XLIId RENCONTRES DE MORIOND
ELECTROWEAK INTERACTIONS AND UNIFIED THEORIES

CLEO-c Results

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CLEO COLLABORATION

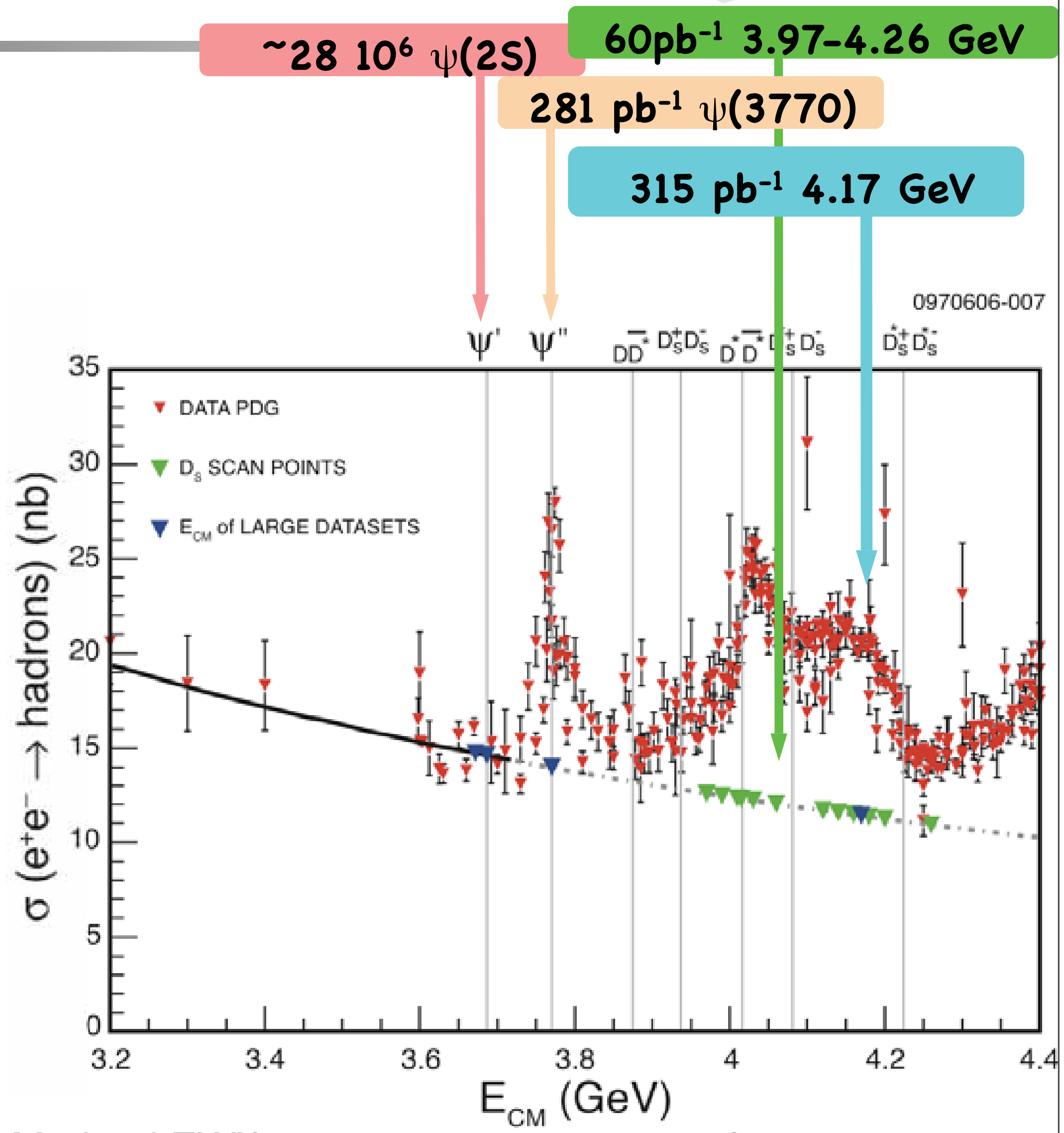
OUTLINE

- Program Overview
- Physics Motivation
- Pure leptonic decays
  - D & D_s Decay constants
- Semi Leptonic decays
  - Exclusive decay ~ CKM & FF
  - Rare Decays

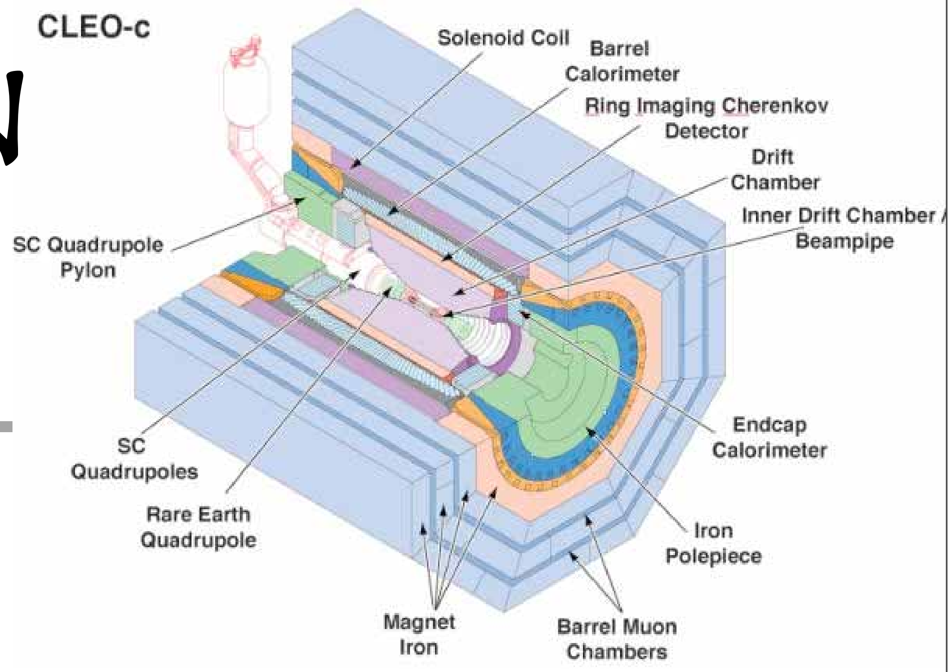
CLEO-C PROGRAM

Charm threshold at various energies

- 4170 MeV: D_s decay
  - Leptonic decays.
  - Hadronic branching fractions.
  - Semi-Leptonic decays.
- 3770 MeV: D decay
  - (Semi) Leptonic decays.
  - Hadronic branching fractions.
  - Dalitz Analysis.
  - D-mixing.
  - Quantum Correlation in D system.
- 3686 MeV: $\psi(2S)$, χ_c, J/ψ, h_c, η_c
- 3970-4260 MeV: Ds scan & Y(4260).



MOTIVATION



CLEO-c provides a unique environment for studying Leptonic & Semi-Leptonic charm decays. Modern detector at charm threshold.

- ✓ Good tracking & particle identification & EM calorimetry
- ✓ Low track multiplicity ~ 5 to 6 tracks/event

Pure Leptonic decays:

- Determine f_D and f_{Ds} use them to test LQCD models.
- Help calibrate LQCD for f_B and f_{Bs} predictions.

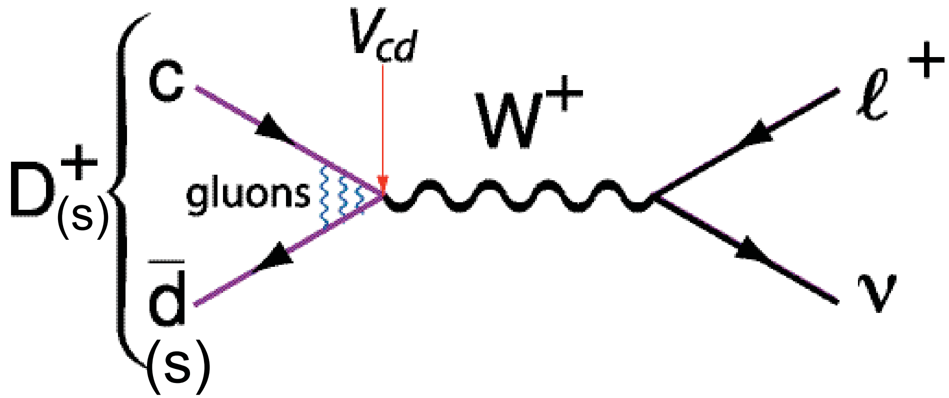
Semi Leptonic decays:

- Form factors and QCD checks.
  - Assuming V_{cs} & V_{cd} known.
- Precision measurements V_{cd} & V_{cs}.
  - Trusting LQCD predictions.

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

Leptonic Decays

- c and $\bar{q}$ annihilation is proportional to overlap function.



$$\Gamma\left(D^+_{(S)} \to l^+\nu\right) = \frac{G_F^2}{8\pi} f^2_{D_{(S)}} m_l^2 M_{D^+_{(S)}} \left(1 - \frac{m_l^2}{M^2_{D_{(S)}}}\right)^2 \left|V_{c(d,s)}\right|^2$$

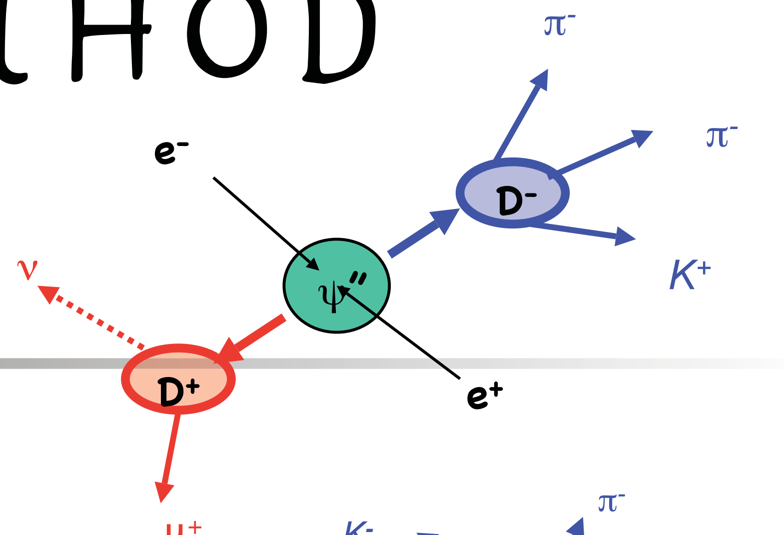
SM

$D \to l\nu$ $\Gamma = 2.35\text{x}10^{-5}:1:2.64$ (e:μ:τ)

$D_s \to l\nu$ $\Gamma = 2.5\text{x}10^{-5}:1:9.7$ (e:μ:τ)

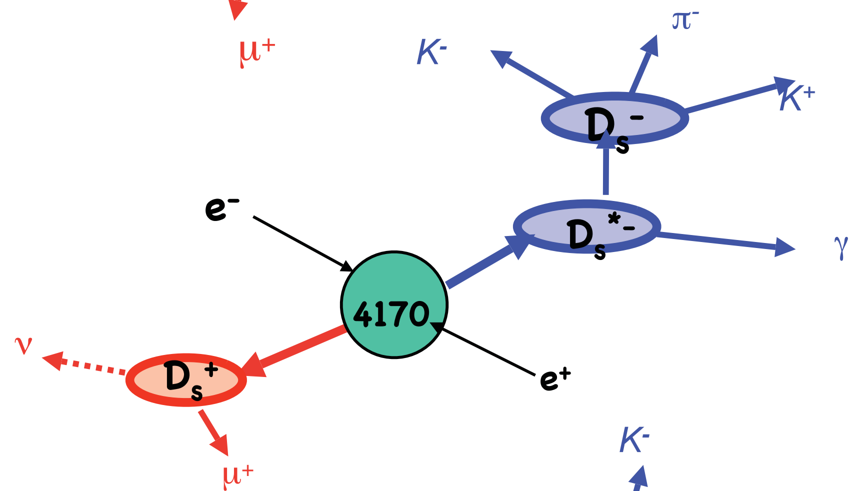
D & D_s TAG METHOD

D TAG



$D\bar{D}$ Tag:

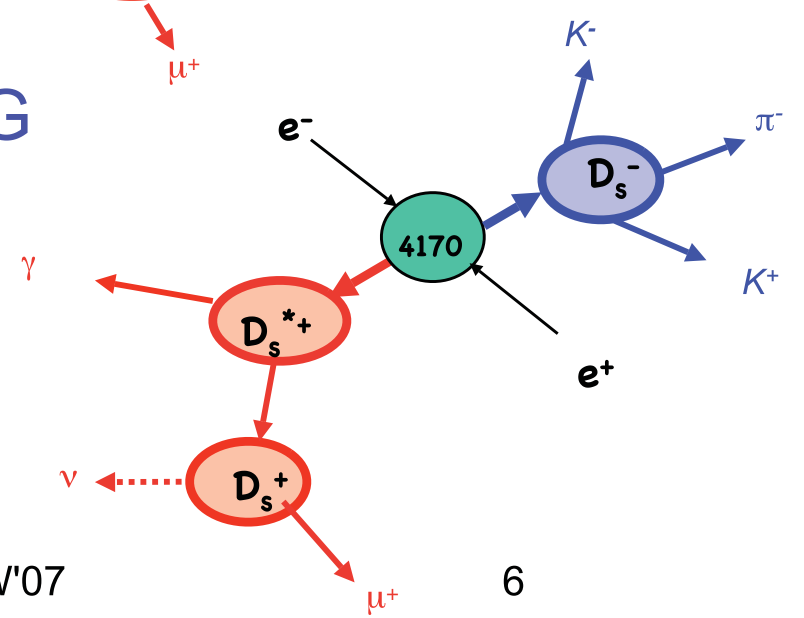
- MarkIII pioneered Dtag method of $D\bar{D}$ production at threshold and used by CLEO and BESII.



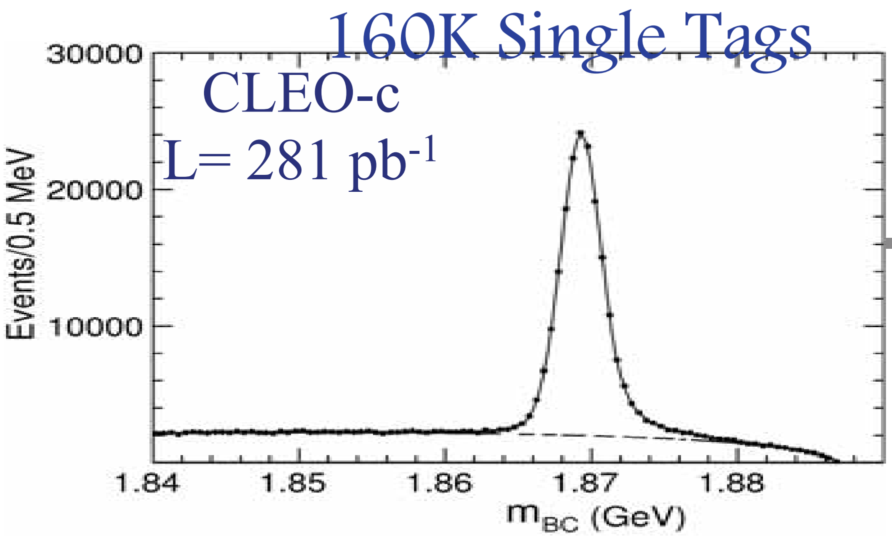
$D_s^*\bar{D}_s$ Tag:

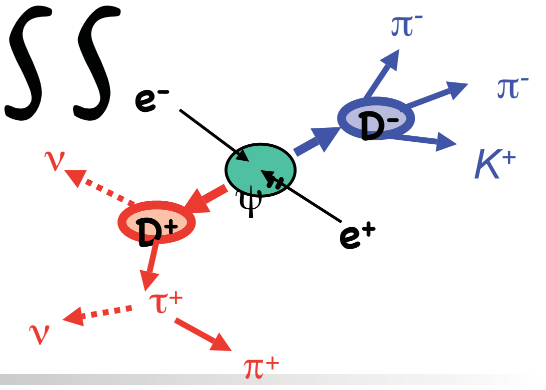
- Tag one in a D_s hadronic mode
  - Add a photon
  - Signal may be from D_s or D_s^*
- Form a χ^2 with both hypothesis and keep the best.
- Look for signal in missing mass.

D_s TAG

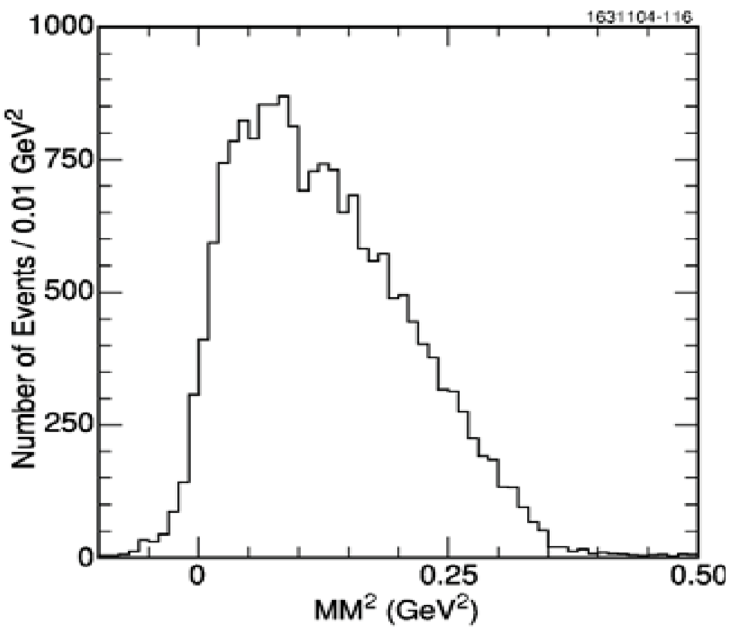


D^- Invariant Mass





$$m_{bc} = \sqrt{\left(E_{beam} - \left|p_{D_{tag}}\right|^2\right)} \approx M_D$$



MM^2

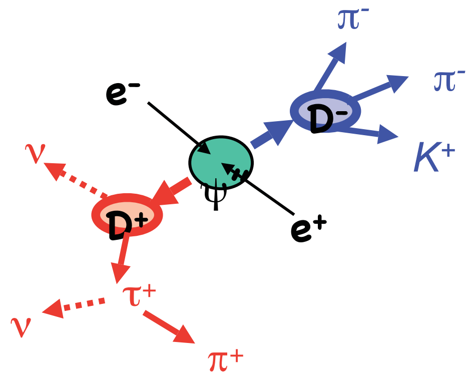
$D^+ \rightarrow \tau^+\nu$ ($\tau^+ \rightarrow \pi^+\nu$)
Two ν s and π^+ in the final state.

Look for π^+ opposite to D tag and calculate Missing mass squared.

$$MM^2 = \left(E_{beam} - E_{trk}\right)^2 - \left(p_D + p_{trk}\right)^2$$

MM^2 for $\tau^+\nu$ will not peak at 0 but rather be spread out.

$D^+ \to \tau^+ \nu$



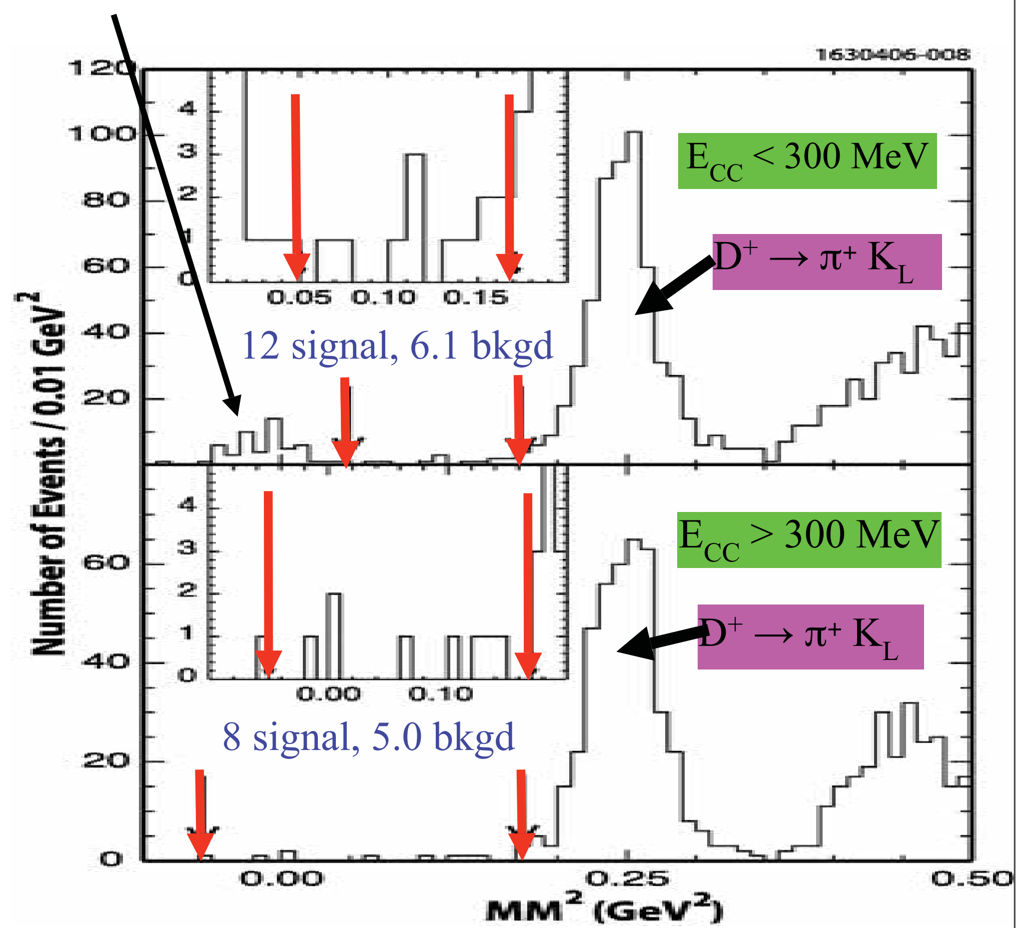
PRD 73, 112005 (2006)

Select π tracks (from τ^+) in two MM^2 regions based on calorimeter (CC) info:

Interactions in calorimeter

- $E_{CC} < 300$ MeV **minimum interacting μ^+ & π^+**
- $E_{CC} > 300$ MeV **interacting π^+**

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



Using CLEO-c $B(D^+ \to \mu^+\nu) = (3.5\pm1.4\pm0.6)\times10^{-4}$
SM: $B(D^+ \to \tau^+\nu) = (1.1 \pm 0.2)\times10^{-3}$

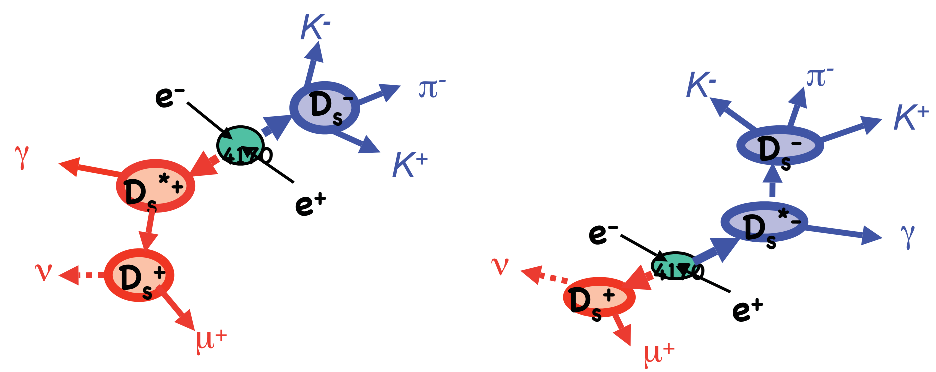
$$\frac{[B(D^+ \to \tau^+\nu)/B(D^+ \to \mu^+\nu)]_{meas}}{[B(D^+ \to \tau^+\nu)/B(D^+ \to \mu^+\nu)]_{SM}} < 1.8 \text{ (90\% CL)}$$

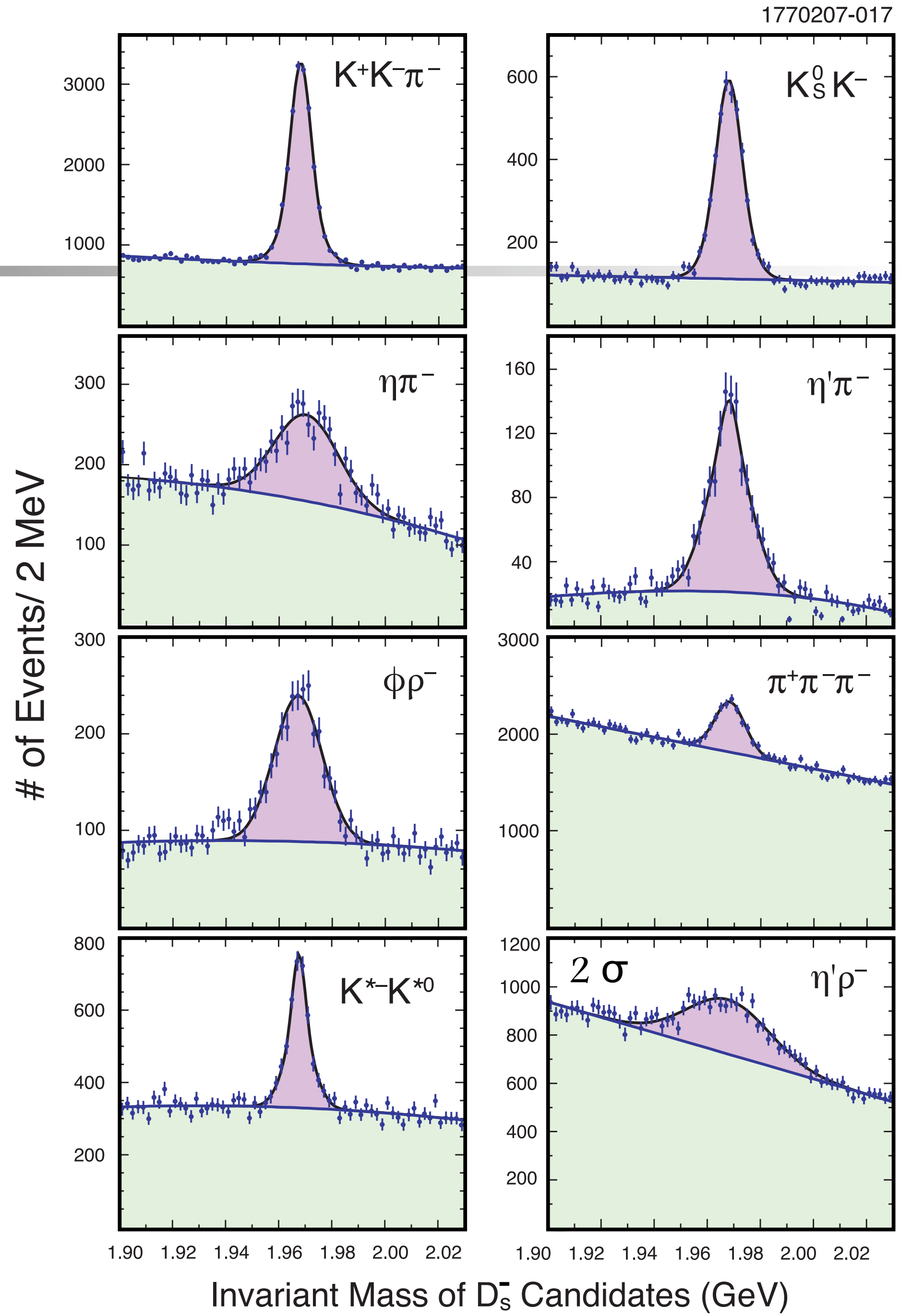
Ds invariant masses

315 pb⁻¹

- Detect all particles except ν
- A kinematic fit is used
  - Improve resolution
- 2.5 σ cut on "tagged D_s" mass
- Total # of D_s Tags:

  31,302±472(stat.)
- Combine γ with the selected D_s tags.

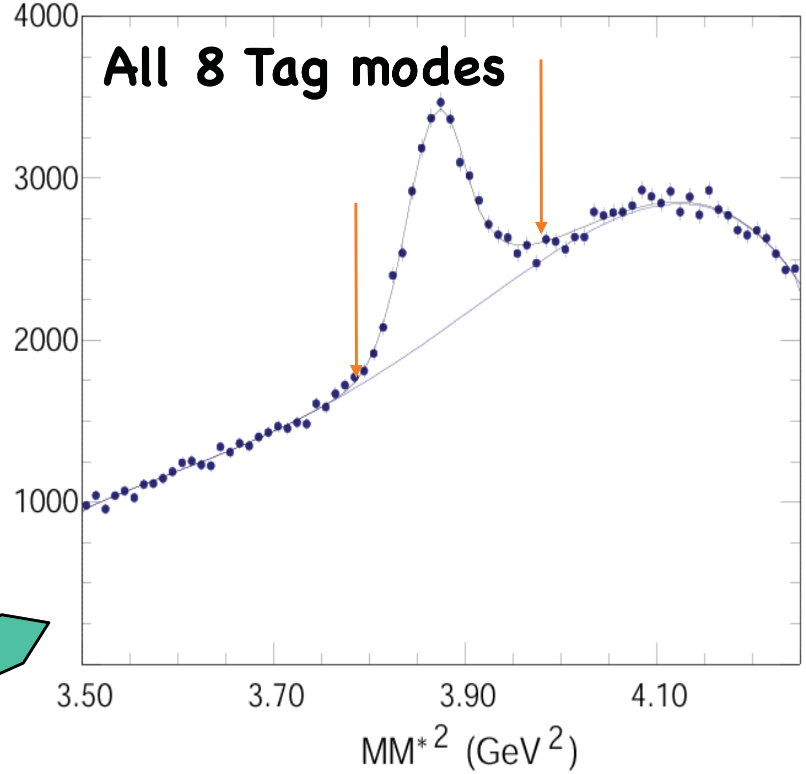




D_s Missing Mass^2

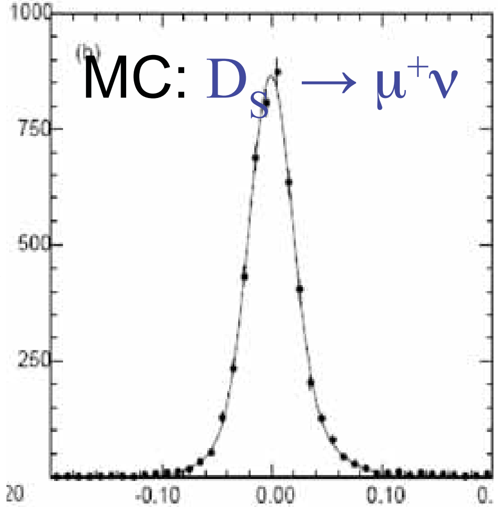
- Look at the recoiling mass against the "8 D_s" tag modes & the γ.

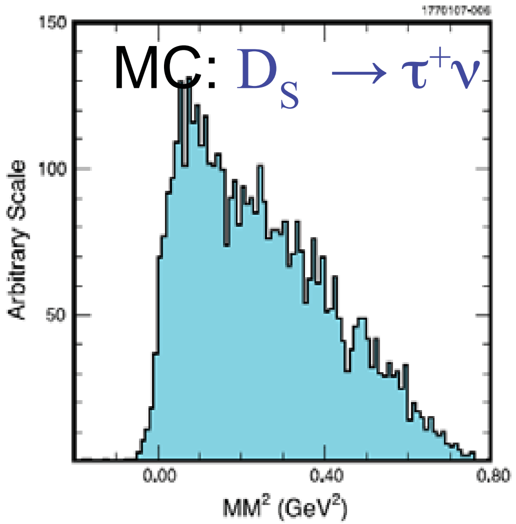
$$MM^{*2} = \left(E_{CM} - E_{D_S} - E_{\gamma}\right)^2 - \left(p_{D_S} + p_{\gamma}\right)^2$$



- Total # of D_s tags after MM^{*2} selection: 18,645±426(stat.) tags
- Look for $\mu^+\nu$ and $\tau^+\nu$ signal at the same time.
- Look at the recoiling ν or 2 ν

$$MM^2 = \left(E_{CM} - E_{D_S} - E_{\gamma} - E_{\mu}\right)^2 - \left(p_{D_S} + p_{\gamma} + p_{\mu}\right)^2$$

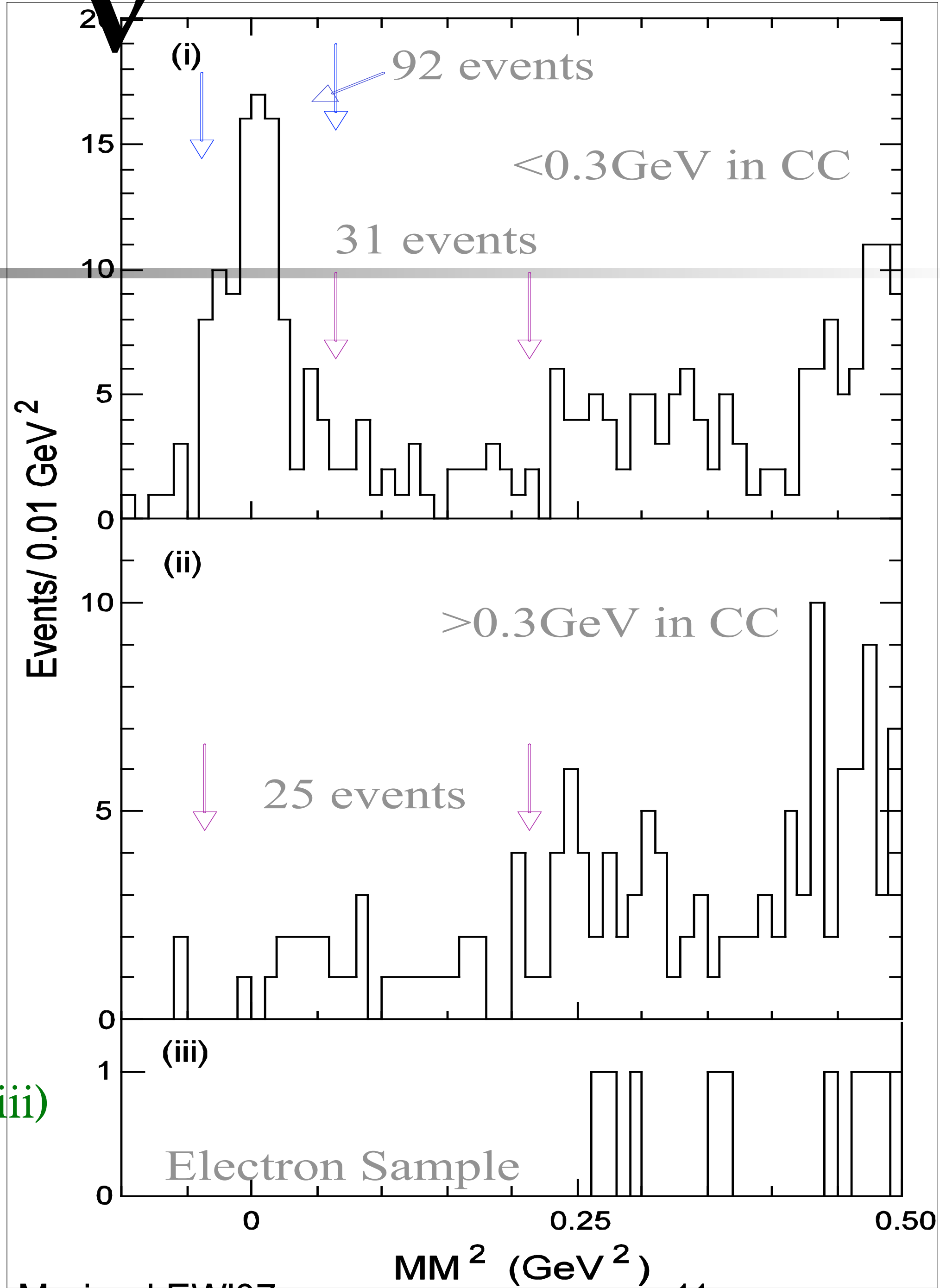




$D_s \to \mu^+\nu, \tau^+\nu$

- Three cases
  - I. Track E_{cc} < 300 MeV (μ,π) accepts ~99% μ^+ & ~60% π^+
  - II. Track E_{cc} > 300 MeV (π) accepts ~1% μ^+ & ~40% π^+
  - III. Track E_{cc} consistent with e.

- Cases 1&2 allow simultaneous study of $D_s \to \tau^+\nu$
  - 31 events in case (i)
  - 25 events in case (ii)
  - No $D_s \to e^+\nu$ seen in case (iii)



$D_s^+ \to \mu^+\nu$ & $\tau^+\nu$

$D_S^+ \to \mu^+\nu$ [Case (i)]

92 signal, 3.5 bkgd events,

$B(D_S^+ \to \mu^+\nu) = (0.59 \pm 0.07 \pm 0.03)\%$

Use SM for $\tau\nu$ bkg near $MM^2=0$

$D_S^+ \to \tau^+\nu, (\pi^+\nu)\,\nu$ [Case (i) + Case (ii)]

Total of 56 signal, 8.6 bkgd events

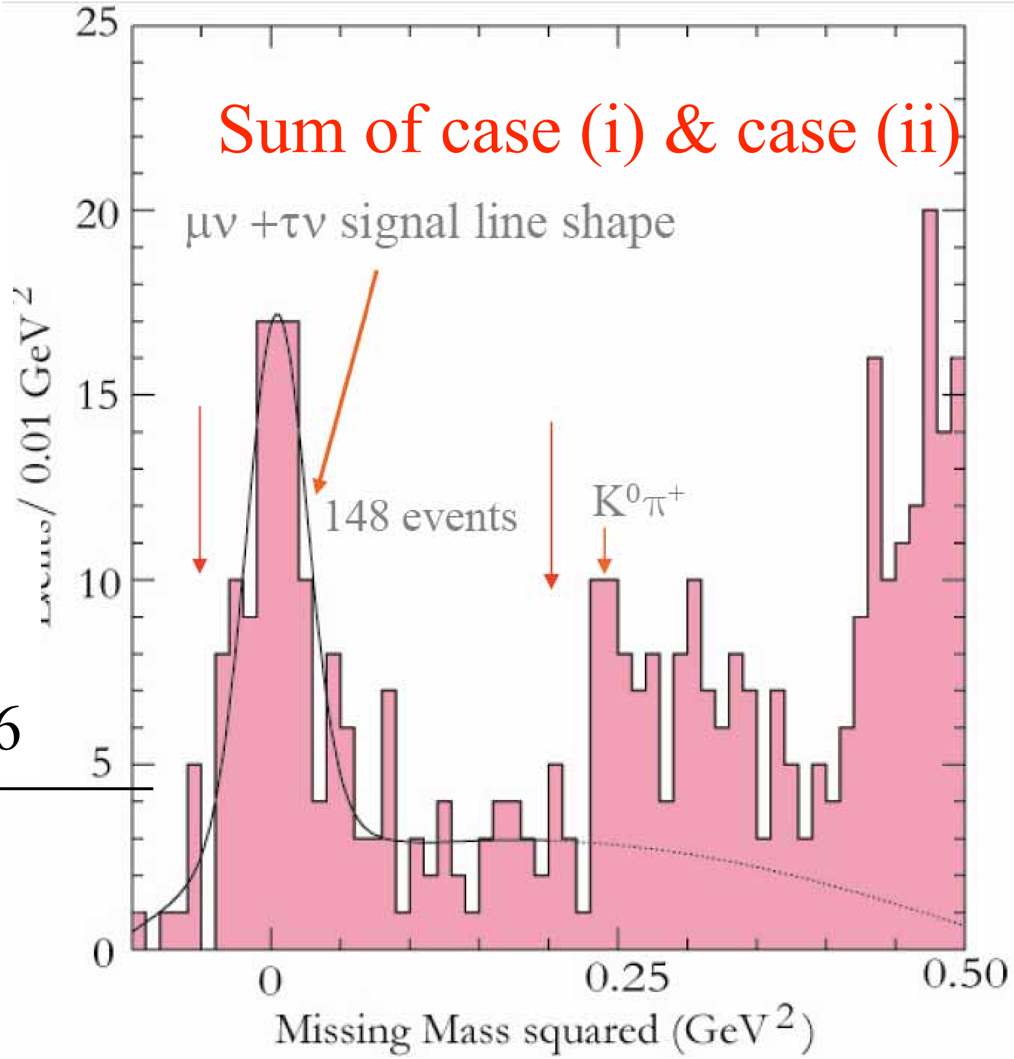
$B(D_S^+ \to \tau^+\nu) = (8.0 \pm 1.3 \pm 0.4)\%$

$[B(D_S \to \tau^+\nu) = (6.4 \pm 1.5)\%$ PDG06]

Sum $\tau\nu+\mu\nu$ signal $MM^2 < 0.2$,

$B^{eff}(D_S \to \mu^+\nu) = (0.62 \pm 0.06 \pm 0.03)\%$

$B(D_S \to \mu^+\nu) = (0.61 \pm 0.19)\%$ PDG06



$D_S^+ \to e^+\nu$ [Case (iii)]

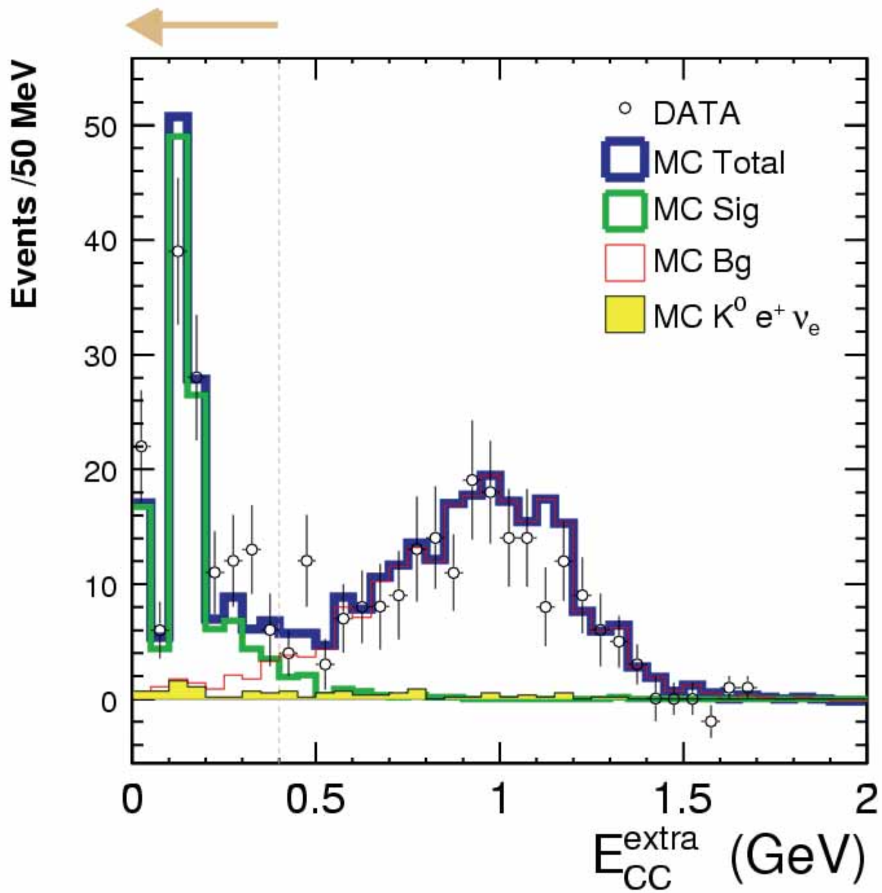
No events in signal region

$B(D_S^+ \to e^+\nu) < 1.3 \times 10^{-4}$ (90% CL)

Measuring $D_s^+ \to \tau^+\nu$, $\tau^+ \to e^+\nu\nu$

Complimentary Analysis

- Three ν s in the final state
- $B(D_s^+ \to \tau^+\nu) \cdot B(\tau^+ \to e^+\nu\nu) \sim 1.3\%$ is "significant" compared with expected $B(D_s^+ \to Xe^+\nu) \sim 8\%$
- Analysis Technique
  - Find D_s tag and e+ ~ no need to find γ from D_s^*
  - No extra track
  - $E_{cc}^{extra} < 400$ MeV



Summary

$B(D_s \to \tau^+\nu) = (6.3 \pm 0.8 \pm 0.5)\%$ from $\tau^+ \to e^+\nu\nu$ analysis

$B(D_s \to \tau^+\nu) = (8.0 \pm 1.3 \pm 0.4)\%$ from $\tau^+ \to \pi^+\nu$ analysis

f_{D_s} Summary

$D_s \rightarrow \mu\nu$:

$f_{Ds} = (264 \pm 15 \pm 7)$ MeV

$D_s \rightarrow \tau\nu$ and $\tau \rightarrow \pi\nu$:

$f_{Ds} = (310 \pm 25 \pm 8)$ MeV

$D_s \rightarrow \tau\nu$ and $\tau \rightarrow e\nu\nu$:

$f_{Ds} = (278 \pm 17 \pm 12)$ MeV

Weighted CLEO-c Results:

$f_{Ds} = (273 \pm 10 \pm 5)$ MeV,

Using the CLEO-c f_D result,

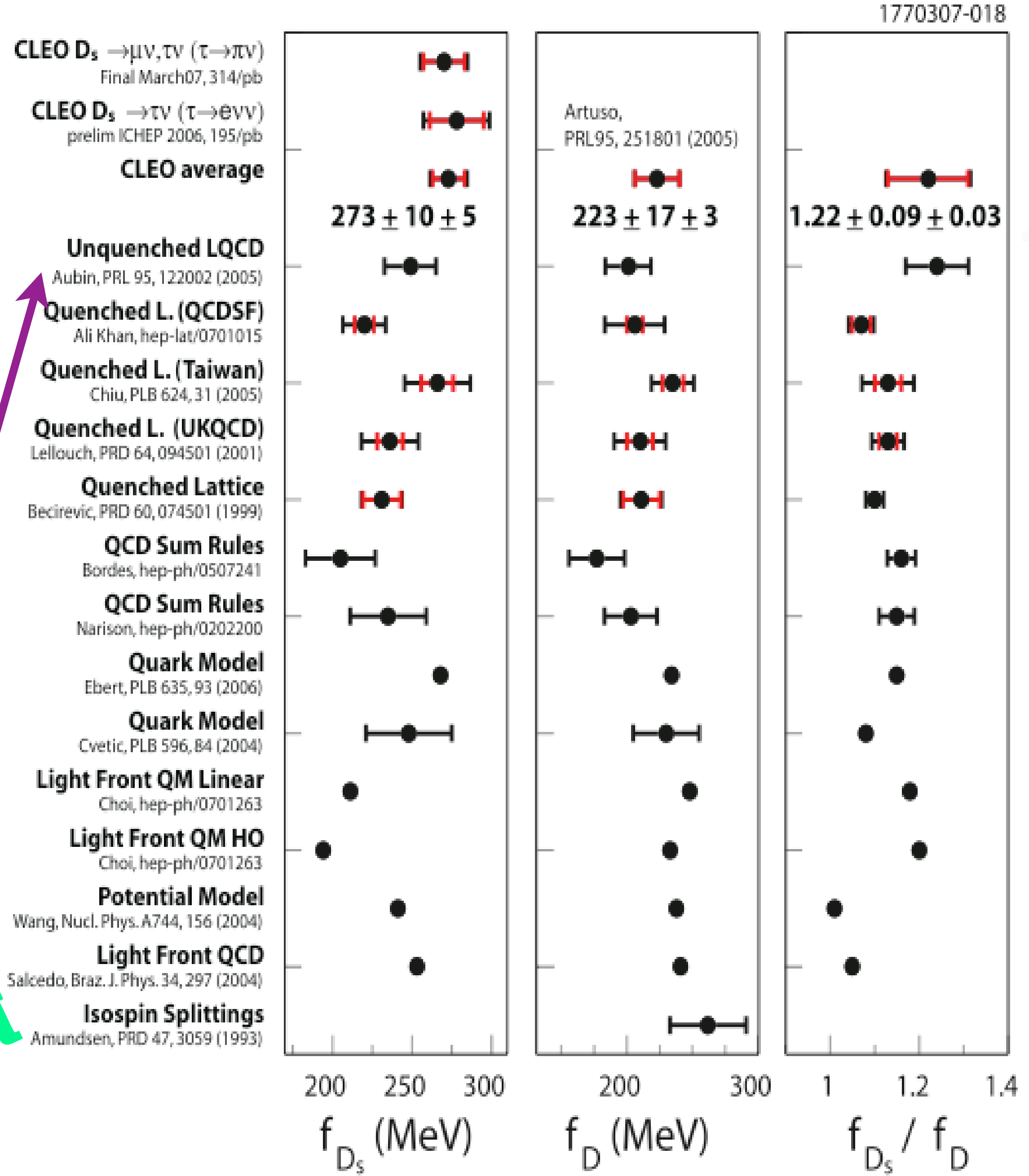
$f_D = (223 \pm 17 \pm 3)$ MeV,

Ratio:

$f_{Ds}/f_D = 1.22 \pm 0.09 \pm 0.03$

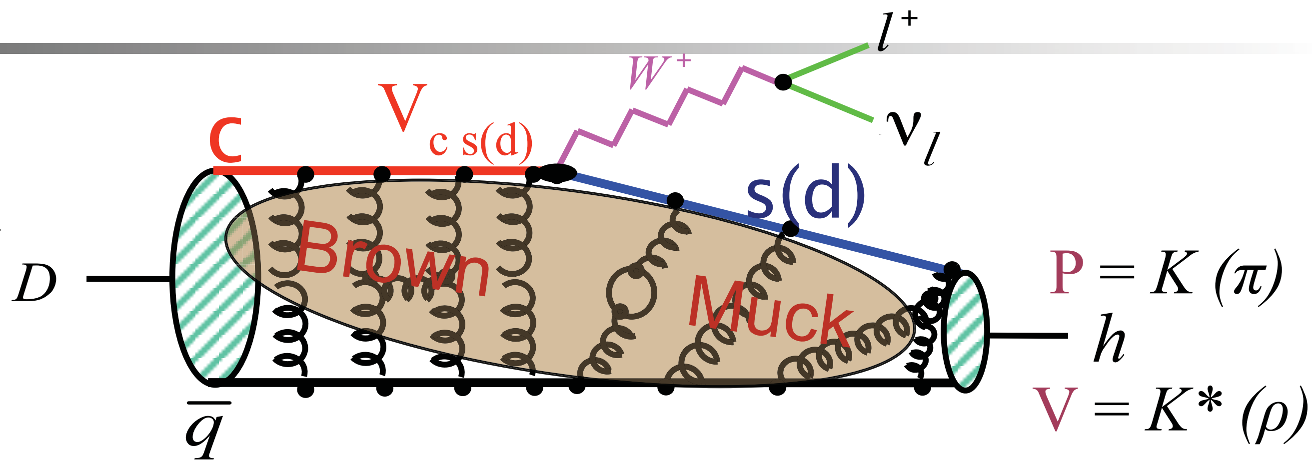
<u>LQCD</u>: $f_{Ds}/f_D = 1.24 \pm 0.07$

Consistent



Semi leptonic decays: CKM elements & form factor

Best way to determine CKM elements is to study semileptonic decays

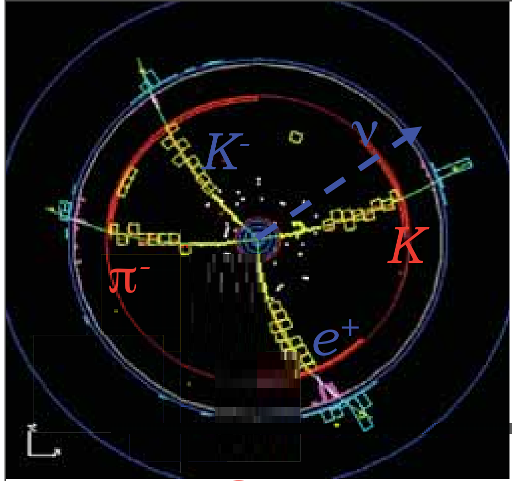


For any pseudoscalars (P)

$$\frac{d\Gamma(D^+ \to Pe\upsilon)}{dq^2} = \frac{G_F^2}{24\pi^3}\left|V_{cq}\right|^2 p_P^3 \left|f_+(q^2)\right|^2$$

Propagator (W^+) q^μ transfer is defined as

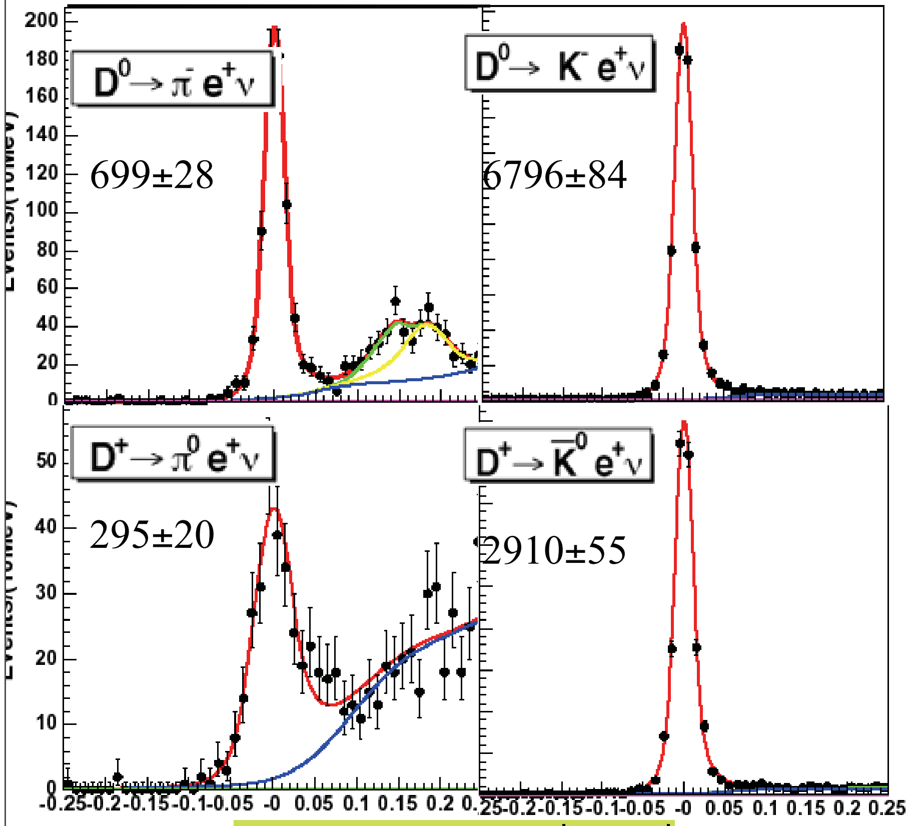
$$q^2 = (p_D^\mu - p_{K(\pi)}^\mu)^2 = m_D^2 - m_{K(\pi)}^2 - 2m_D E_{K(\pi)}$$



D-Exclusive Semi-Leptonic Decays

Missing 4-Mom → $p^{\mu}_{miss} = p^{\mu}_{event} - p^{\mu}_{visible}$ $\quad p_{visible} = \Sigma p_{charge} + \Sigma p_{neutral}$

Standard D-Tag Method



$$U_{miss} = E_{miss} - |p_{miss}|$$

Untagged ν reconstruction

281pb-1

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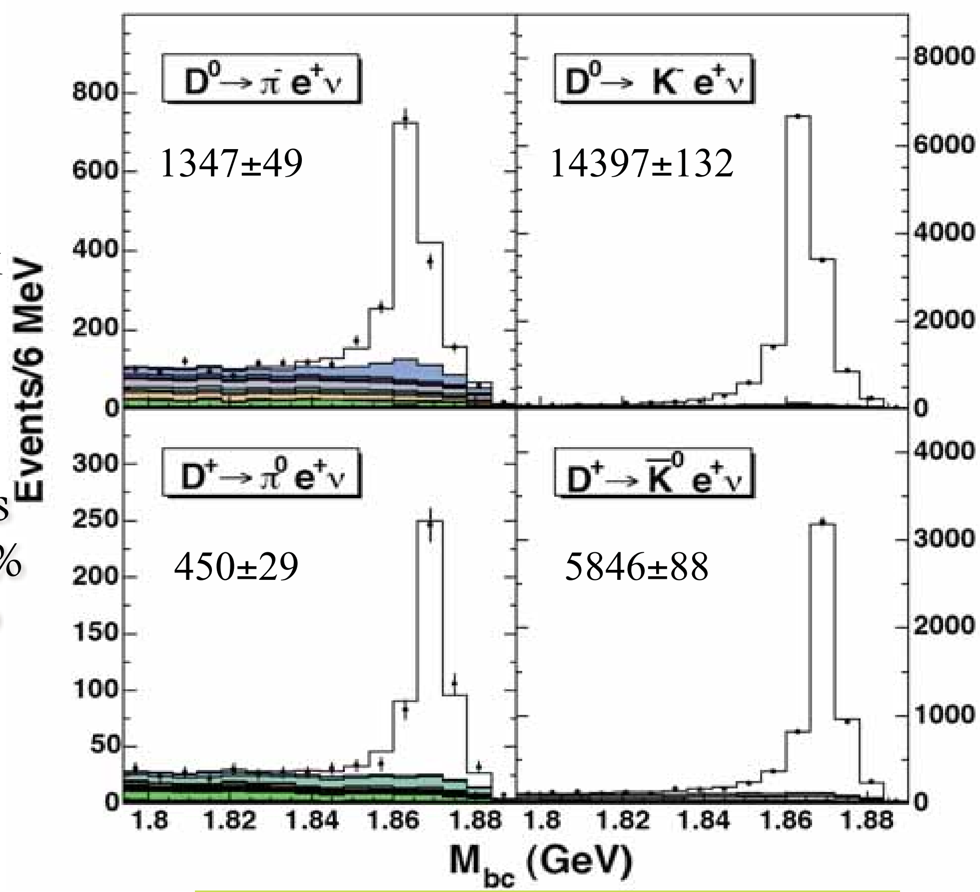
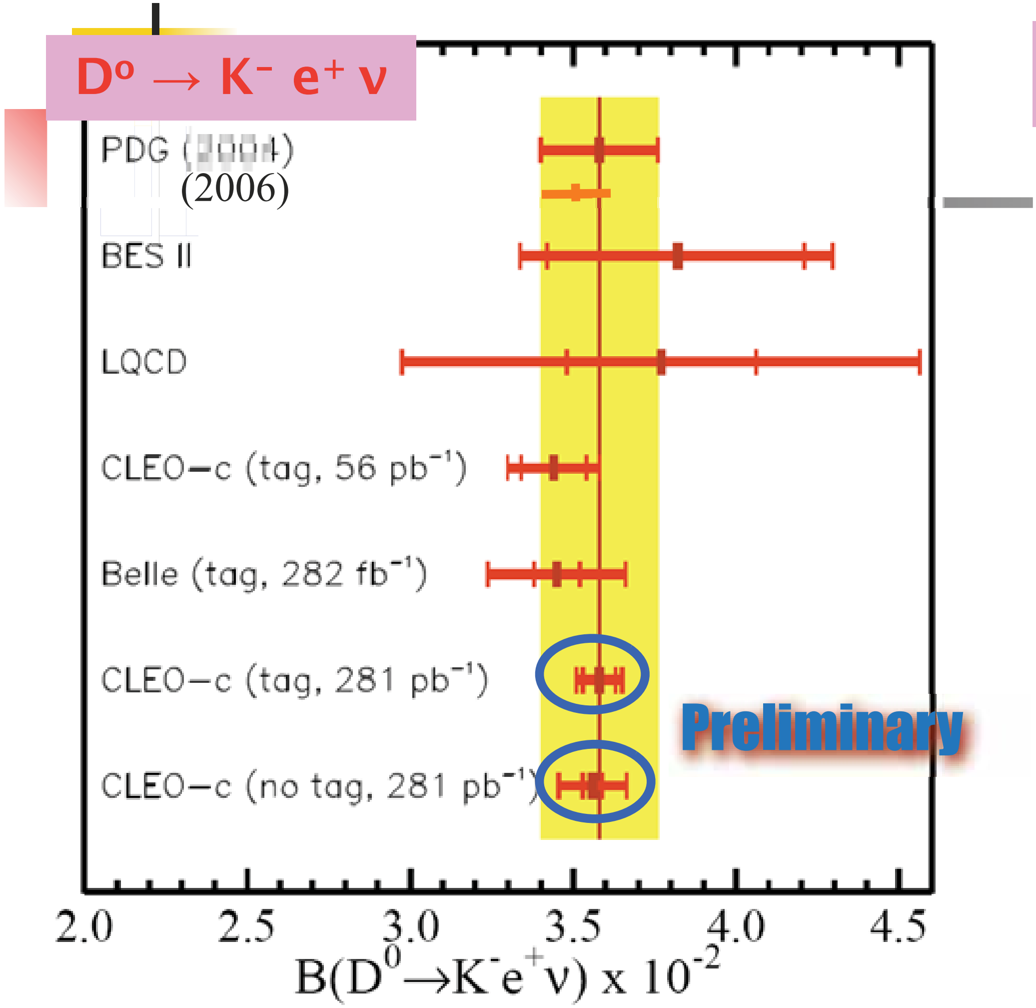
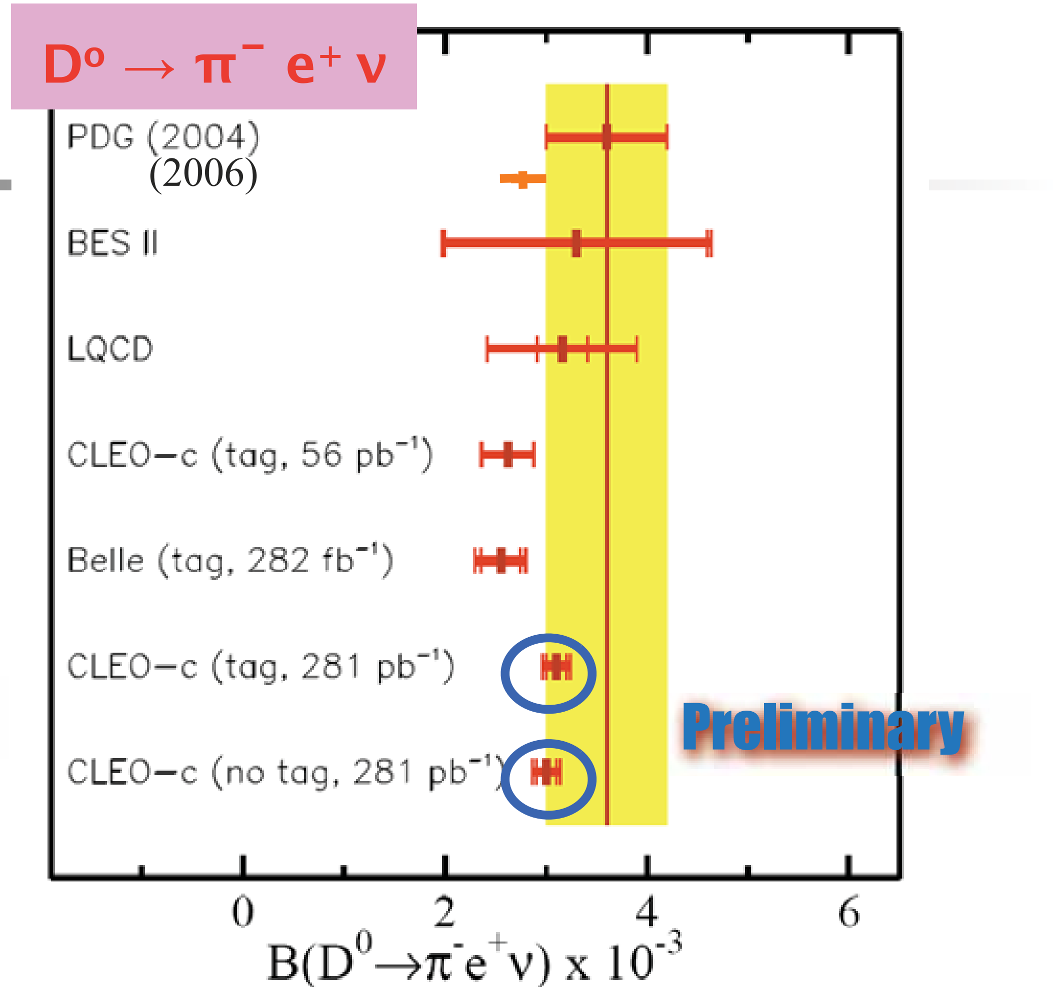
Two methods have 40% overlap



$$M_{bc} = \sqrt{\left(E^2_{beam} - \left(p_{K(\pi)} + p_e + \xi p_{miss}\right)^2\right)}$$

Exclusive Branching Ratio Comparison





Good consistency between two methods.
LQCD precision lags experiment.

FORM FACTOR FIT COMPARISON(TAG)

3 popular FF parameterizations methods

Simple Pole Model

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

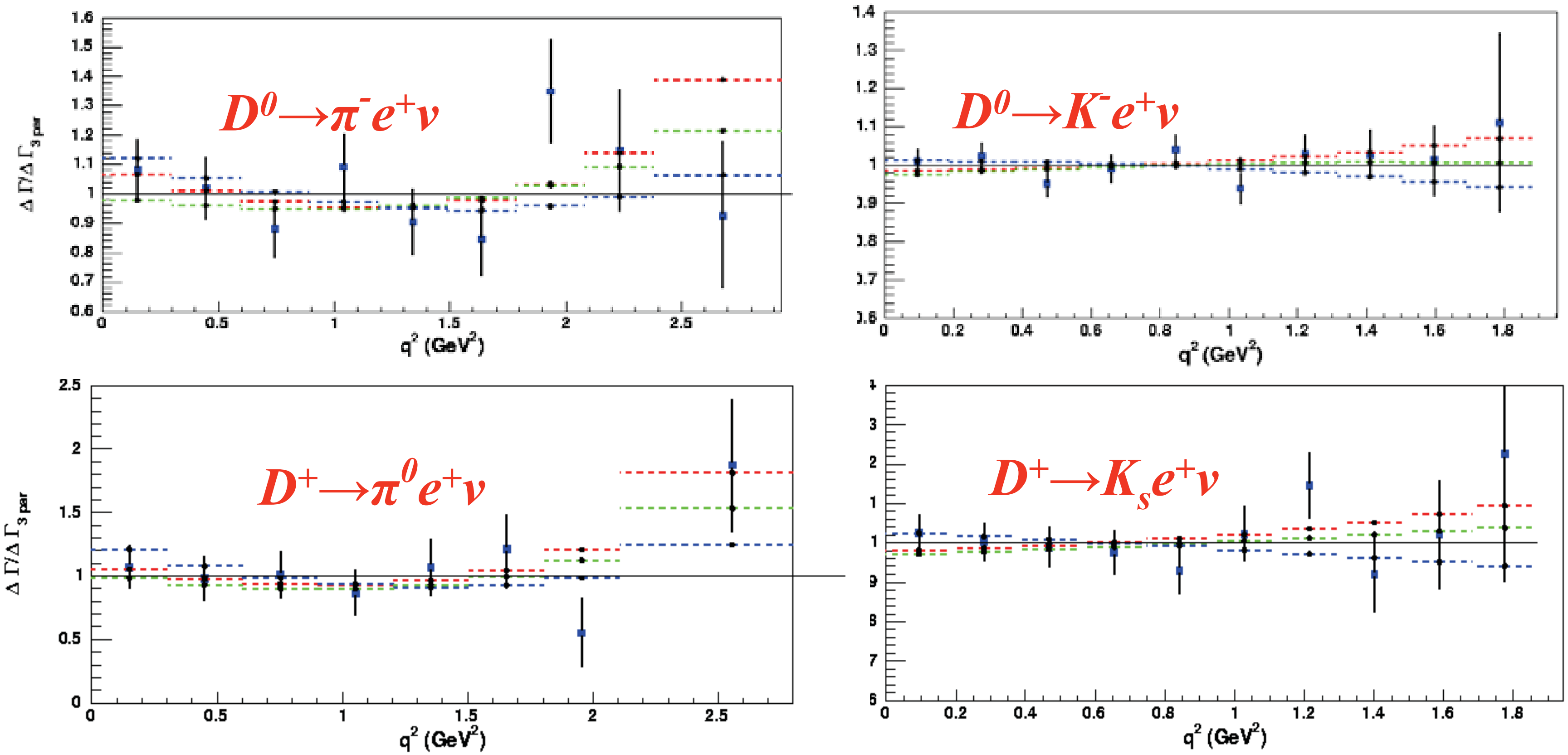
Modified Pole Model

$$f_{+}(q^2) = \frac{f_{+}(0)}{\left(1 - q^2/m_{pole}^2\right)\left(1 - \alpha\, q^2/m_{pole}^2\right)}$$

Hill series expansion

(Phys. Lett. B 633, 61 (2006)))

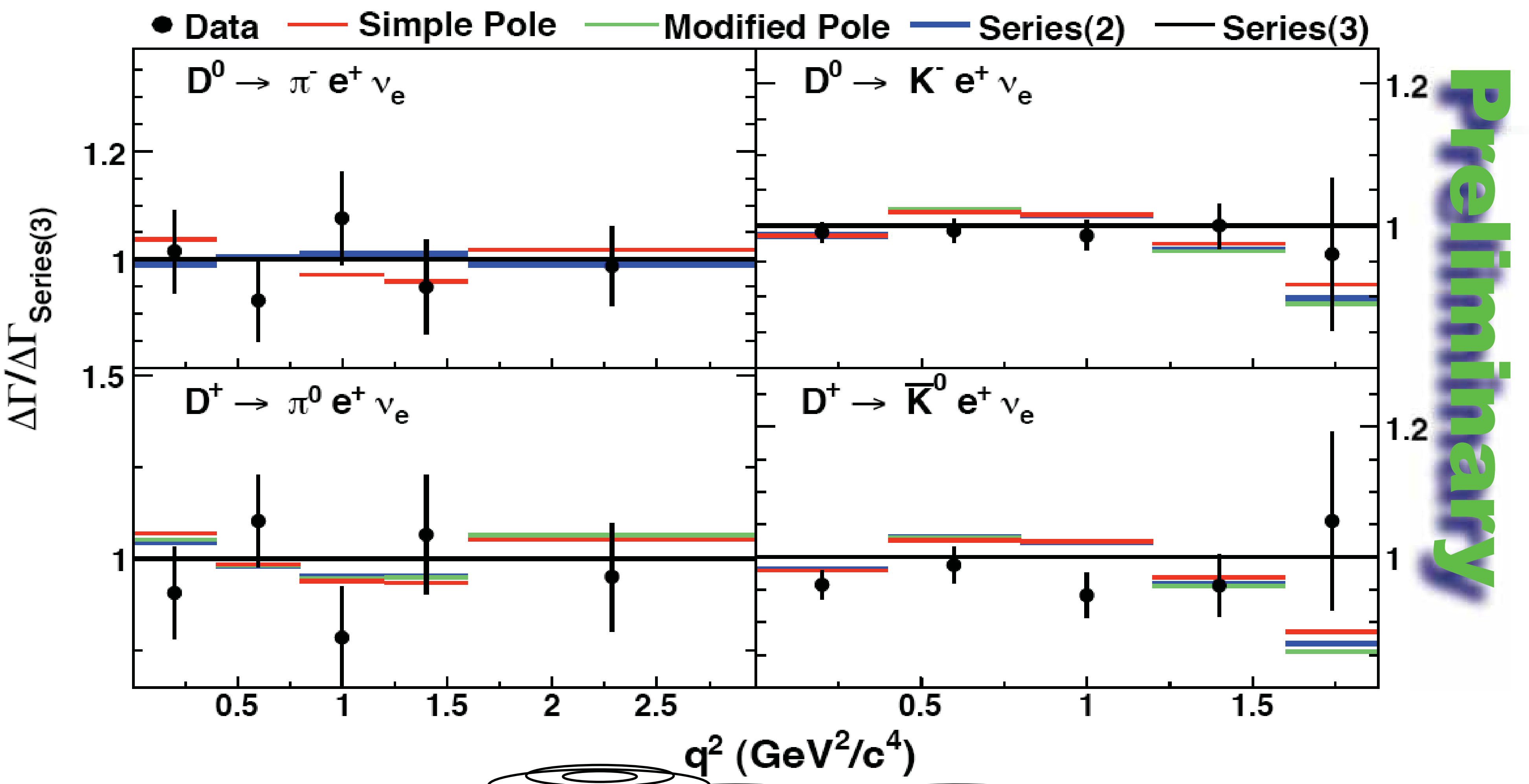
• ***Data*** ***--- Simple pole*** ***--- Modified Pole*** ***--- Series with 2 par*** ***— Series with 3 par***



Preliminary

Data and Fit results are normalized to the fit results for the series parameterization with 3 parameters.

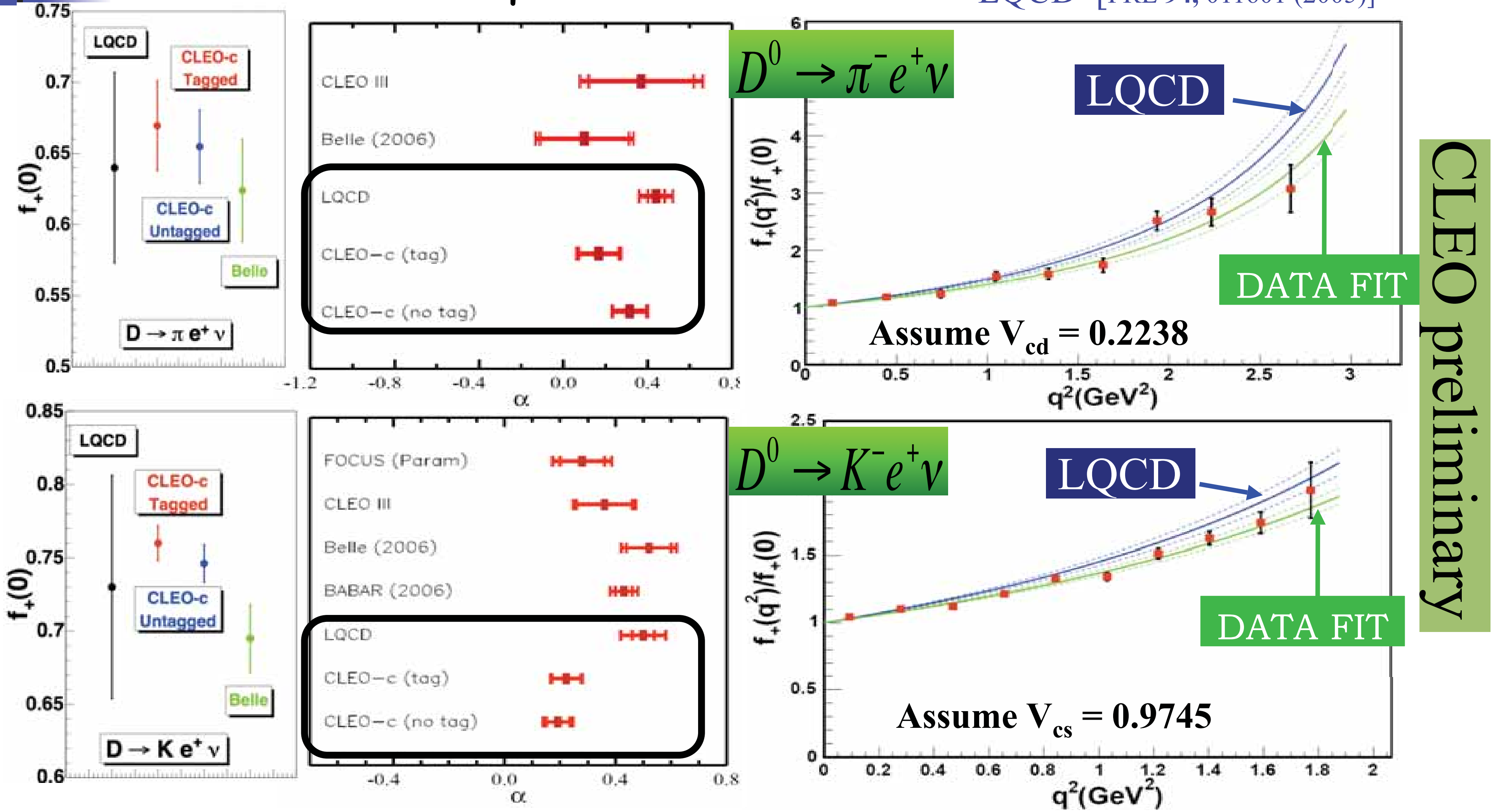
Form Factor Fit Comparison (Untagged)



All these models describe the data pretty well

Data-LQCD Comparison

$f_+(0)$ α_{pole} LQCD [PRL **94,** 011601 (2005)]



V_{cd} & V_{cs} Summary

Combine $|V_{cx}|f_+(0)$ values from fits with unquenched LQCD $f_+(0)$ results ⇒ $|V_{cs}|$ and $|V_{cd}|$

PRL 94, 011601 (2005)

Decay Mode	$\lvert V_{cx}\rvert$ ± (*stat*) ± (*syst*) ± (*theory*)	*PDG/HF Value*
D → πeν (tagged)	0.234 ± 0.010 ± 0.004 ± 0.024	
D → πeν (untagged)	0.229 ± 0.007 ± 0.005 ± 0.024	0.224 ± 0.012
D → Keν (tagged)	1.014 ± 0.013 ± 0.009 ± 0.106	
D → Keν (untagged)	0.996 ± 0.008 ± 0.015 ± 0.104	0.976 ± 0.014

Tagged and untagged consistent.
40% of events are common to both analyses: **DO NOT AVERAGE!**
Uncertainties: Experiment V_{cs}~2%, V_{cd}~4% - LQCD $f_+(0)$ prediction: 10%

Unitarity constraint on the second row along with $|V_{cb}|$ =(41.0±0.6)x10^{-3}(PDG)

Untagged ⇨ $\Delta = 1 - (|V_{cd}|^2+|V_{cs}|^2+|V_{cb}|^2) = 0.012 \pm 0.18$

V_{cs}(W→ cs LEP) and V_{cd}(ν N) well measured ⇨ good agreement between PDG (HF) and CLEO-c results primarily check of the **LQCD value for $f_+(0)$**. Nevetheless, the most **precise** & **robust** V_{cs} & V_{cd} measurements using SL decays to date.

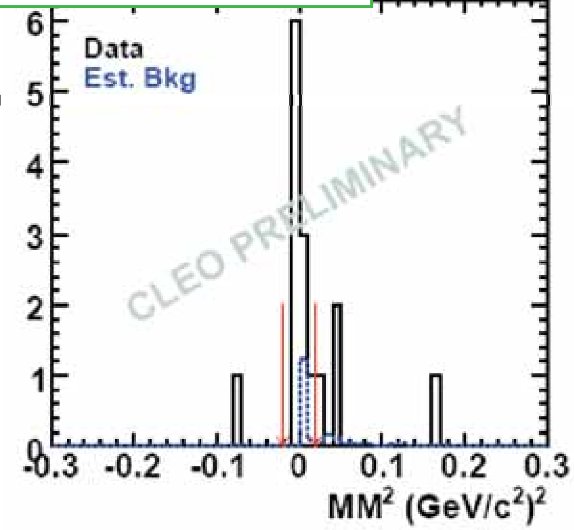
Rare Semi Leptonic Decays

Preliminary

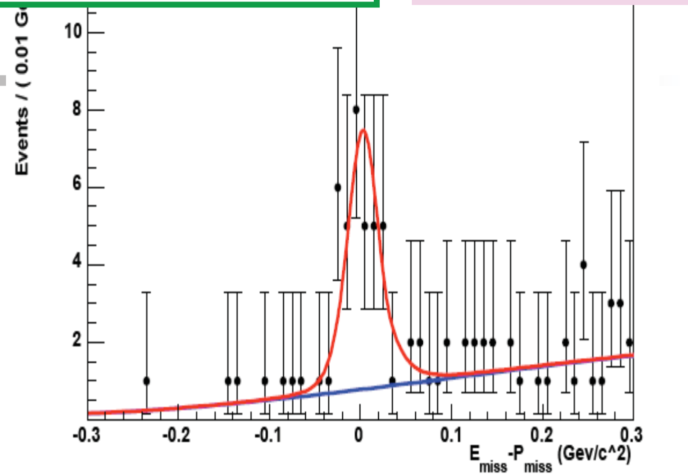
Mode	BR (10^{-4})
* $\eta e^+\nu$	$12.9\pm1.9\pm0.7$
* $K^-\pi^+\pi^-e^+\nu$ $K_1(1270)e^+\nu$	$2.9^{+1.5}_{-1.0}\pm0.5$ $2.2^{+1.4}_{-1.0}\pm0.2$
$\omega e^+\nu$	$14.9\pm2.7\pm0.5$

* First observation

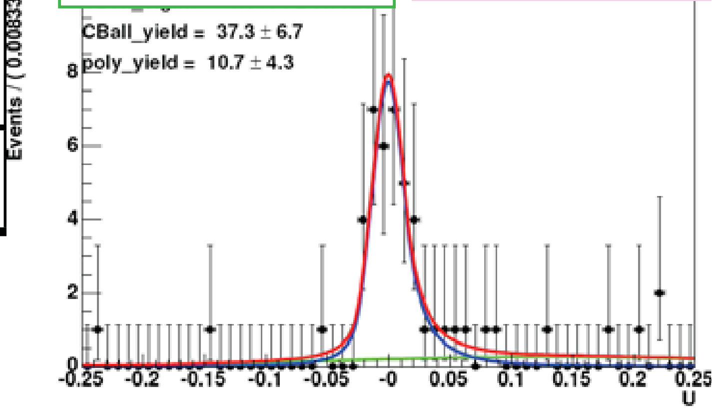
$D^0\to K^-\pi^+\pi^-e^+\nu$ $8.5^{+4.5}_{-3.2}$



$D^+\to\eta(\gamma\gamma)e^+\nu_e$ 32.7 ± 6.7

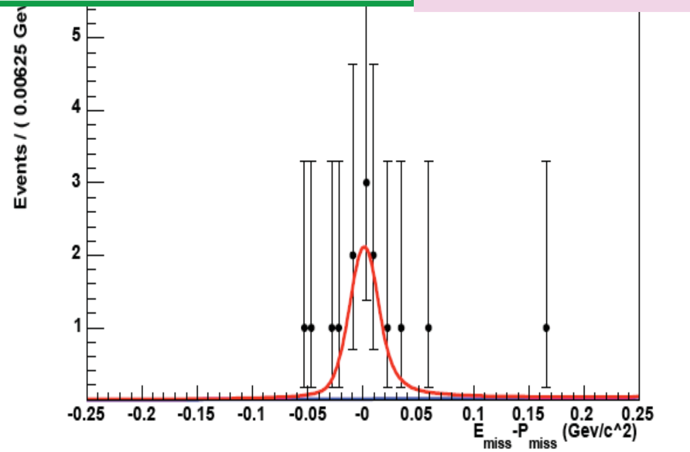


$D^+\to\omega e^+\nu$ 37.3 ± 6.7



$U_{miss} = E_{miss} - P_{miss}$ (GeV)

$D^+\to\eta(\pi^+\pi^-\pi^0)e^+\nu_e$ 13.3 ± 4.0



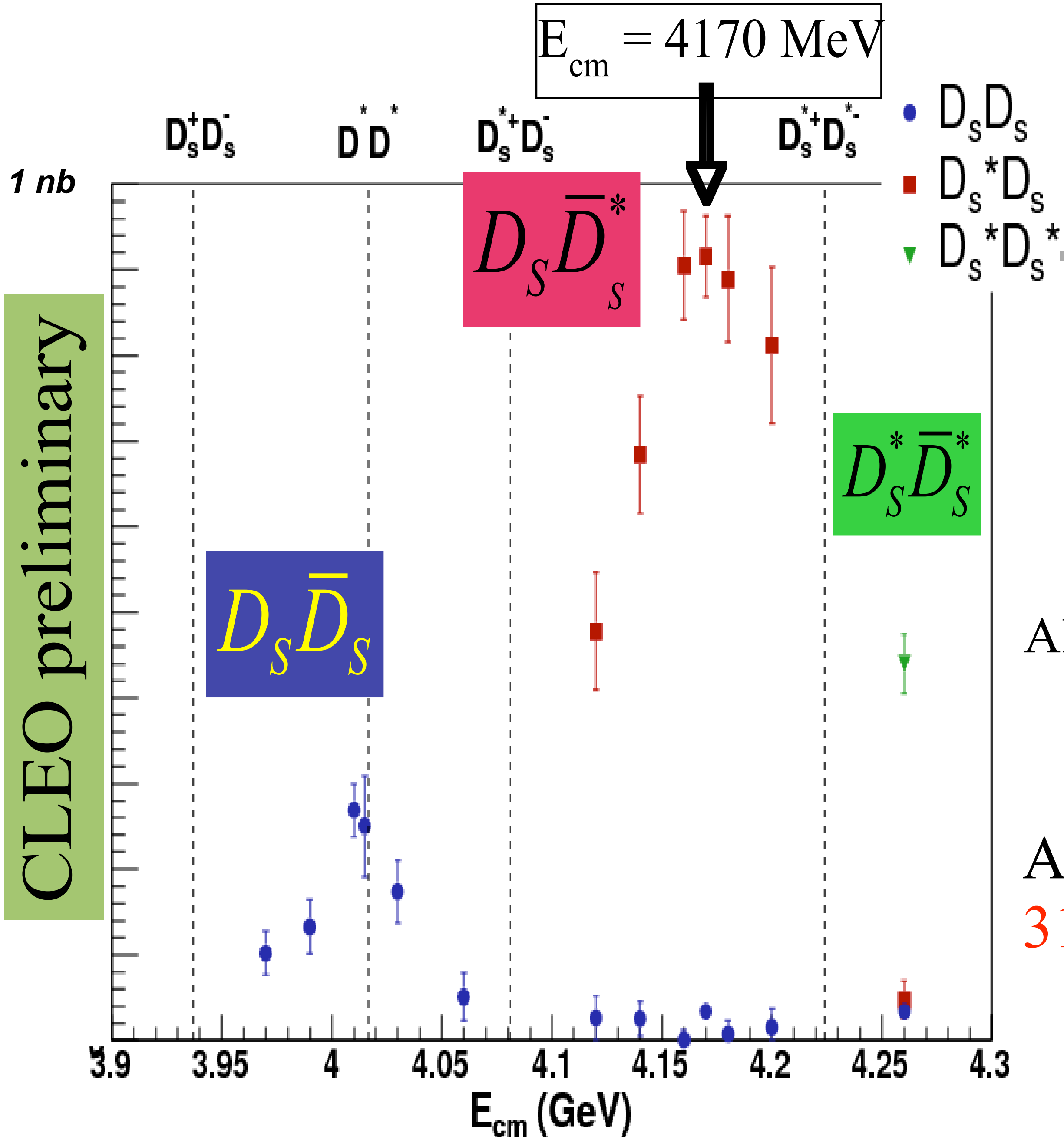
$U_{miss} = E_{miss} - P_{miss}$ (GeV^2)

SUMMARY

3770 & 4170 MeV

- By March 2008 double our data sets.
  - Improve precision on Leptonic decay constants
  - Improve precision on V_{cd} and V_{cs}.
  - Understand the form factor shape better.
  - Improve signal significance in RARE D decays.
- CLEO-c at Charm threshold
  - Great place to do charm physics.

Back Up



Fall 2005:
Scanned E_{cm} = 3.97 – 4.26 GeV to find optimal D_S production

Optimal E_{cm} = 4170 MeV

Almost all Ds from $e^+e^- \to D_S\bar{D}_S^*$

As of Summer 2006,
315 pb^{-1} collected at 4170 MeV