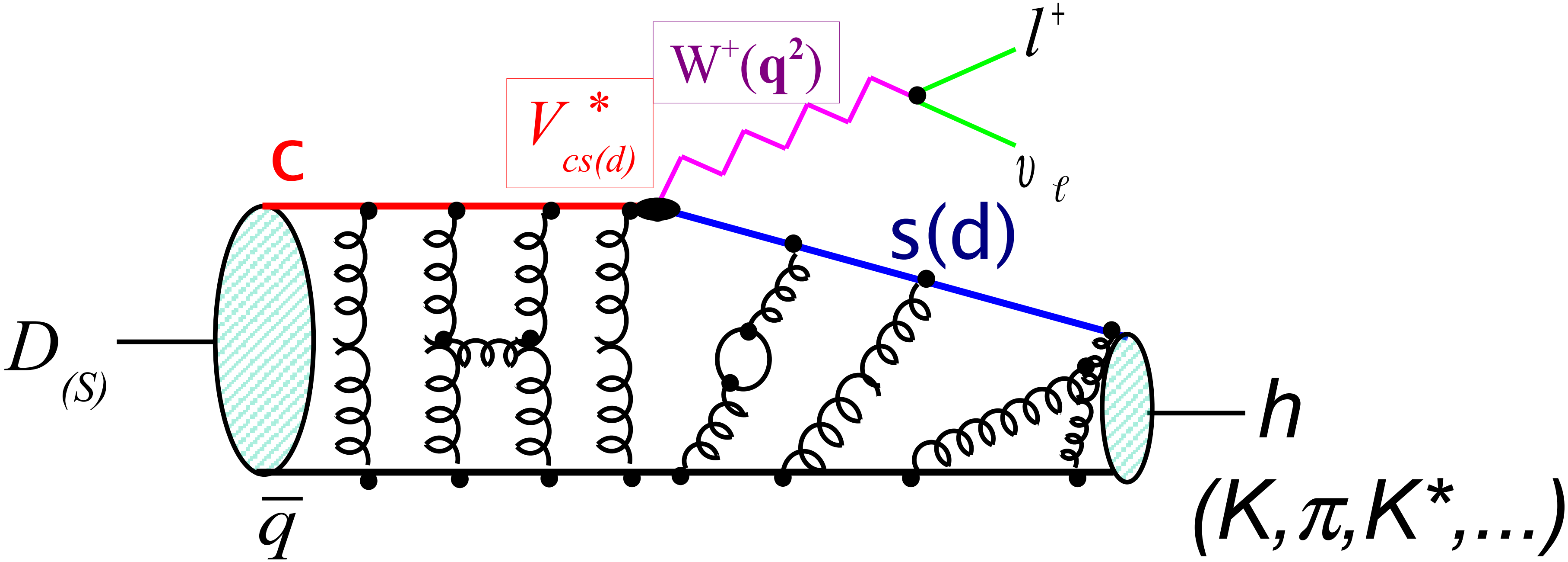
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Measuring form factors in semileptonic decays provide very stringent constraints on LQCD

A validated theory can be used in precision measurements of $V_{cs}$ and $V_{cd}$

This talk: Form factors analyses of $D^0/D^+ \rightarrow K/\pi\ e^+\ \nu$, $D^+ \rightarrow \eta\ e^+\ \nu$
Exclusive semileptonic $D_S^+$ decays
Inclusive semileptonic $D^0$, $D^+$, $D_S^+$ decays

# Semileptonic Decays

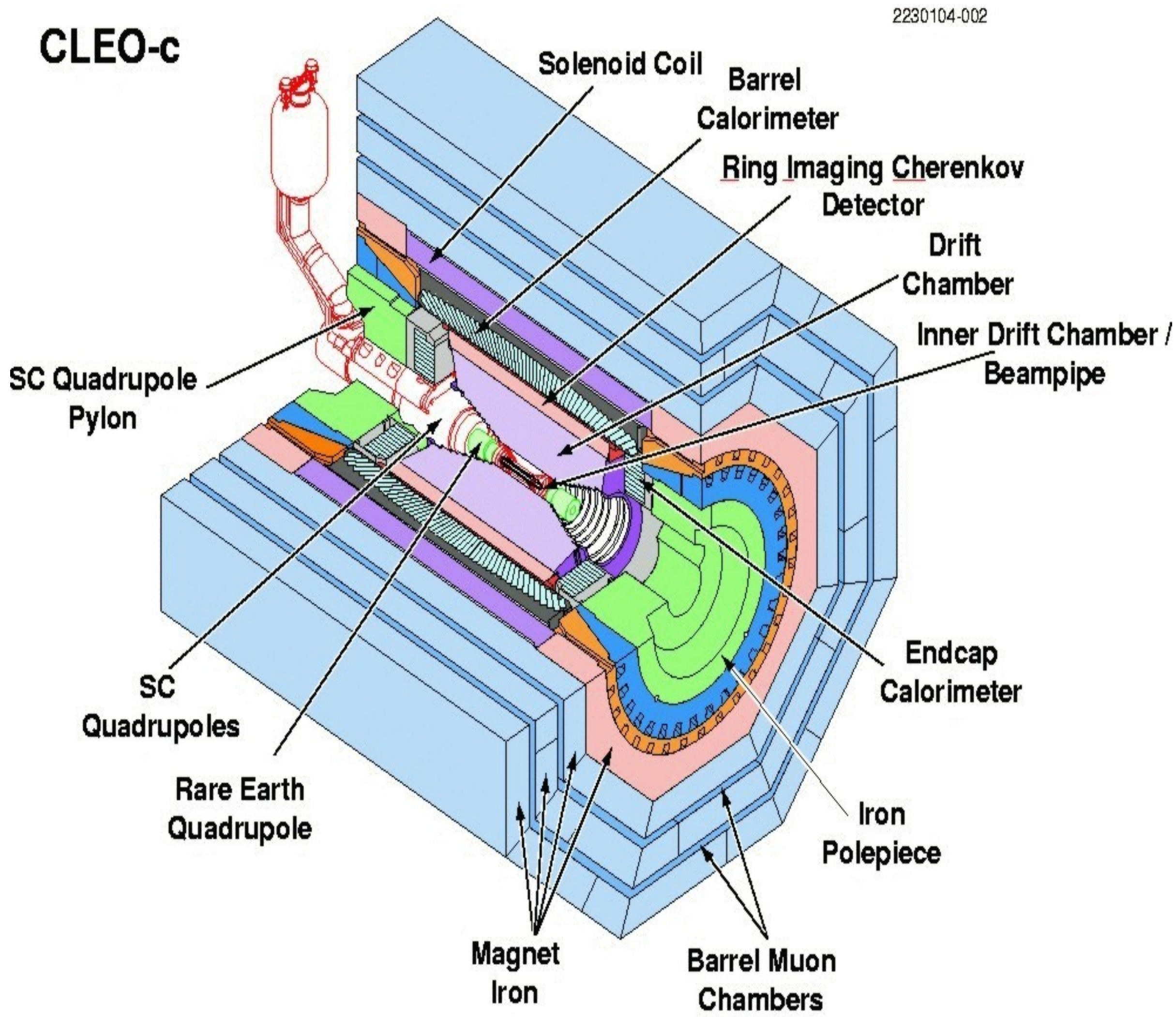



Branching fraction for pseudoscalar-to-pseudoscalar decays

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

Need to understand $f_+(q^2)$ to precisely measure $V_{cs\,(d)}$

# CLEO-c Detector




Covered 93% of solid angle
Operated within 1.0 T B-field

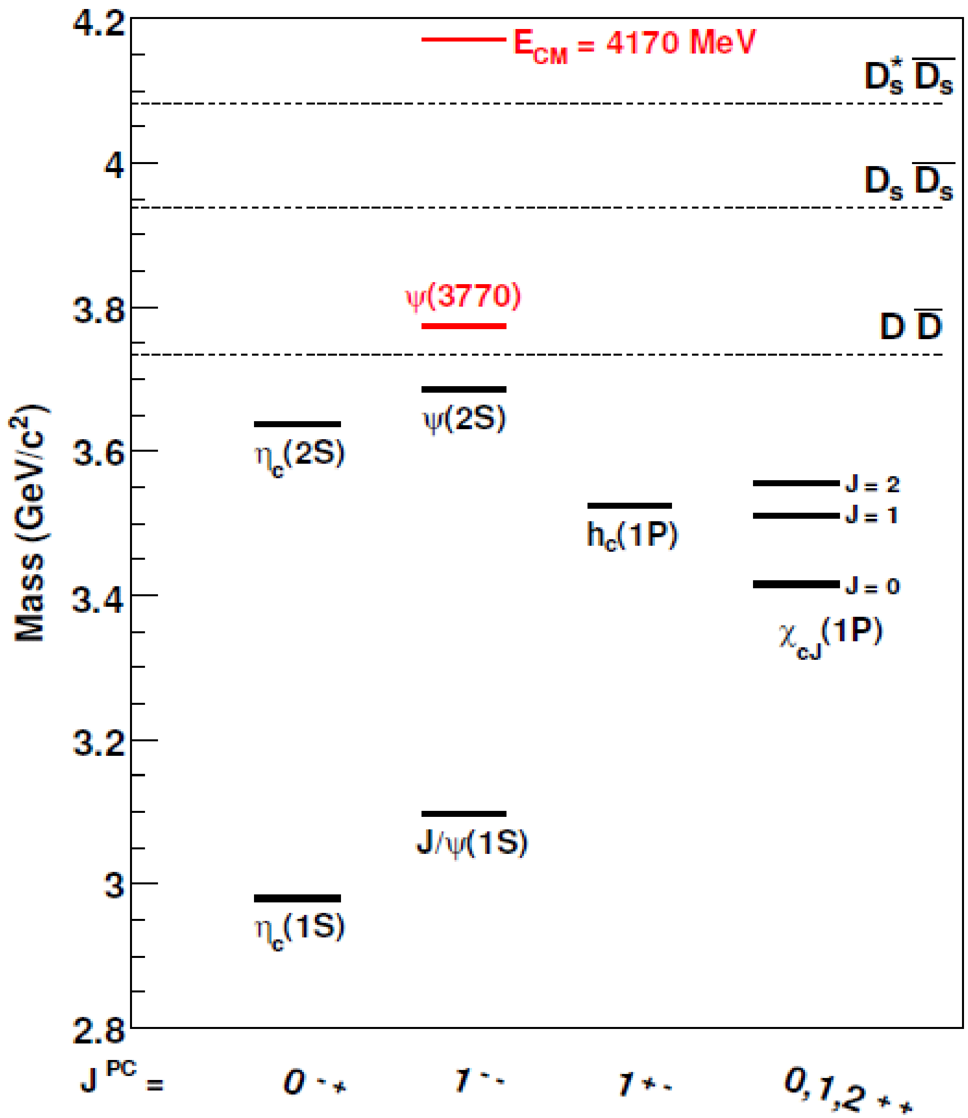
Tracking: $\sigma_{\mathbf{p}} / \mathbf{p} = 0.6\%$ @ 1GeV

Shower Calorimetry:
$\sigma_E / E = 5\ (2.2)\ \%$ @ 0.1 (1) GeV

Charged PID (dE/dx + RICH):
Good K/$\pi$ separation
for $\mathbf{p} < 2.5$ GeV

Muon Chamber not very useful:
$\mathbf{p}_{min} = 1$ GeV,
$\varepsilon \sim 90\%$ @ $\mathbf{p} > 1.5$ GeV

# Open Charm Samples




ψ(3770): 281 $pb^{-1}$ (2003-05)
+ 537 $pb^{-1}$ (2006-07)
818 $pb^{-1}$

$D_S$ Scan: 60 $pb^{-1}$ (2005)
[12 pts; $E_{CM}$ = 3.97 - 4.26 GeV]

$E_{CM}$ = 4.17 GeV: 16 $pb^{-1}$ (from scan)
298 $pb^{-1}$ (2005-06)
+288 $pb^{-1}$ (2007-08)
602 $pb^{-1}$

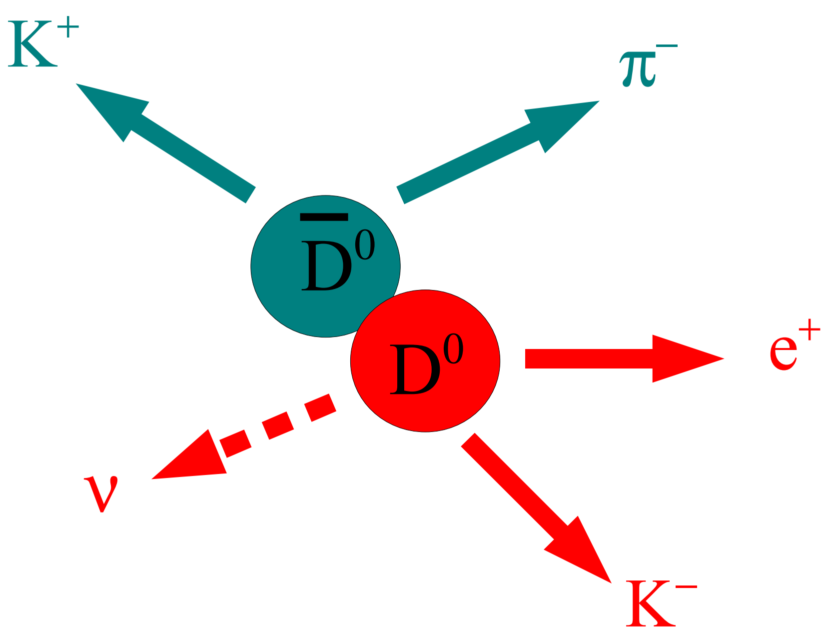
# D Tagging

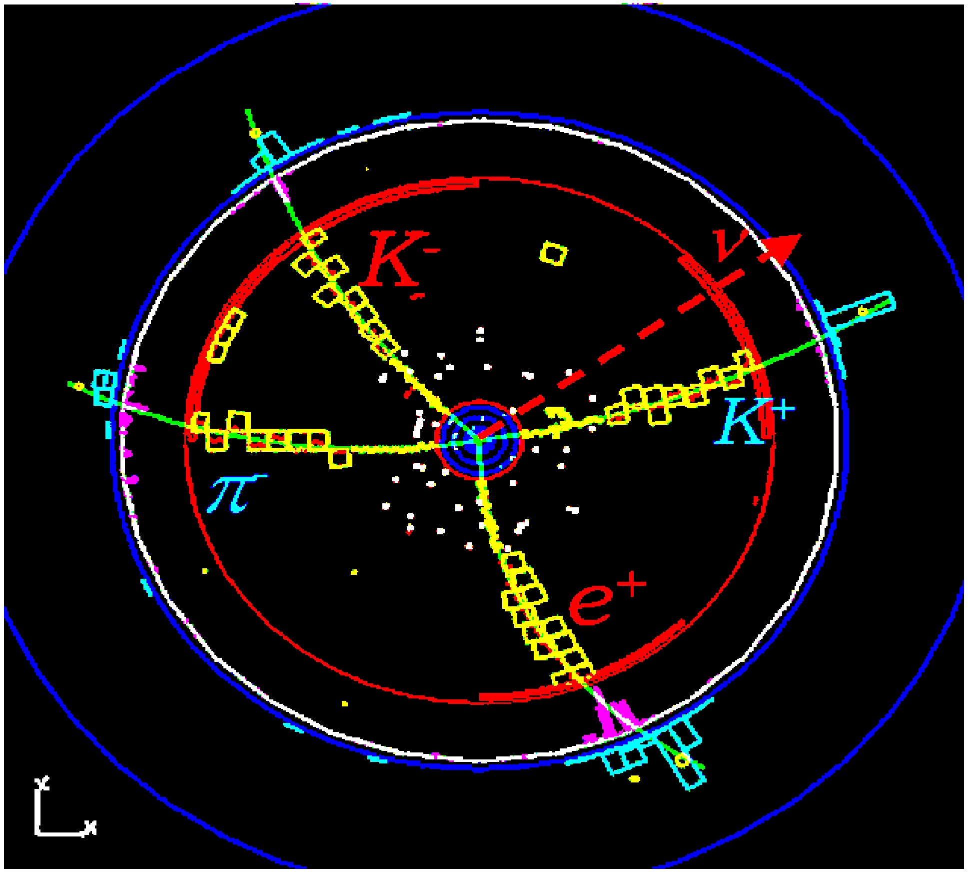
"<u>MARK III Method</u>"

Fully reconstruct hadronic D decay on one side (tag), reconstruct other side and look for neutrino in missing mass or $U_{miss} = E_{miss} - |\mathbf{P}_{miss}|$

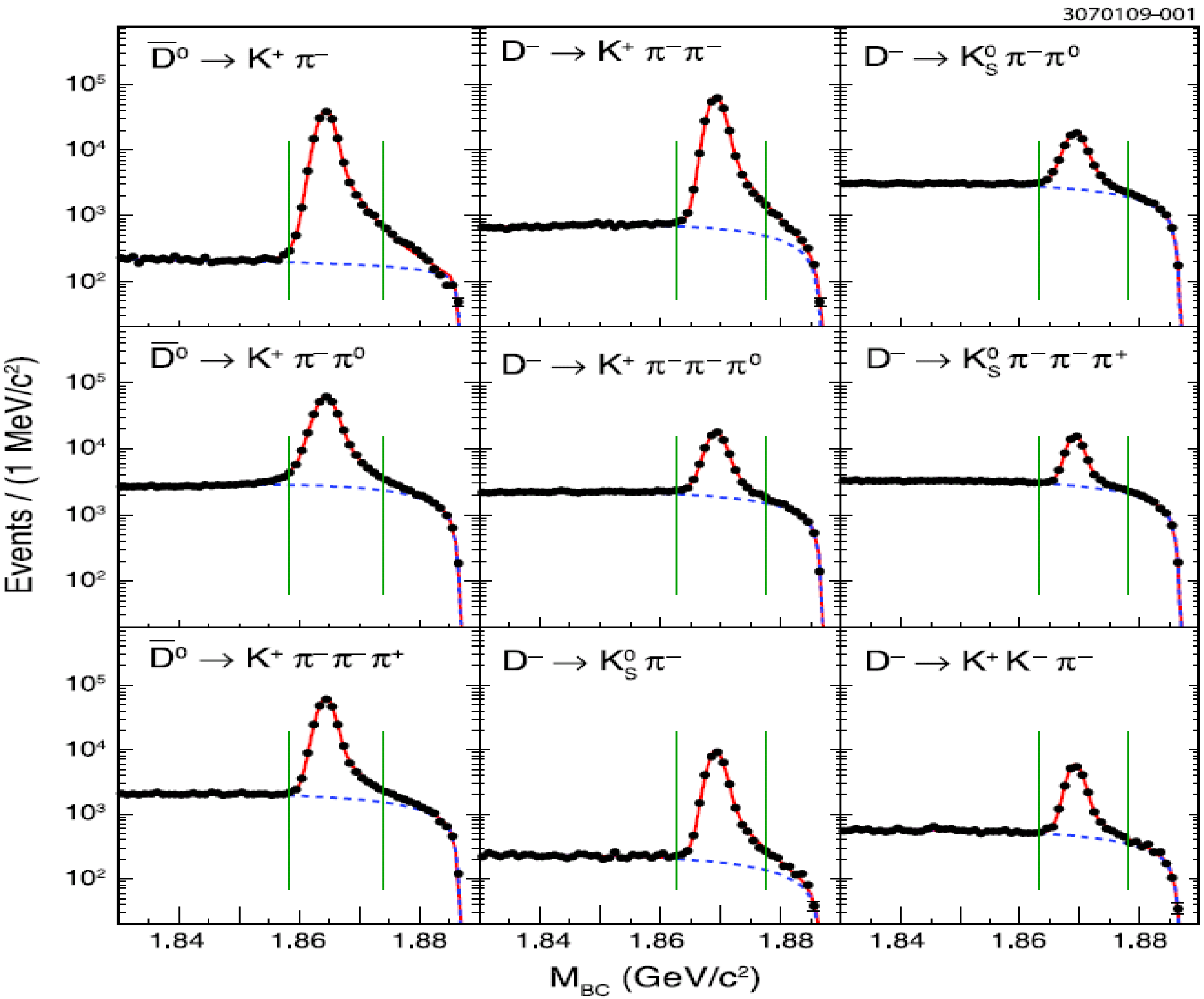
Allows you to determine absolute branching fractions: $BF = N_{obs} / (\varepsilon\, N_{tags})$

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



# Tagging for $D \to K/\pi\, e^+ \nu$




$$M_{BC} = \sqrt{E^2_{beam}/c^4 - |\mathbf{P}_{tag}|^2/c^2}$$

PRD 80, 032005 (2009)

Full ψ(3770) sample

Mode-dependent cuts on $\Delta E = E_{tag} - E_{beam}$

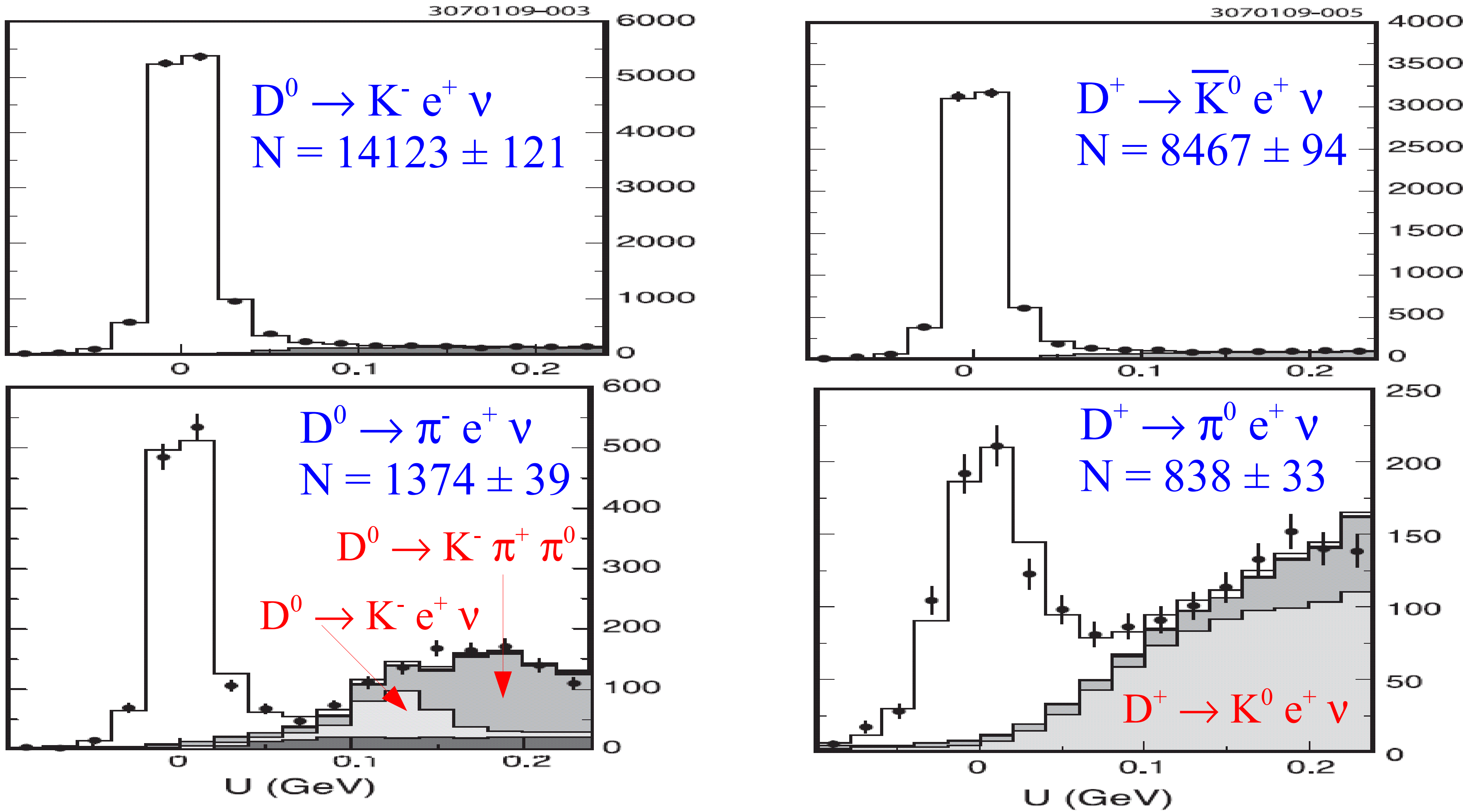
3 $D^0$ tag modes
$N_{tags} \sim 662{,}000$

6 $D^+$ tag modes
$N_{tags} \sim 481{,}000$

Includes charge conjugate modes

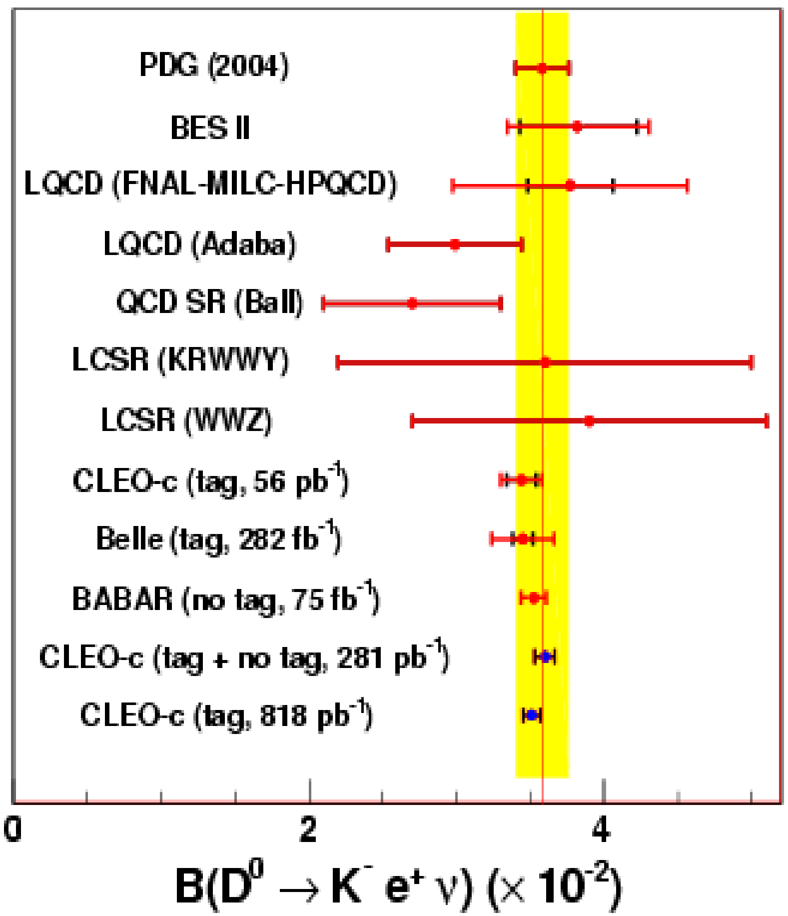
# Signal Yields for D → K/π $e^+$ ν

Find $e^+$ and hadron, look at missing energy-momentum difference

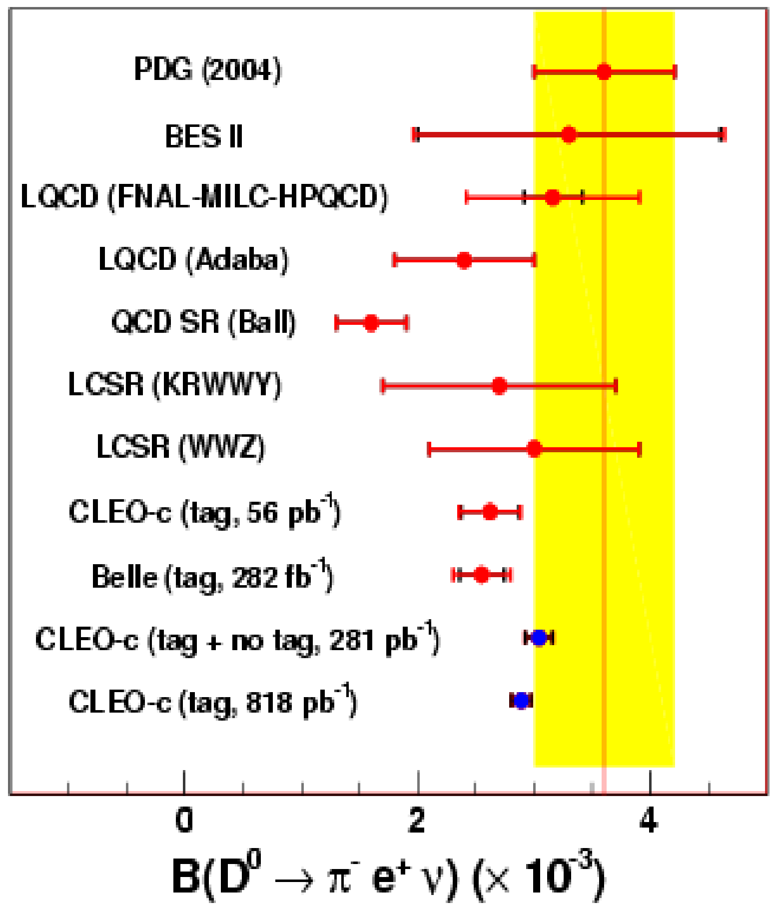



$$U = E_{miss} - c|\mathbf{P}_{miss}|$$

# Branching Fractions of $D^0 \to K^-/\pi^- e^+ \nu$




$(3.50 \pm 0.03 \pm 0.04)\%$




$(2.88 \pm 0.08 \pm 0.03) \times 10^{-3}$

Most precise measurements of branching fractions

# $D \to K/\pi\, e\, \nu$ Form Factors

Form factor is an analytic function which satisfies the dispersion relation

$$f_+(q^2) = \frac{f_+(0)/(1-\alpha)}{1 - q^2/M^2_{D^*_{(S)}}} + \frac{1}{\pi}\int_{(m_D+m_P)^2}^{\infty} \frac{\mathrm{Im} f_+(t)}{t - q^2 - i\epsilon} dt$$

Simple mode model

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

Fit for $f_+(0)$ and $M_{pole}$

Modified mode model

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

Fix $M_{pole}$, fit for $f_+(0)$ and $\alpha$

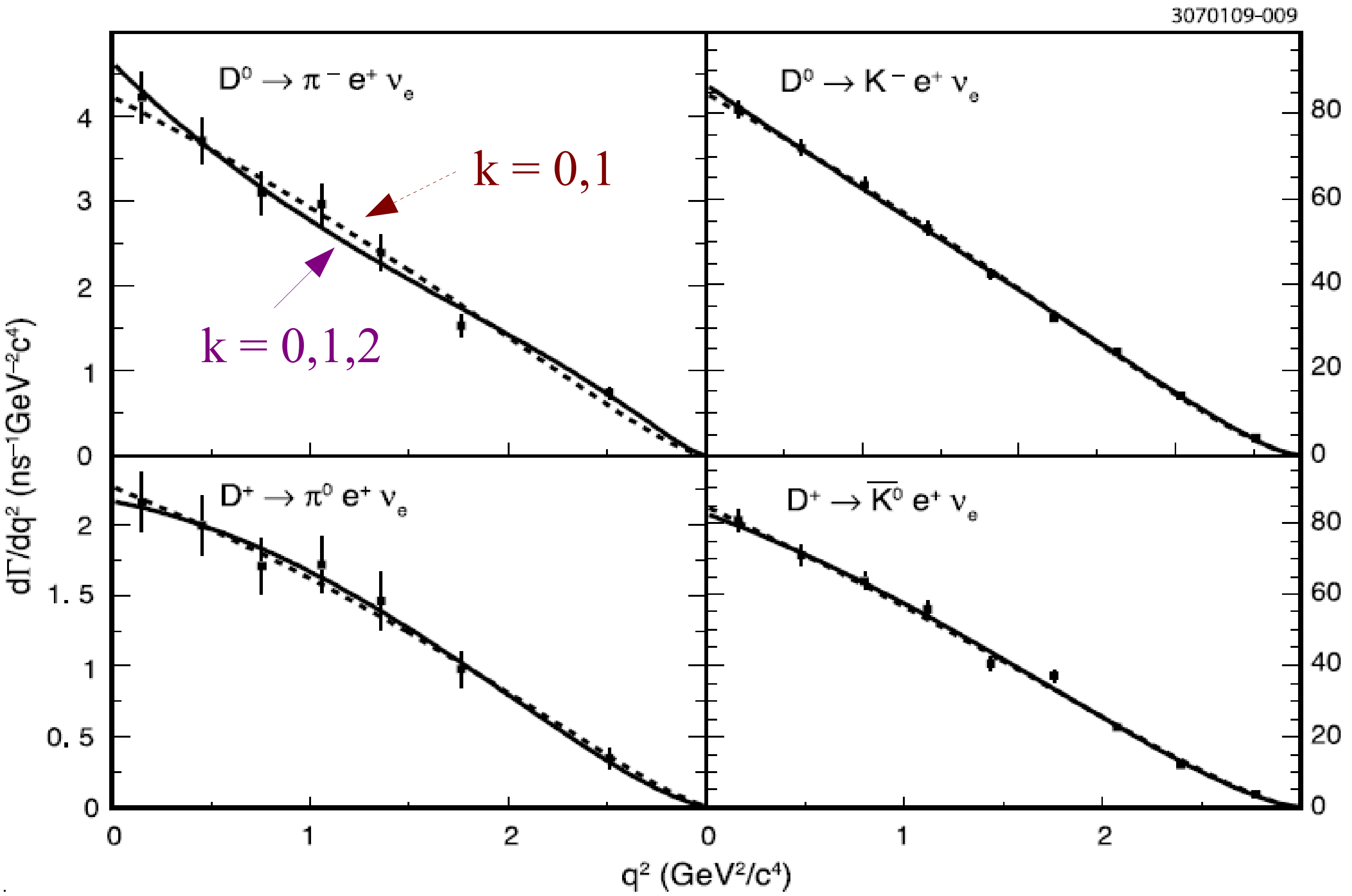
$M_{pole} = D_S^{*+}$ ($D^{*+}$) for $D \to K$ ($\pi$) $e\, \nu_e$

Series Expansion Model (Becher-Hill)

$$f_+(q^2) = \frac{a_0}{P(q^2)\phi(q^2, t_0)} \left(1 + \sum_{k=1}^{\infty} a_k(t_0) z(q^2, t^0)^k\right)$$

Map $q^2$ in complex z-space, poles are along real axis, fit for $a_i$

# Form Factor Fits




9 $q^2$ bins for K $e^+$ $\nu$

7 $q^2$ bins for $\pi$ $e^+$ $\nu$

Yields determined from fits of $q^2$ binned U distributions

Fit to Becher-Hill Series

$$f_+(q^2) = \frac{a_0}{P(q^2)\phi(q^2,t_0)}\left(1+\sum_{k=1}^{\infty} a_k(t_0) z(q^2,t^0)^k\right)$$

# Model Comparison

Simple Pole [GeV/c$^2$]

$\pi e^+ \nu$: $m_{pole}$ = 1.91(2)(1)

M(D*) = 2.0103(2)

$K e^+ \nu$: $m_{pole}$ = 1.93(2)(1)

M($D_S$*) = 2.1123(5)

Modified pole

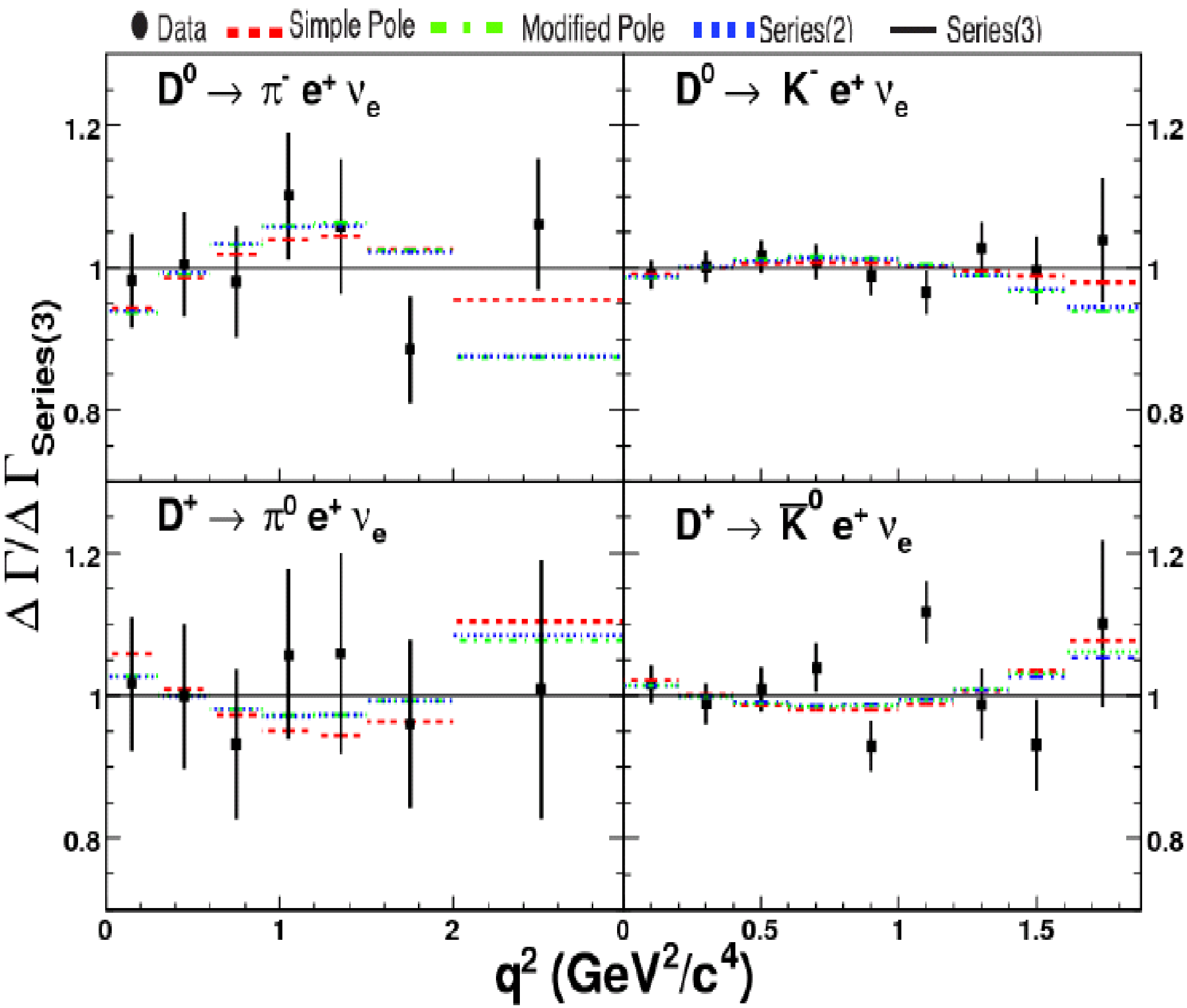
Assumes MP = 1 + 1/β – δ ≡

$$\frac{m_D^2 - m_P^2}{f_+(0)} \frac{df_+(q^2)}{dq^2} \bigg|_{q^2=0} \approx 2$$

$\pi e^+ \nu$: MP = 0.93(9)(1)

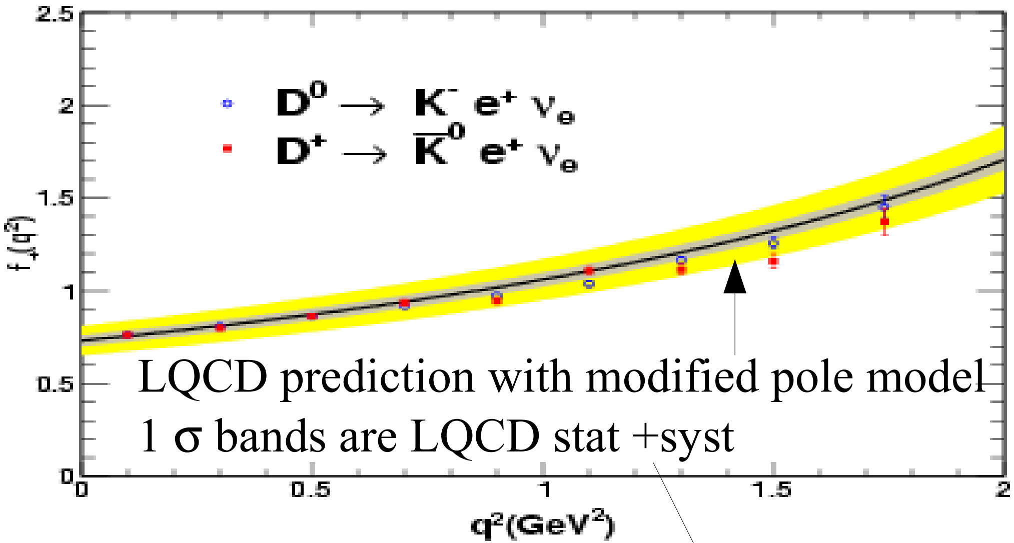
$K e^+ \nu$: MP = 0.89(4)(1)

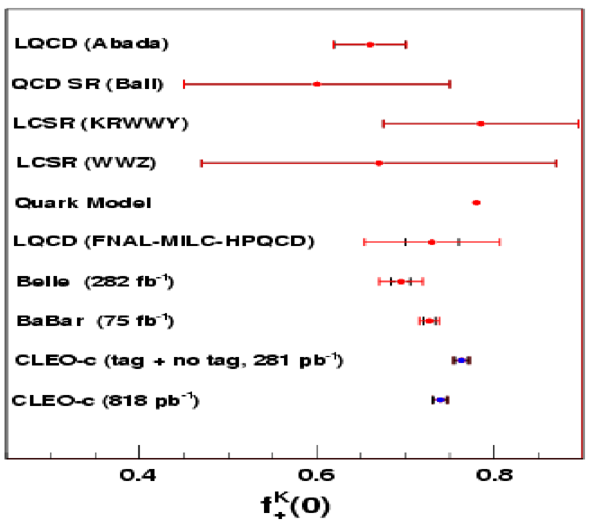
Assumptions made by simple and modified pole models are not valid



# Comparison to LQCD

LQCD:FNAL- MILC-HPQCD [PRL 94, 011601 (2005), PRD 80, 034026 (2009)]



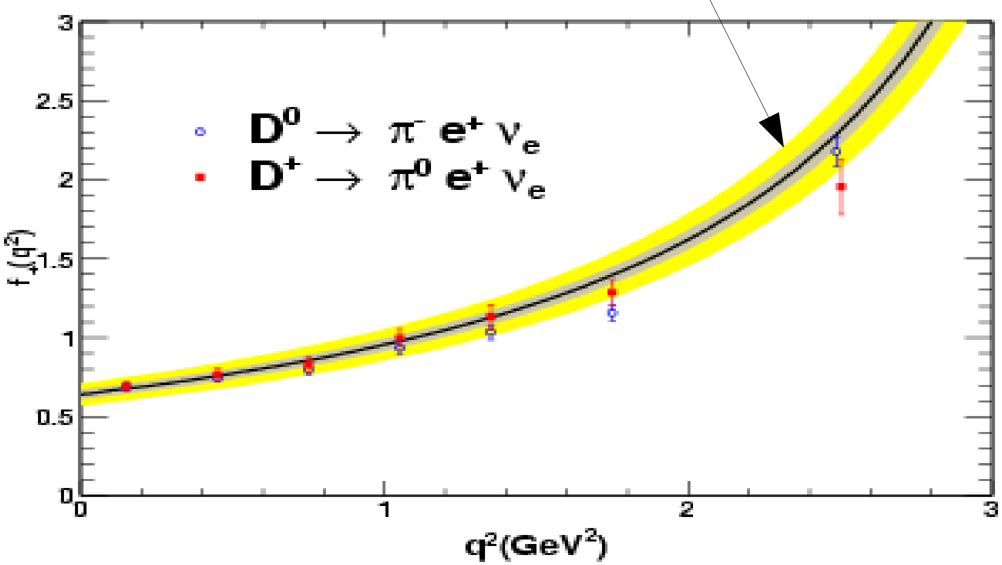



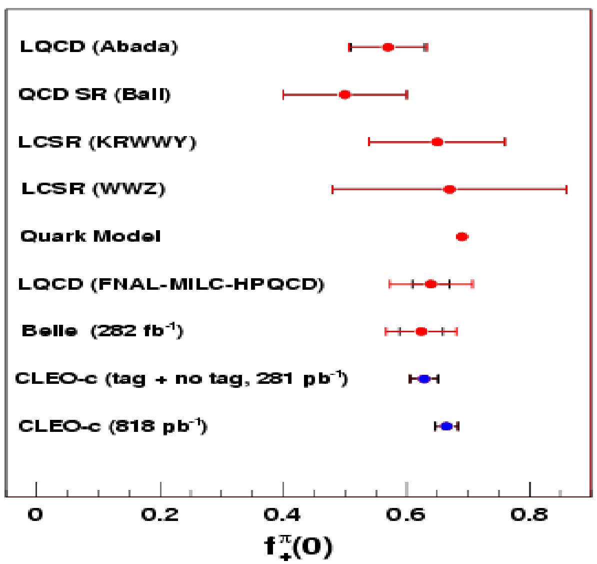

$f_+^K(q^2 = 0)$

Uncertainties

expt = 1.2%

LQCD = 10%




$f_+^\pi(q^2 = 0)$

Uncertainties

expt = 2.9%

LQCD = 10%

# $D \to K/\pi\, e^+ \nu$ Results

PRD 80, 032005 (2009)

With 818 $pb^{-1}$ $\psi(3770)$ data, CLEO has measured

$$f_+^{\pi}(0)\,|V_{cd}| = 0.150 \pm 0.004\ (\text{stat}) \pm 0.001\ (\text{syst})$$

$$f_+^{K}(0)\,|V_{cs}| = 0.719 \pm 0.006\ (\text{stat}) \pm 0.005\ (\text{syst})$$

using the series parameterization form factor model with three parameters

Using LQCD: $f_+^{\pi}(0) = 0.64(3)(6)$ $f_+^{K}(0) = 0.73(3)(7)$

$$|V_{cd}| = 0.234 \pm 0.007 \pm 0.002 \pm 0.025$$

$$|V_{cs}| = 0.985 \pm 0.009 \pm 0.006 \pm 0.103$$

stat syst LQCD

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PDG: $|V_{cd}| = 0.230 \pm 0.011$ (neutrino beam)

$|V_{cs}| = 1.04 \pm 0.06$ ($D_S^+ \to \mu^+,\tau^+ \nu$; $D \to K\, \ell^+ \nu$)

Most precise measurements of $|V_{cd}|$ & $|V_{cs}|$ using semileptonic decays

# $D^+ \to \eta e^+ \nu$

Alternative technique:
General Reconstruction (GR)

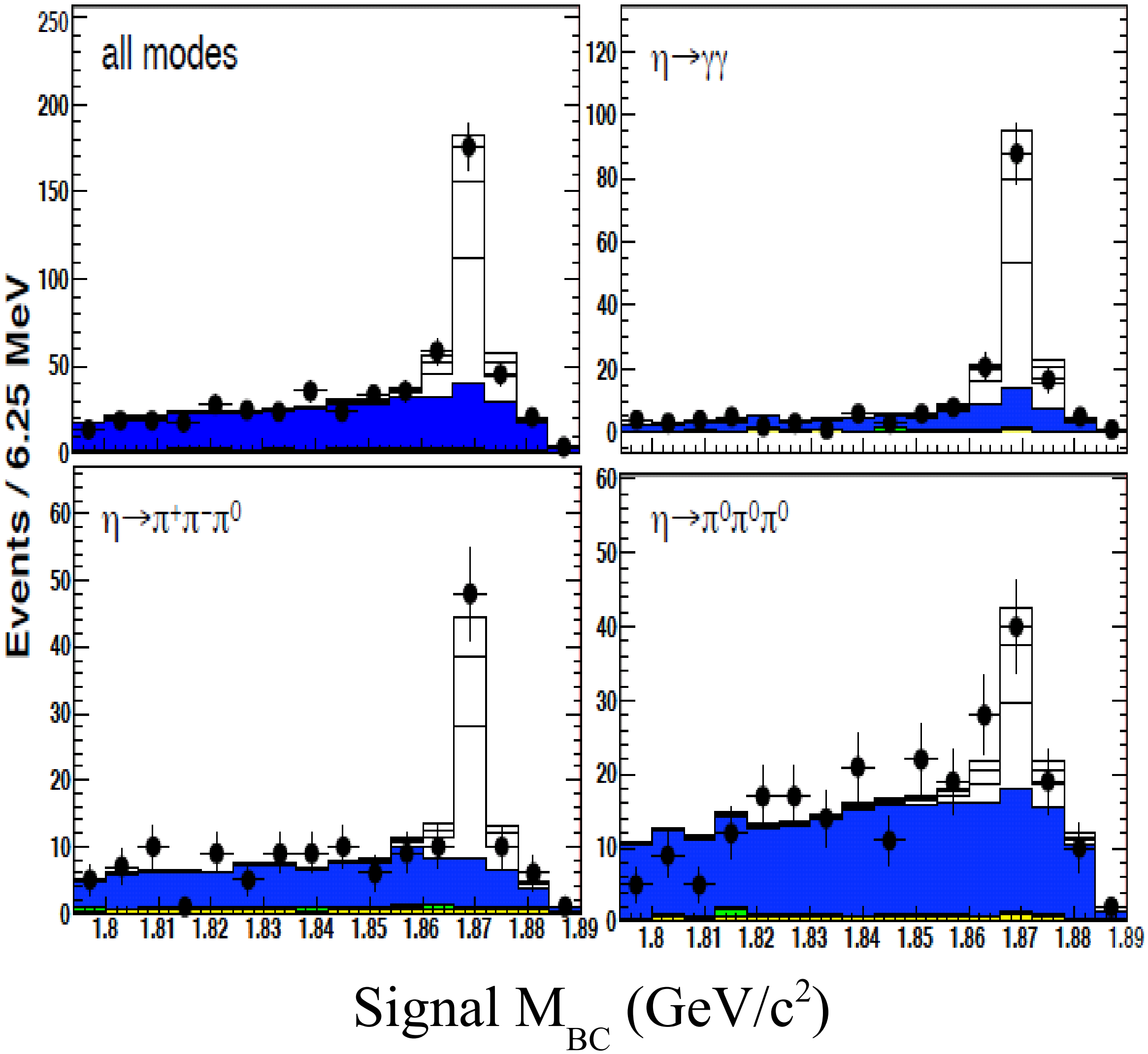
Reconstruct signal mode (e.g., $\eta$ and $e^+$)

Look for $\pi^\pm$; $K^\pm$; $K_S$; $\pi^0$, $\eta \to \gamma\gamma$ in other side D

Infer neutrino from all observed particles in event, results normalized to $K^-\pi^+\pi^+$

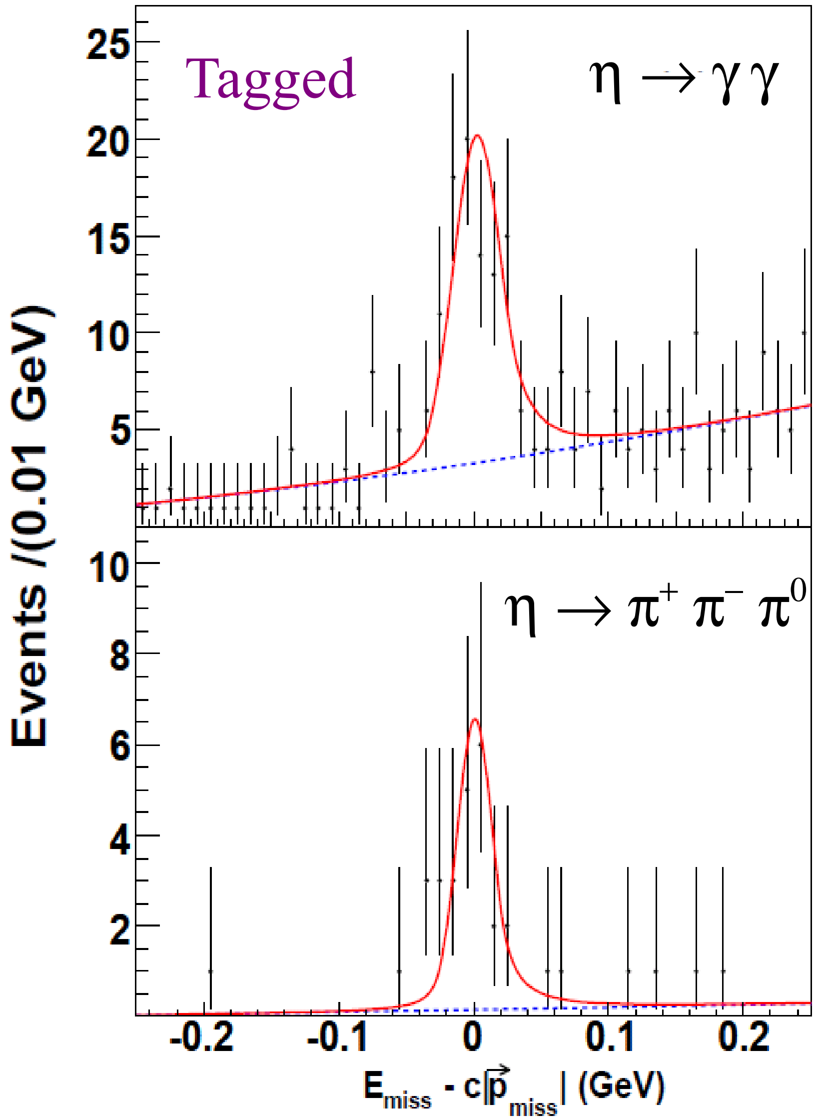
Byproduct: Observed 28 other side $D^+$ hadronic decays (13 not reported in PDG),
Tagged: 6 $D^+$ hadronic decays

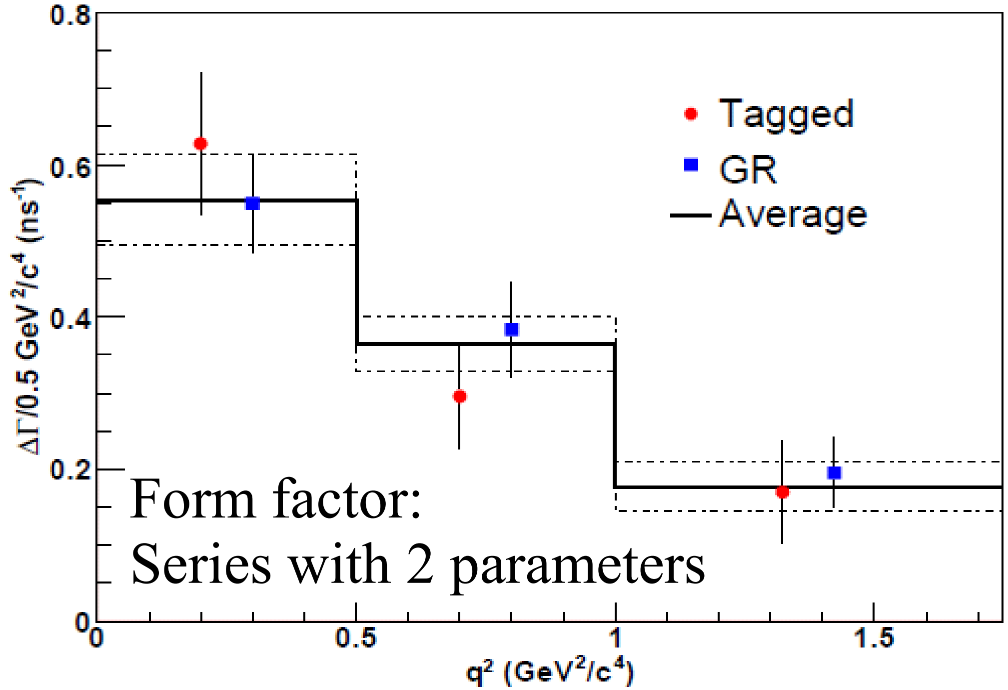
Full $\psi(3770)$ sample PRELIMINARY



# $D^+ \to \eta\, e^+ \nu$

PRELIMINARY




First form factor measurement of $D^+ \to \eta\, e^+ \nu$

$B(D^+ \to \eta\, e^+ \nu) = (11.4 \pm 0.9 \pm 0.4)\text{x}10^{-4}$

[average of both methods]

Full ψ(3770) sample

# $D^+ \to \eta', \varphi\ e^+ \nu$

PRELIMINARY

Full $\psi(3770)$ sample

GR: $B(D^+ \to \eta' e^+ \nu)$

$= (2.16 \pm 0.53 \pm 0.05 \pm 0.05) \times 10^{-4}$

stat syst $K\pi\pi$

Tagged: 5 observed events with

0.04 ± 0.03 background events

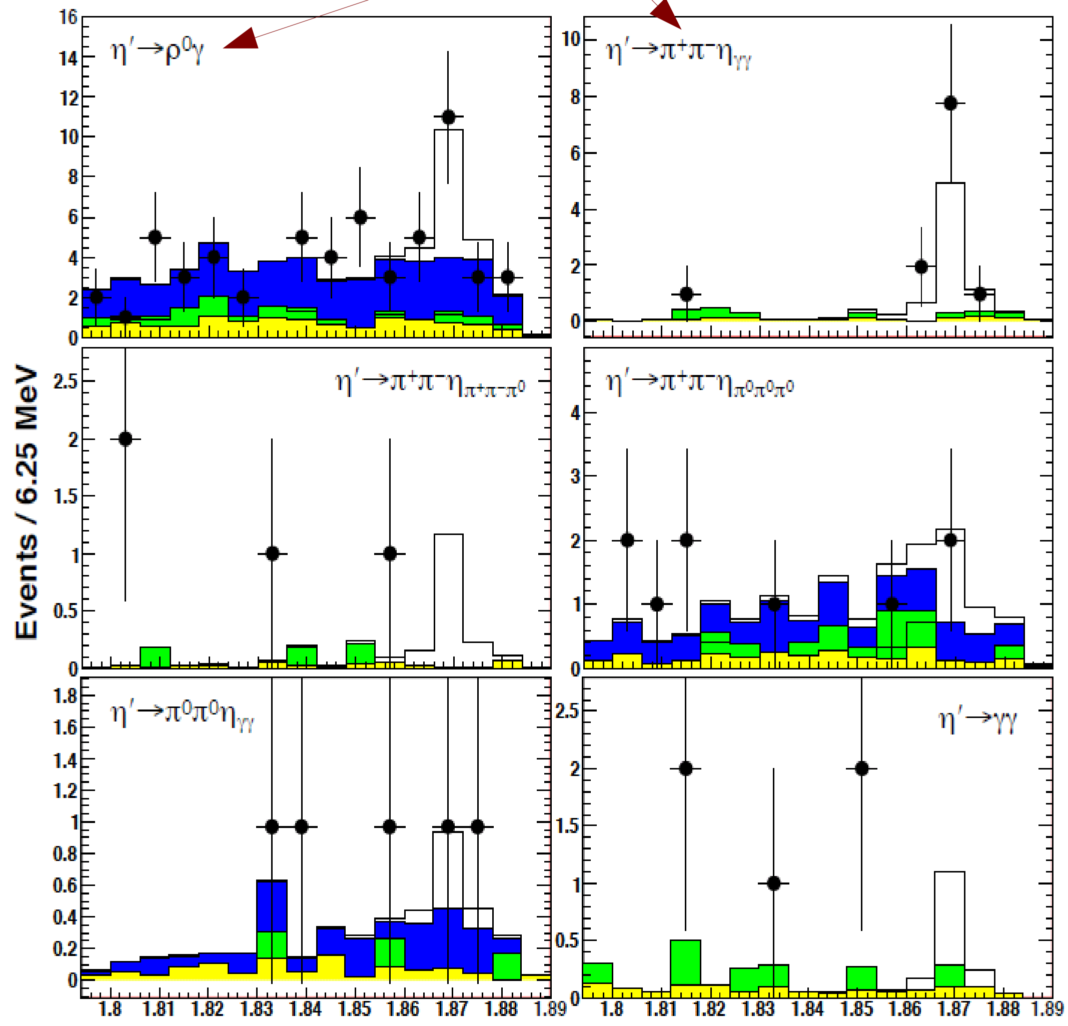
⇒ 5.6 statistical significance

First observation of $D^+ \to \eta' e^+ \nu$

Tagged: $B(D^+ \to \phi e^+ \nu) < 0.9 \times 10^{-4}$

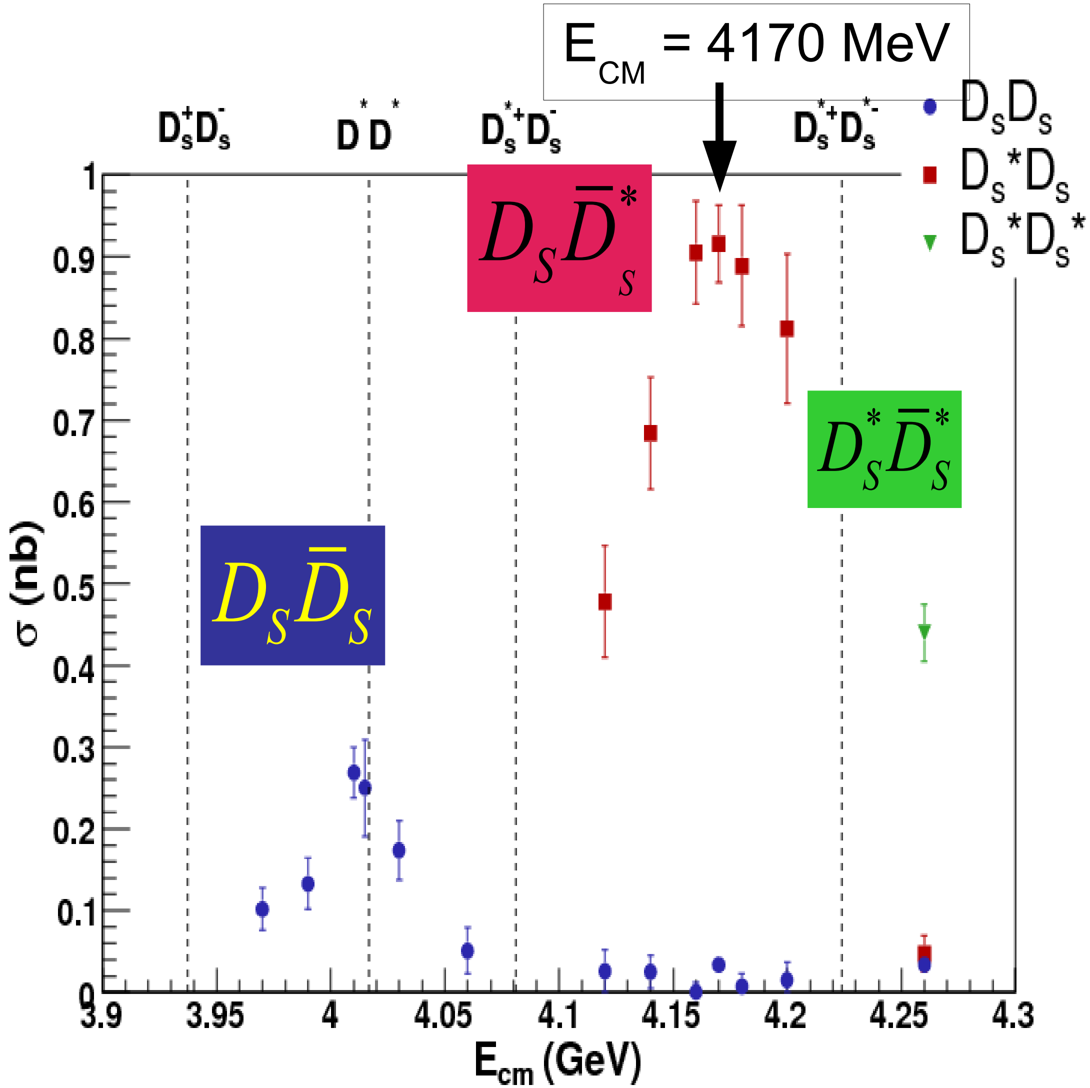
(90% C.L.)

Dominant modes




Signal $M_{BC}$ (GeV/$c^2$)

# Scanning for Optimal $D_s$ Production




Fall 2005:

Scanned $E_{CM} = 3.97 - 4.26$ GeV to find optimal $D_s$ production

Optimal $E_{CM} = 4170$ MeV

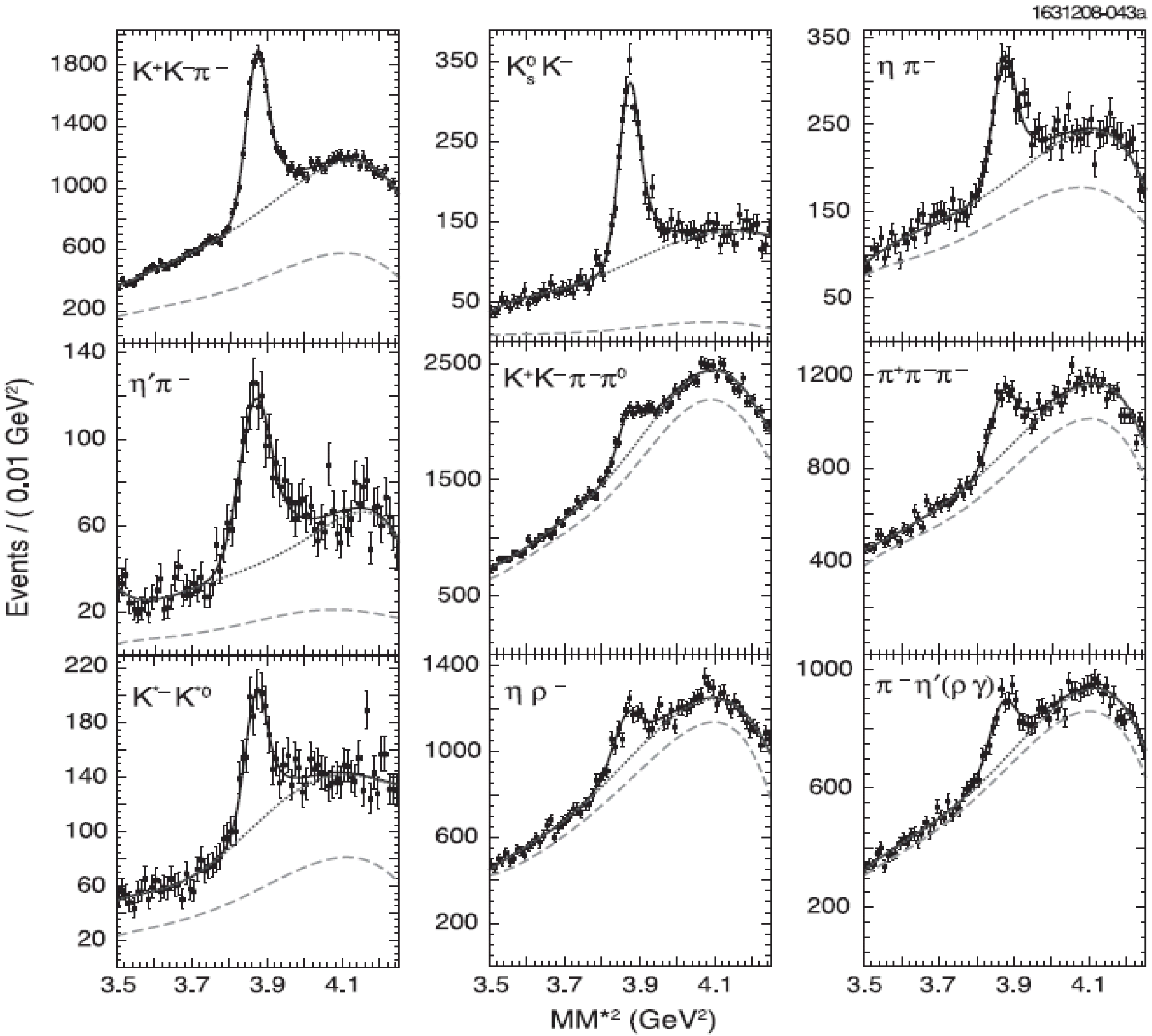
Almost all $D_s$ from $e^+e^- \to D_s \overline{D}_s{}^*$

$\sigma(e^+e^- \to D_s \overline{D}_s{}^*) = 0.9$ nb

$\sigma(\psi(3770) \to D^0\overline{D}^0 + D^+D^-) = 6.4$ nb

CLEO: PRD 80, 072001 (2009)

# $D_s$ Tags




$$MM^{*2} = (E_{CM} - E_{D_S} - E_\gamma)^2 - (\mathrm{p}_{CM} - \mathrm{p}_{D_S} - \mathrm{p}_\gamma)^2$$

300 pb$^{-1}$ @ 4170 MeV
(half of full sample)

| Mode | $D_S^+ + \gamma$ Tags | Bkgd |
|---|---|---|
| $K^+K^-\pi^-$ | $8245 \pm 245$ | 13970 |
| $K_S^0K^-$ | $1749 \pm 146$ | 1555 |
| $K^+K^-\pi^-\pi^0$ | $2913 \pm 289$ | 24985 |
| $K_S^0K^+\pi^-\pi^-$ | $841 \pm 87$ | 2440 |
| $\pi^+\pi^-\pi^-$ | $2439 \pm 558$ | 16619 |
| $\eta\pi^-$ | $1241 \pm 123$ | 3936 |
| $\eta\rho^-$ | $2168 \pm 268$ | 18450 |
| $\eta'(\pi^+\pi^-\eta)\pi^-$ | $907 \pm 109$ | 1036 |
| $\eta'(\rho^0\gamma)\pi^-$ | $1817 \pm 212$ | 12061 |
| Sum | $22320 \pm 792$ | 95052 |

Tags determined from 2-D binned maximum likelihood fit of tag $D_s$ invariant mass and $MM^{*2}$ (uses $D_s + \gamma$)

# Exclusive $D_s$ decays

PRD 80, 052007 (2009)

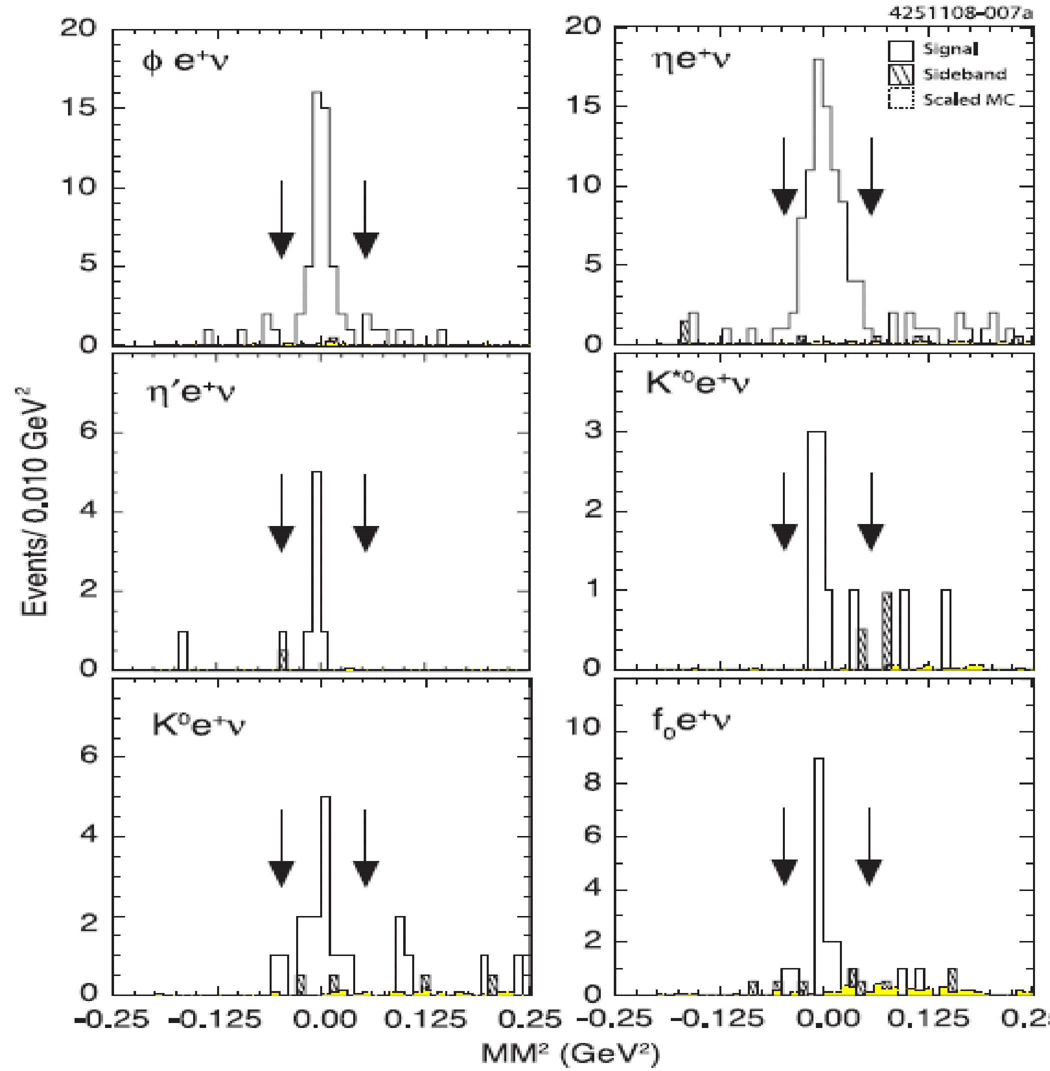
300 pb$^{-1}$ @ 4170 MeV
(half of full sample)

| Mode | $\mathcal{B}(D_S^+ \to X)$ (%) |
|---|---|
| $\phi\ e^+\nu_e$ | $2.29 \pm 0.37 \pm 0.11$ |
| $\eta\ e^+\nu_e$ | $2.48 \pm 0.29 \pm 0.13$ |
| $\eta'\ e^+\nu_e$ | $0.91 \pm 0.33 \pm 0.05$ |
| $K^0\ e^+\nu_e$ | $0.37 \pm 0.10 \pm 0.02$ |
| $K^{*0}\ e^+\nu_e$ | $0.18 \pm 0.07 \pm 0.01$ |
| $f_0(\pi^+\pi^-)\ e^+\nu_e$ | $0.13 \pm 0.04 \pm 0.01$ |

$B(D_S^+ \to f_0 e^+ \nu) B(f_0 \to \pi^+\pi^-)$

First absolute branching fraction measurements of these decay modes.

Analysis on full 600 pb$^{-1}$ data sample in progress.




$$MM^2 = (E_{CM} - E_{D_S} - E_\gamma - E_e - E_{had})^2 - (\mathrm{p}_{CM} - \mathrm{p}_{D_S} - \mathrm{p}_\gamma - \mathrm{p}_e - \mathrm{p}_{had})^2$$

# $D_s \to \phi$, $f_0(980)$ e ν

PRD 80, 052009 (2009)

600 pb$^{-1}$ @ 4170 MeV (full data sample)

Suggestion that $B_s \to J/\psi f_0$ can be an alternative to $B_s \to J/\psi\, \phi$ to measure CP violation in the $B_s$ system

($J/\psi f_0$ is CP-state, no angular analysis)

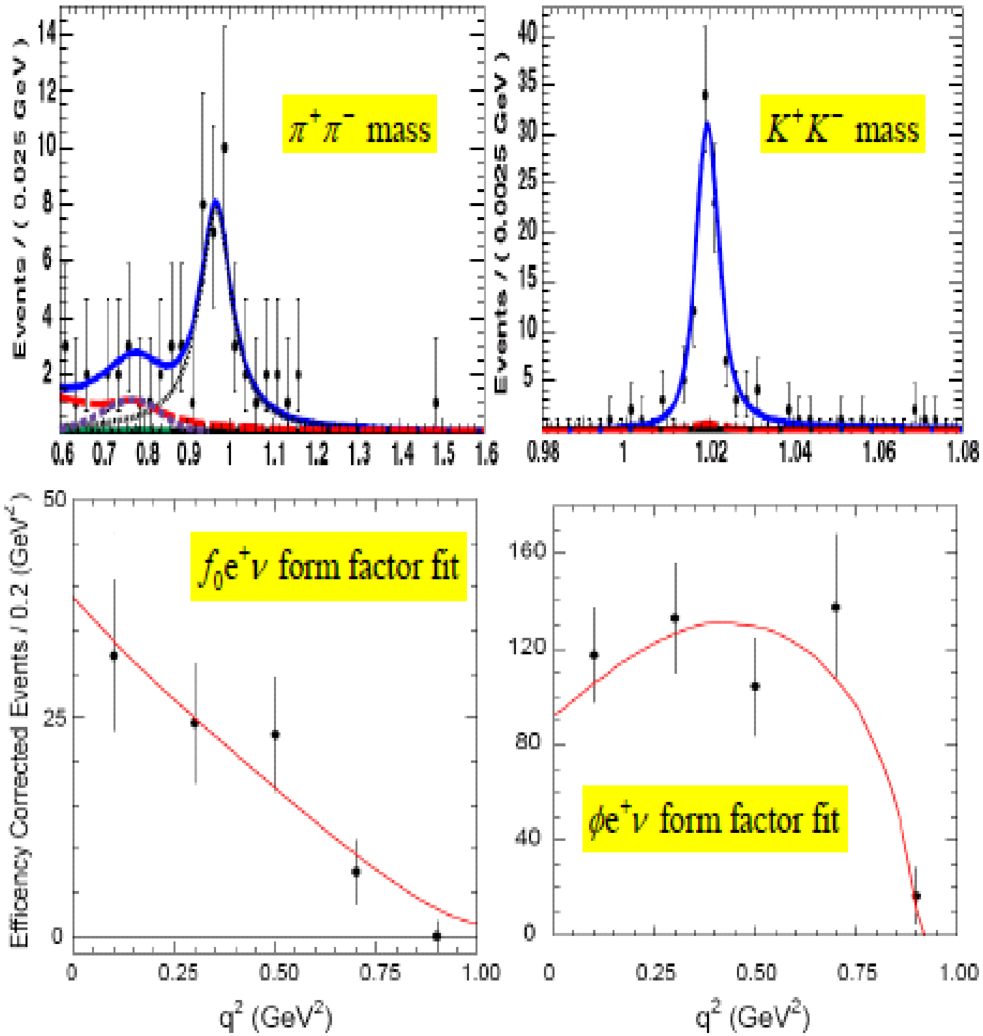
Stone & Zhang [PRD 79, 074024 (2008)]

$$\left.\frac{\Gamma(D_s^+ \to f_0(980)e^+\nu, f_0 \to \pi^+\pi^-)}{\Gamma(D_s^+ \to \phi e^+\nu, \phi \to K^+K^-)}\right|_{q^2=0} = (42 \pm 11)\%$$

$$\left[\text{Predicted to equal } \frac{\Gamma(B_s \to J/\Psi f_0(980), f_0 \to \pi^+\pi^-)}{\Gamma(B_s \to J/\Psi\phi, \phi \to K^+K^-)}\right]$$

$B(D_S^+ \to f_0(\pi^+\pi^-)\, e^+ \nu) = [0.20(3)(1)]\%$

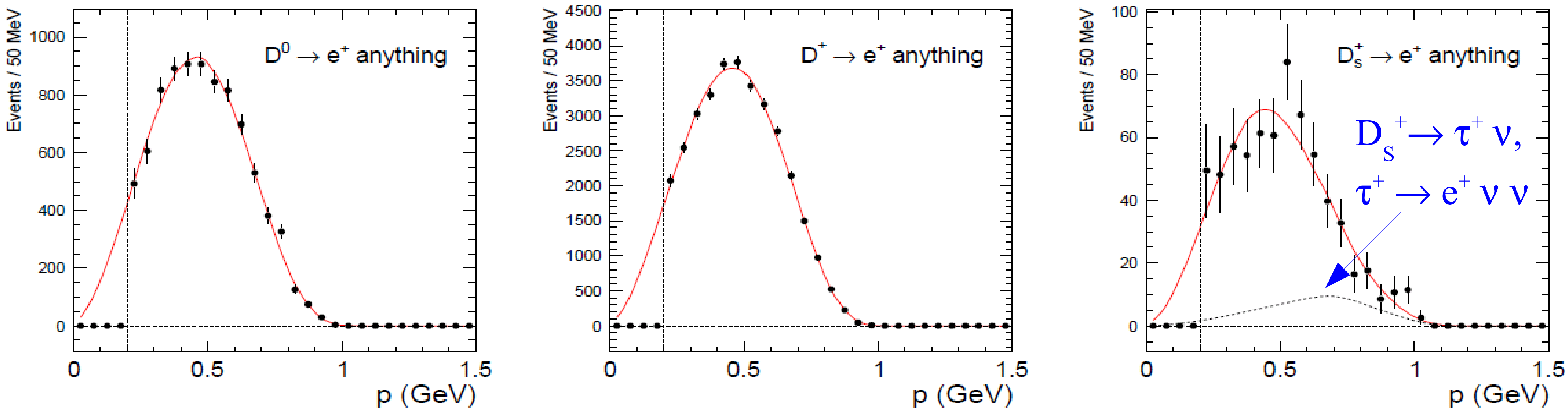
$B(D_S^+ \to \phi\, e^+ \nu) = [2.36(23)(13)]\%$



# Inclusive Semileptonic Charm Decays

Uses clean $D^0 \to K^+ \pi^-$, $D^- \to K^+ \pi^- \pi^-$, $D_s^- \to \phi(K^+K^-) \pi^-$ tags

PRELIMINARY




| | $\mathcal{B}(D^0 \to Xe^+\nu)$ | $\mathcal{B}(D^+ \to Xe^+\nu)$ | $\mathcal{B}(D_S^+ \to Xe^+\nu)$ | |
|---|---|---|---|---|
| Inclusive (%) | $6.55 \pm 0.10 \pm 0.09$ | $16.36 \pm 0.11 \pm 0.29$ | $6.49 \pm 0.40 \pm 0.18$ | CLEO |
| Σ Exclusive (%) | $6.34 \pm 0.18$ | $14.8 \pm 0.4$ | $6.5 \pm 0.6$ | PDG |

$$\frac{\Gamma(D^+ \to Xe^+\nu)}{\Gamma(D^0 \to Xe^+\nu)} = 0.985 \pm 0.016 \pm 0.024$$

(Consistent with isospin)

$$\frac{\Gamma(D_S^+ \to Xe^+\nu)}{\Gamma(D^0 \to Xe^+\nu)} = 0.813 \pm 0.052 \pm 0.028$$

Voloshin suggests difference between $D^0$ and $D_s$ may be non-factorizable terms, similar effect in $B^0, B^\pm \to X_u l\nu$ and determination of $V_{ub}$ [PLB 515, 74 (2001)]

# Summary

CLEO has begun to finalize its charm semileptonic decay results

* $D \to K e^+ \nu$, $\pi e^+ \nu$ are in general agreement with LQCD, form factor normalization uncertainties (Keν: 1%, πeν: 3%) leads uncertainties from LQCD (10%)
* First form factor measurement of $D^+ \to \eta e^+ \nu$ (preliminary)
* First observation of $D^+ \to \eta' e^+ \nu$ (preliminary)
* First absolute branching fraction measurements of 6 largest $D_s^+$ decays
* Precise measurements of inclusive $D^0$, $D^+$, $D_s^+$ decays (preliminary)

Other analyses still in progress using full data samples

* $D^- \to K^{*0} e^- \nu$, $K^{*0} \mu^- \nu$
* $D \to \rho e^+ \nu$, $D^+ \to \omega e^+ \nu$
* Exclusive $D_s^+$ decays

All of these measurements will be improved upon by BESIII with their soon-to-be collected open charm data samples

# Backup Slides

# Electron ID

CLEO-c could only make precision measurements of $D \to X e \nu$ decays
[could not identify $\mu$ in $D \to X \mu \nu_\mu$ decays ($\mathbf{p}_{max} \approx 1.2$ GeV in these decays)
because $\mathbf{p} > 1.5$ GeV needed for Muon Chamber]

Electron ID: Likelihood fit using information from RICH, dE/dx,
associated shower energy in EM calorimeter
and momentum measured in tracking volume [$E_{CC}/\mathbf{p}$]

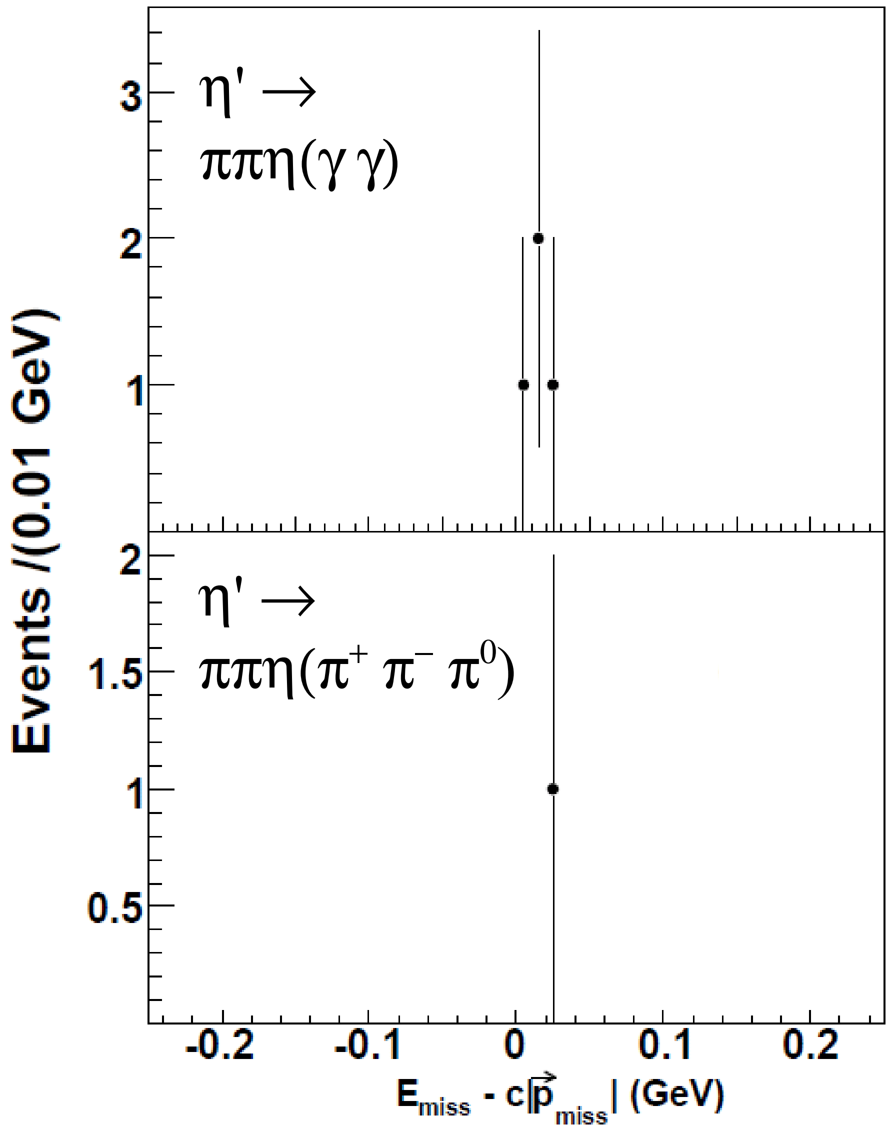
Criteria: $\mathbf{p} > 200$ MeV, $|\cos\theta| < 0.9$, satisfies Likelihood Fit
Results: $\varepsilon = 71\%$ ($\mathbf{p}$ = [0.2,0.3] GeV), 95% ($\mathbf{p}$ = [0.3,1.0] GeV)
K/π-faking-e rate ≈ 0.1% (whole momentum range)

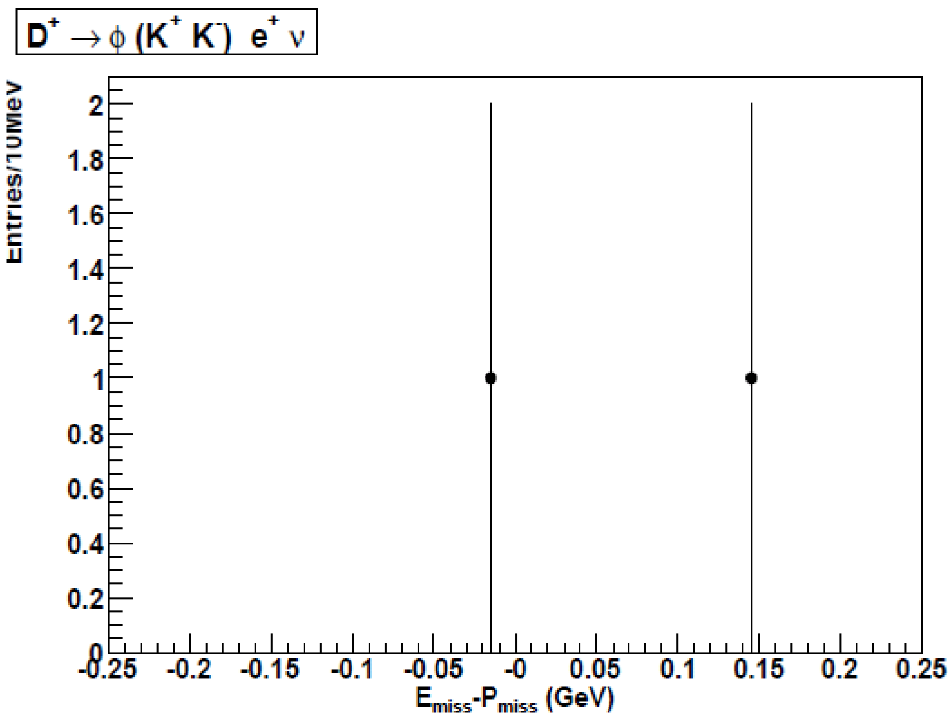
80% of all electrons from D semileptonic decays fall in this range

All X e ν semi-leptonic analyses used this electronID package

# Tagged $D^+ \to \eta', \varphi\, e^+ \nu$

PRELIMINARY



# Difficulties with $D_s$ $D^*_s$

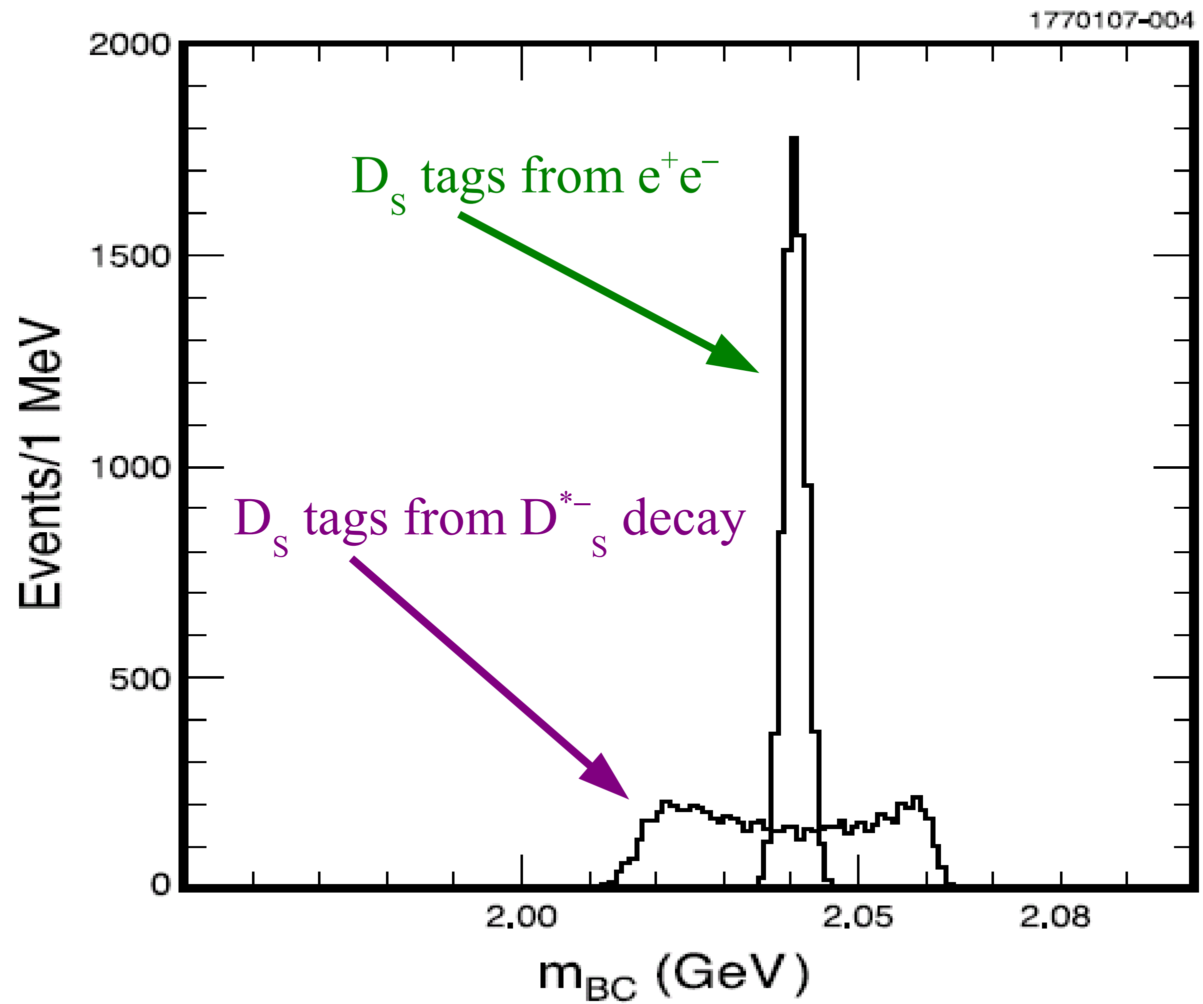
$e^+e^- \to D^+_s D^{*-}_s \to D^+_s (D^-_s \gamma)$

<u>Two Tagging Issues</u>

* $\gamma$ detection from $D^{*-}_s$ decay
  ($\varepsilon \sim 70\%$ based on ang dist)

* Distorted $m_{BC}$

CLEO-c:
Use $D_s$ inv mass to select tags ($\sigma_{InvMass} > \sigma_{mBC}$)



# Tag $D_s$ Invariant Mass

600 $pb^{-1}$ @ 4170 MeV
(full data sample)