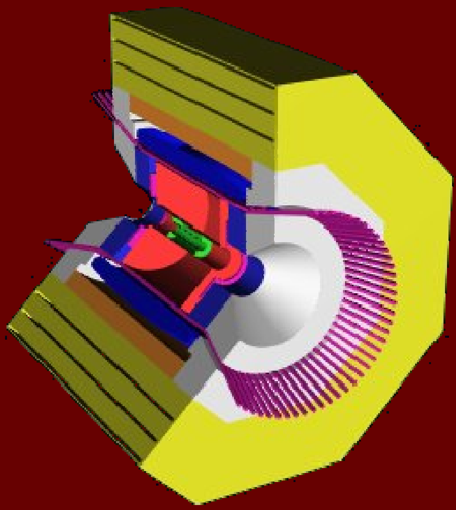
CLEO-c Hot Topics



Ron Poling
CLEO Collaboration
and
University of Minnesota

FPCP Vancouver
April 9, 2006

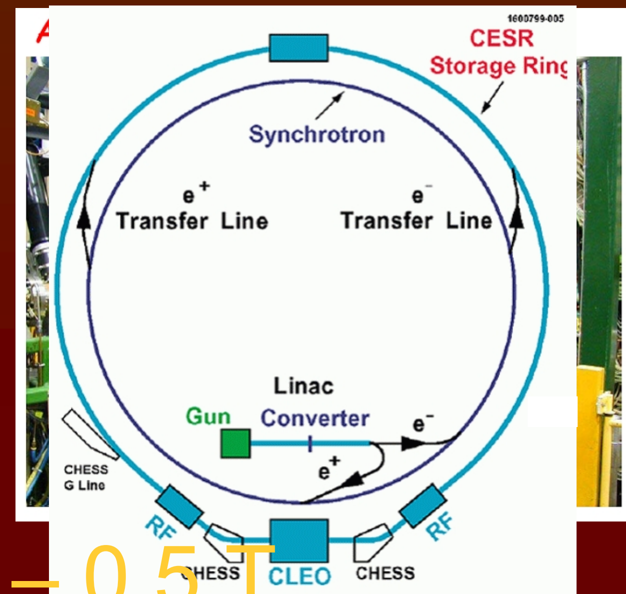
Outline

- Introduction and overview of CLEO-c
- Leptonic *D* decays
- Semileptonic *D* decays
- Closed and open charm production
  E_{cm}=3970 – 4260 MeV
- Conclusions

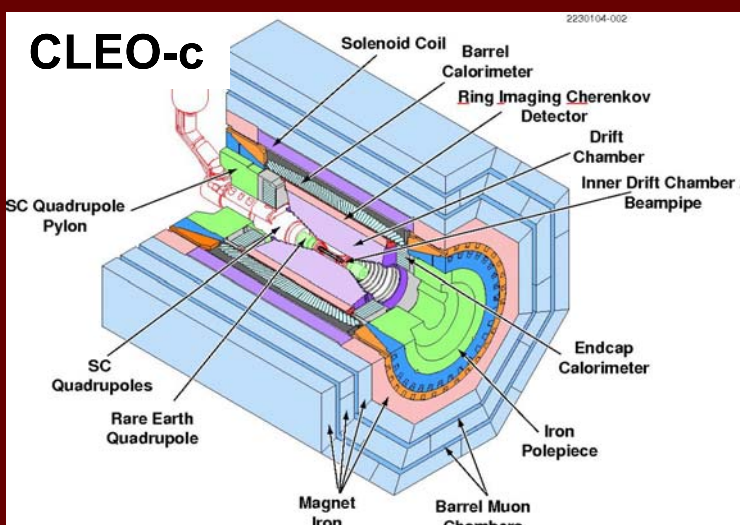
CESR-c ≈ CESR – 6.5 GeV + 12(wigglers)

Initial luminosity < original design. Various challenges, energy sensitivity in solenoid compensation →“antisolenoid” a la DAΦNE.

Initial results: +20% instantaneous (6.7×10^{31}) and “best day” (4.2 pb^{-1}), expect >5 pb^{-1}/day.



CLEO-c ≈ CLEO III – SVX + ZD – 0.5 T



Still at the top of its game:

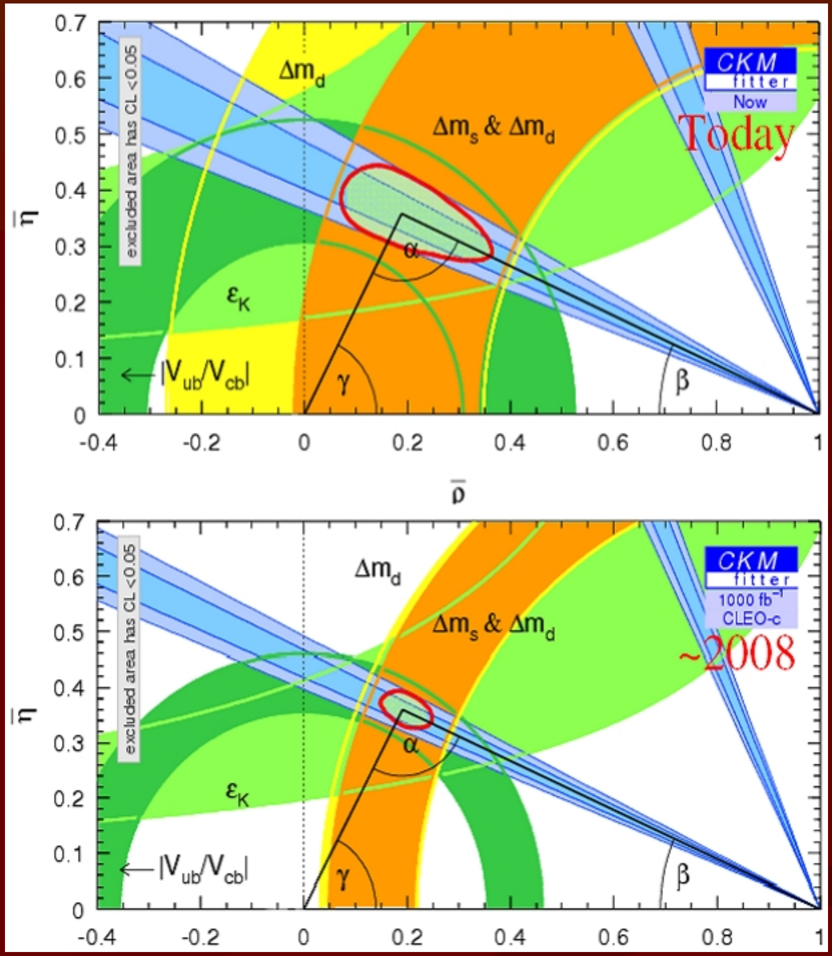
$\Delta p/p$ = 0.6% at 1 GeV/c

$\Delta E/E$ = 2.2% at 1 GeV, 5% at 100 MeV

Excellent electron and particle ID

Goals and Impact of CLEO-c

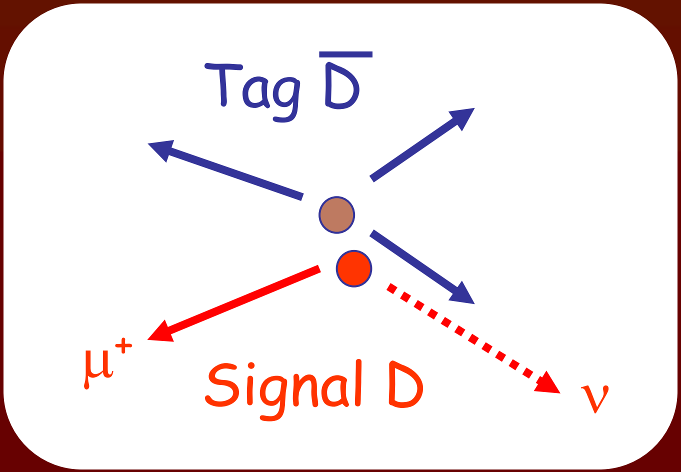
- Significant input for worldwide CKM program, both direct and indirect
- Precision charm measurements + theory → reduced uncertainties in *B* measurements
- Validation of lattice for QCD and (potentially) other strongly-coupled theories
- Crucial "engineering" input for others: branching fractions for normalization modes, etc.

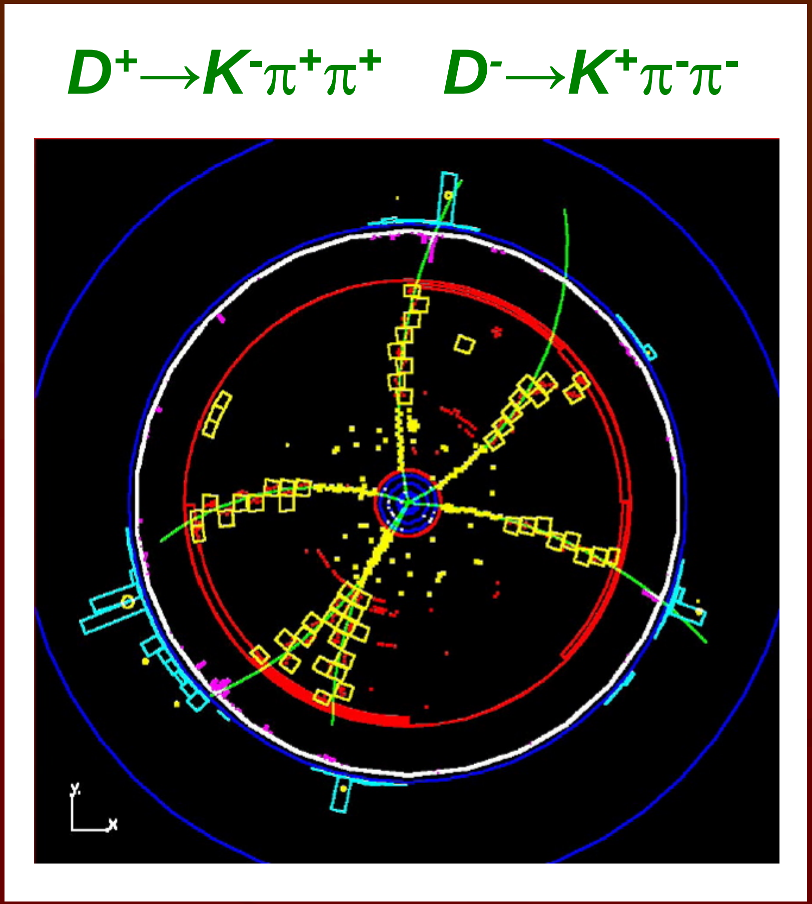


CLEO-c Data Samples

- $\psi(3770)$ – for *D* decays
  - Initial results from 57 pb^{-1}
  - Updates with 281 pb^{-1} (some at FPCP)
- Above $\psi(3770)$ – for D_s decays
  - Preliminary – scan to determine optimal energy
  - First run under way now (initial results at FPCP)
- $\psi(2S)$ – one-stop charmonium shopping
  - Appetizer: 5.6 pb^{-1} → 3M $\psi(2S)$ → 40 analysis results
- Scheduled to run through April, 2008. Luminosity improving, but still short of projections.
- What are the priorities for apportioning the remainder of the full CLEO-c data sample? (Stay tuned for “Conclusions”)

D Physics at $\psi(3770) \to D\bar{D}$



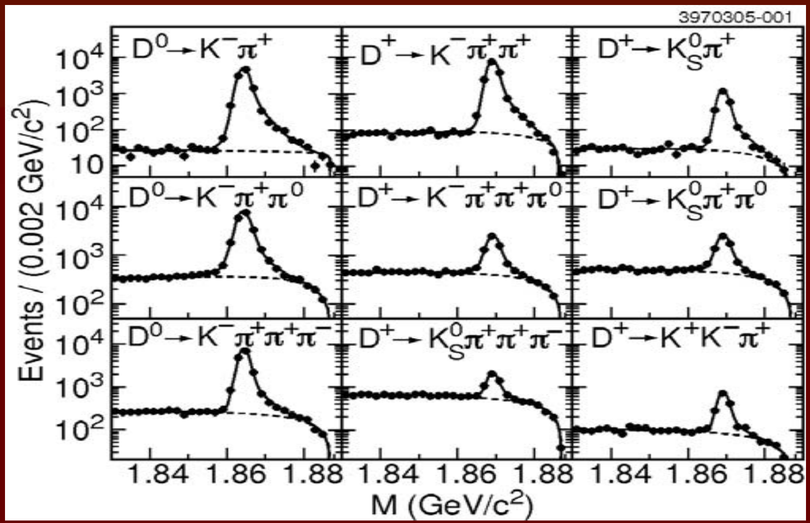


- Tagging *D* gives pure sample of *D* of known 4-momentum
- "Golden Modes" for best purity
- Additional modes (higher multiplicity, π^0) for best efficiency
- Typical tagging efficiencies 15% for D^0 and 10% for D^+.

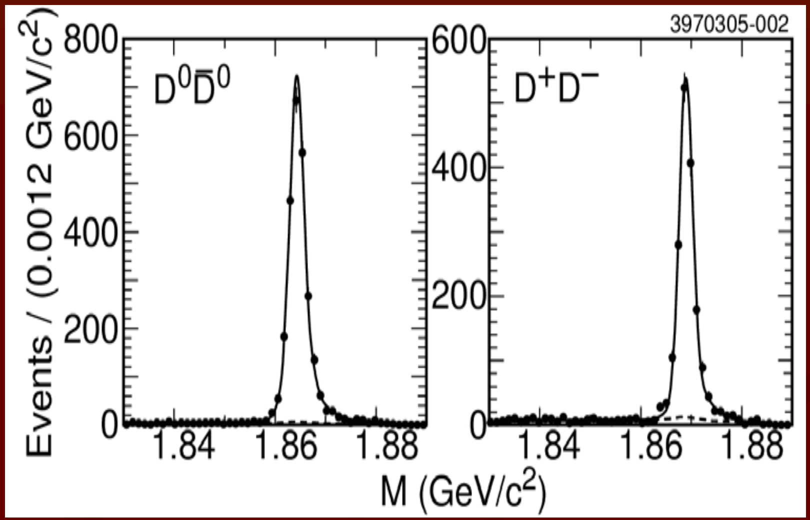
Tags in action…

D Hadronic Decays (Details in talk of S. Stone)

Single Tags



Double Tags



- Single Tags + Double Tags → Hadronic BFs
  - 57 pb^{-1} - PRL **95**, 121801 ('05) – update (281 pb^{-1}) coming soon
  - 3 D^0, 6 D^+ modes, including key normalization modes
  - Precision already comparable to PDG, benefits from cancellation of many systematic uncertainties

Other CLEO-c Results on Hadronic *D* Decays

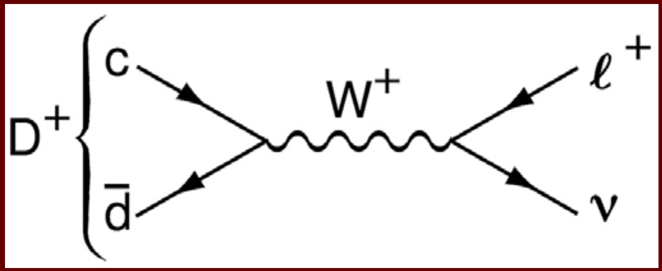
- Non-tagged analyses, including Cabibbo-suppressed decays $D \to 2$ to 5 pions. (Stone)
- Measurements of mixing, strong phases in *D* decays through quantum correlations at $\psi(3770)$ and above. (Cinabro, Stone)
- First results on hadronic decays of D_s. (Stone)

Leptonic and Semileptonic *D* Decays

See also the review from J. Wiss.

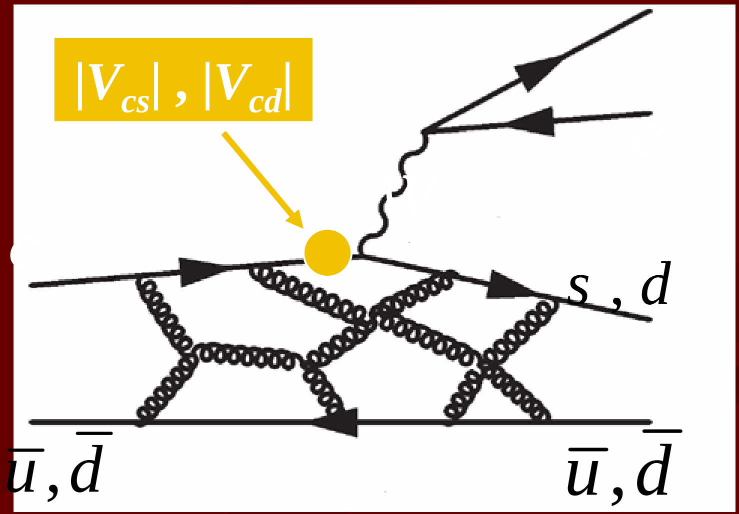
B decays: use leptons to get to unknown Standard Model parameters.

D decays: use leptons to master hadronic effects (LQCD training/testing).



$$\Gamma\left(D^{+}\to l^{+}\nu\right)=\frac{G_F^2}{8\pi}f_{D^+}^2 m_l^2 M_{D^+}\left(1-\frac{m_l^2}{M_{D^+}^2}\right)^2\left|V_{cd}\right|^2$$

$$\Gamma\left(D\to Pl\nu\right)=\frac{G_F^2\left|V_{cq}\right|^2 p^3}{24\pi^3}\left|f_+\left(q^2\right)\right|^2$$



Leptonic *D* Decays

$D^+ \rightarrow \mu^+\nu$

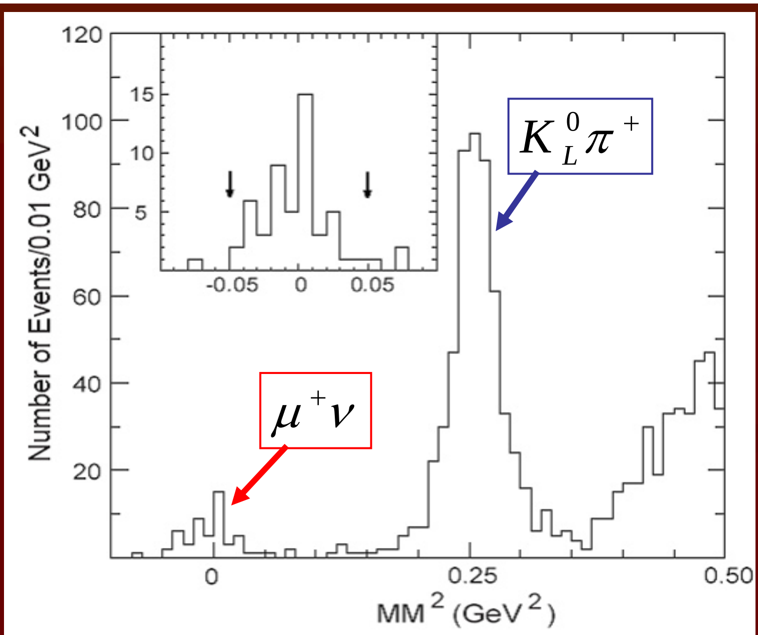
281/pb PRL **95 251801 ('05)**

160K charged *D* tags (6 modes)

Demand exactly 1 additional muon-like track, minimal extra energy.

$$\mathrm{MM}^2 = (E_{\mathrm{beam}} - E_{\mu^+})^2 - \left(-\boldsymbol{p}_{D^-} - \boldsymbol{p}_{\mu^+}\right)^2$$

Mode	Events
Data	50
$D^+ \rightarrow \pi^+ \pi^0$	1.4
$D^+ \rightarrow K_{long} \pi^+$	0.33
$D^+ \rightarrow \tau^+ \nu_\tau$	1.08
Total Bck:	2.81



BF($D^+ \rightarrow \mu^+\nu$)=$(4.4 \pm 0.7 \pm 0.1) \times 10^{-4}$

Same procedure, select *e*'s:

BF($D^+ \rightarrow e^+\nu$)<2.3×10^{-5} (90% CL)

$\Rightarrow$ f_{D+} = (223±17±3) MeV

f_{D+} = (201±3±17) MeV
LQCD (PRL 95 251801, '05)

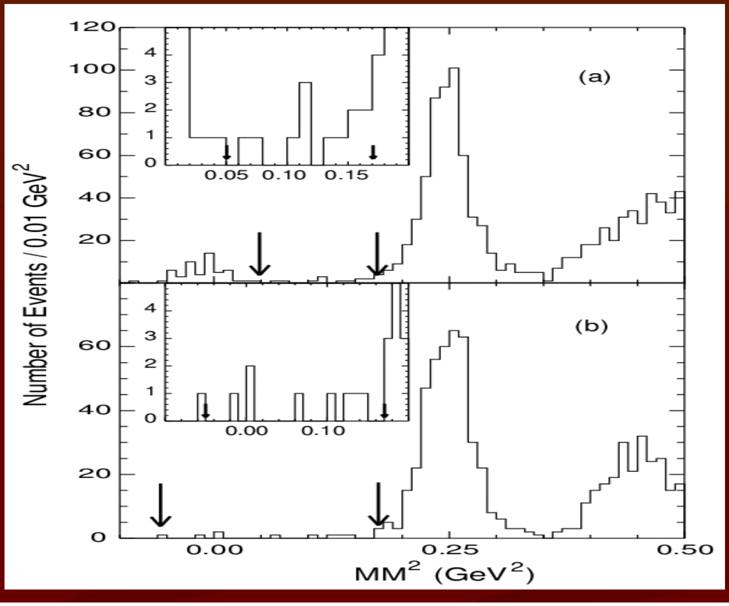
Leptonic *D* Decays

$D^+ \to \tau^+\nu$
281 pb^{-1} to be submitted to PRD

Complementary info: SM/lepton universality predicts BF 2.65×$\mu\nu$.

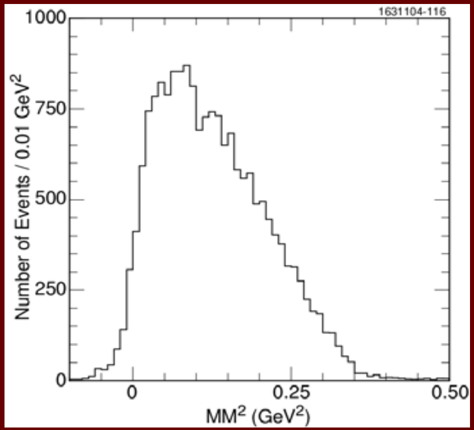
Complementary analysis: selection of $D^+ \to \tau\nu$ ($\tau^+ \to \pi^+\nu$) in events with tags selected as for $D^+ \to \mu^+\nu$.

Sample subdivided based on energy deposit of candidate track: (a) <300 MeV and (b) >300 MeV.



	(a)	(b)
Signal Region	12	8
Estimated BG	6.1±0.6±0.3	5.0±0.6±0.2
Net	5.9±3.5±0.3	3.0±2.9±0.2

Very slow $\tau \Rightarrow$ MM^2 peaks at low values



BF($D^+ \to \tau^+\nu$)<2.1×10^{-3} (90% CL)

Ratio to SM rate <1.8

Semileptonic *D* Decays

Inclusive $D \to Xe^+\nu$

281 pb^{-1} to be submitted to PRL

- Motivations:
  - Cross-check with exclusives: saturation by lightest V & PS modes?
  - Check equality of charged and neutral – evidence of WA?
  - Input for others: BF and spectra.

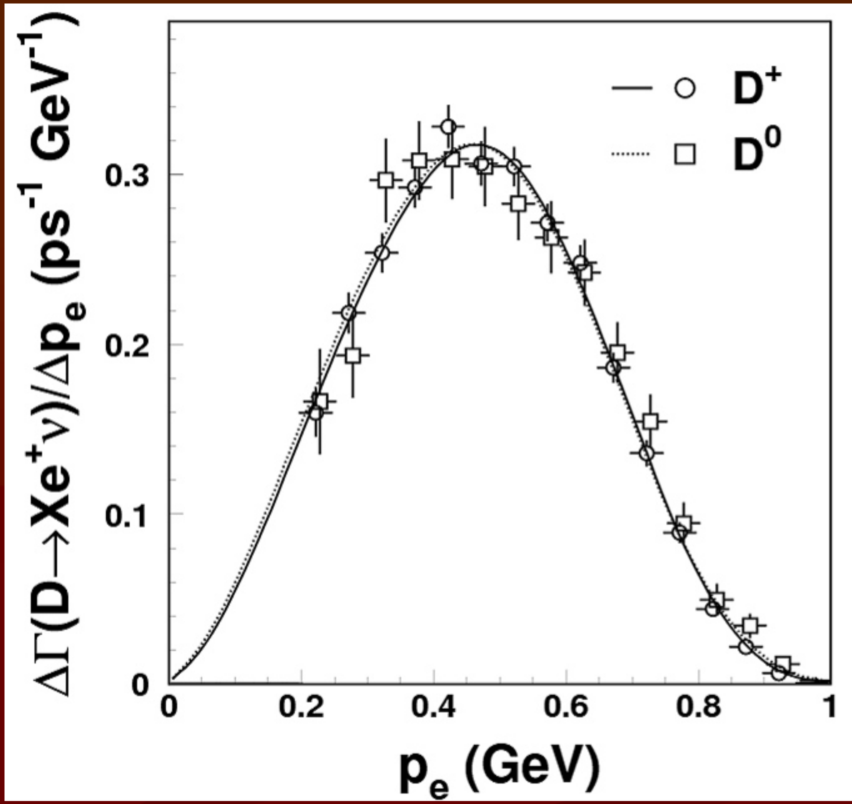
- Use only purest tags:
  - 47K $D^0 \to K^-\pi^+$ (S/B≈60)
  - 74K $D^+ \to K^-\pi^+\pi^+$ (S/B≈25)
- e ID by *dE*/*dx* and RICH, *p*>200 MeV/*c*
- Unfold right- and wrong-sign electrons to obtain true lab-frame spectra.

	D^+	D^0
Signal e^+		
Right-sign (raw)	8275 ± 91	2239 ± 47
Wrong-sign (raw)	228 ± 15	233 ± 15
Right-sign (unfolded)	9186 ± 103	2453 ± 54
Wrong-sign (unfolded)	231 ± 19	203 ± 19
Sideband e^+(RS)	168 ± 13	15 ± 4
Sideband e^+(WS)	11 ± 5	11 ± 4
Net e^+	8798 ± 105	2246 ± 57

$D \to Xe^+\nu$

Results

- Lab-frame momentum spectra $d\Gamma/dp_e$
- Fit observed spectra to models, including FSR. Use results to correct for p<200 MeV/*c* production.



- $BF(D^+\to Xe^+\nu)=(16.13\pm0.20\pm0.33)\%$ (Exclusive sum: 15.1%)
- $BF(D^0\to Xe^+\nu)=(6.46\pm0.17\pm0.13)\%$ (Exclusive sum: 6.2%)

- $\Gamma(D^+\to Xe^+\nu)=(0.1551\pm0.0020\pm0.0035)\text{ps}^{-1}$
- $\Gamma(D^0\to Xe^+\nu)=(0.1574\pm0.0041\pm0.0032)\text{ps}^{-1}$

$D \to Xe\nu$ Exclusive with D Tags

D^+ PRL **95,** 181801 (2005)

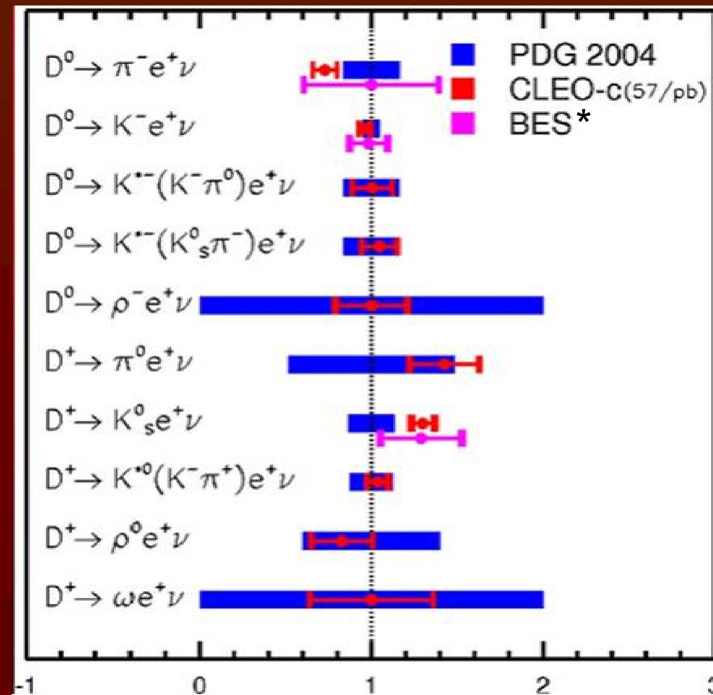
D^0 PRL 95, 181802 (2005)

57 pb^{-1} – 60K D^0 tags, 32K D^+ tags

Select semileptonic decays among non-tag tracks, requiring

$$U = E_{\mathrm{miss}} - c|\boldsymbol{p}_{\mathrm{miss}}| \approx 0$$

($\sigma \sim 10$ MeV)



* Note – Not updated with winter 2006 preliminary BES results.

Upcoming: updated branching fractions with 281 pb^{-1} and form factors for $Ke\nu$ and $\pi e\nu$. Longer term: more modes, form factors in $D \to Ve\nu$.

$D \to P e \nu$ Branching Fractions and Form Factors with ν Reconstruction

CLEO-c
Preliminary

No D tag required: reconstruct semileptonic D decay from its decay products, including the ν.

$$P_\nu \equiv P_{miss} = P_{event} - P_{visible}$$

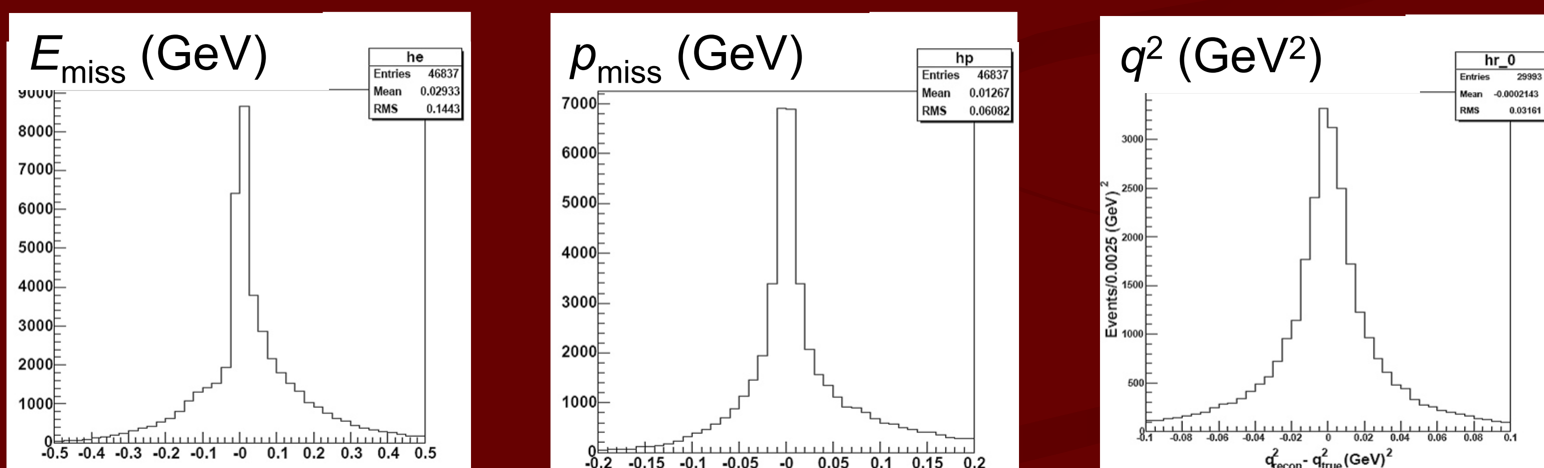
$$q^2 = (P_e + P'_{miss})^2$$

$$P'_{miss} = \beta P_{miss} \quad (\beta \text{ gives } \Delta E = 0)$$

Tricks of the trade:

Get all the true showers/tracks, no false ones or duplicates.

Exclude impossible events!



MC: Reconstructed – True for $D^0 \to \pi^+ e^- \nu$

$D \to Pe\nu$ Branching Fractions and Form Factors with ν Reconstruction

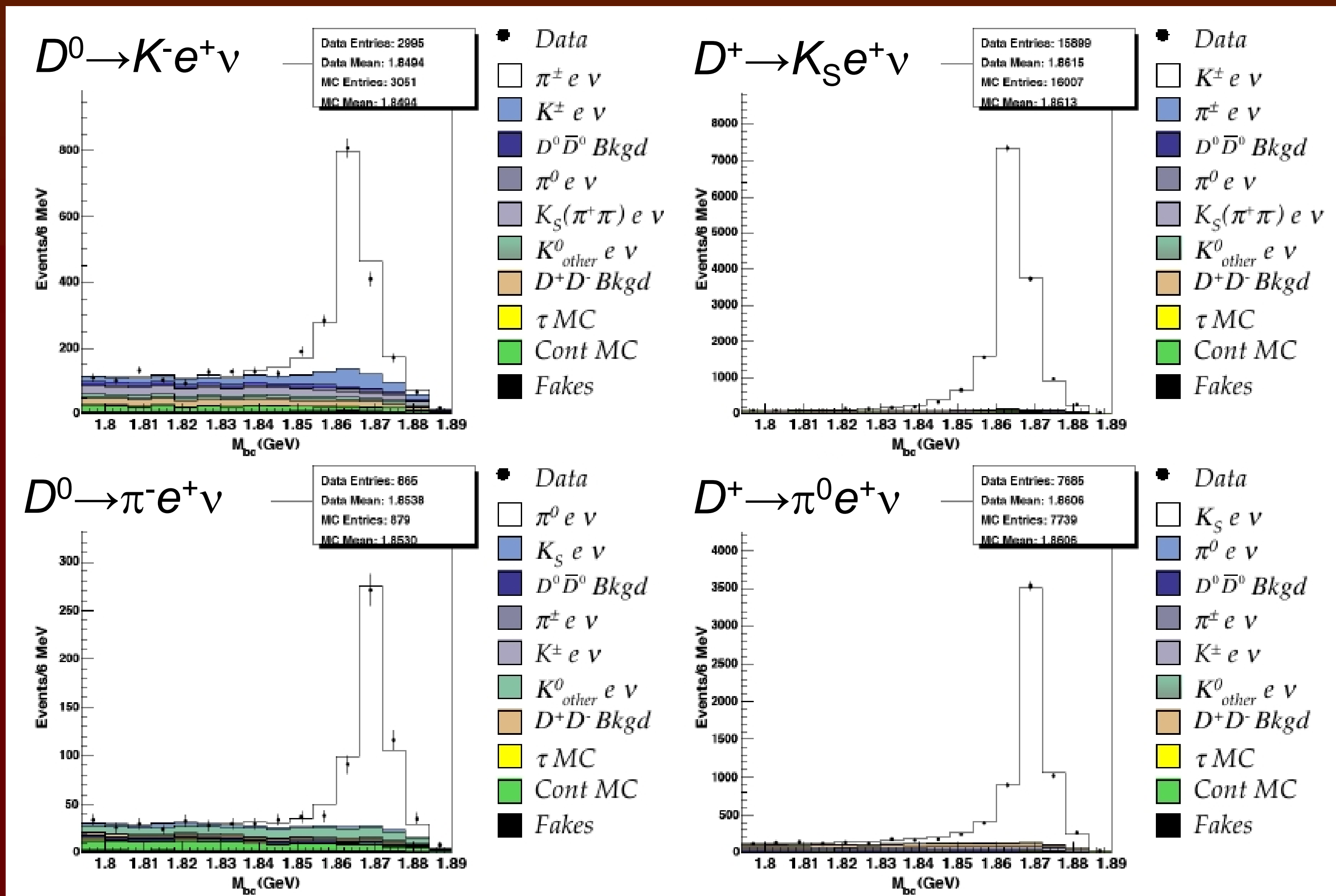
Using the reconstructed ν and a signal K or π, reconstruct D in the usual way:

$$\Delta E = E_K + E_e + |\boldsymbol{p}_{\text{miss}}| - E_{\text{beam}}$$

$$M_{\text{bc}} = \sqrt{E^2_{\text{beam}} - (\boldsymbol{p}_K + \boldsymbol{p}_e + \boldsymbol{p}'_{\text{miss}})^2}$$

M_{bc} distributions fitted simultaneously in 5 q^2 bins to obtain $d(\text{BF})/dq^2$. Integrate to get branching fractions and fit to obtain form-factor parameters.

M_{bc} fits for the four $D \to Pe\nu$ modes (all q^2)



PRELIMINARY

Yields and Branching Fractions (281pb^{-1})

D Decay	Yield (Eff. Corr.)	Yield (Uncorr.)	Br. Frac.
$D^0 \to K^{\pm} e\ \nu$	$72076 \pm 663 \pm 1230$	14395 ± 78	$3.56 \pm 0.03 \pm 0.10$ %
$D^0 \to \pi^{\pm} e\ \nu$	$6097 \pm 223 \pm 139$	1346 ± 28	$0.301 \pm 0.011 \pm 0.010$ %
$D^{\pm} \to K^0 e\ \nu$	$136736 \pm 2054 \pm 2415$	5842 ± 54	$8.70 \pm 0.13 \pm 0.27$ %
$D^{\pm} \to \pi^0 e\ \nu$	$5988 \pm 385 \pm 176$	450 ± 17	$0.381 \pm 0.025 \pm 0.015$ %

Ratio	Measured	Ratio	Measured
$\frac{D^0 \to \pi^{\pm} e\ \nu}{D^0 \to K^{\pm} e\ \nu}$	$8.46 \pm 0.32 \pm 0.13$ %	$\frac{\Gamma(D^0 \to \pi^{\pm} e\ \nu)}{\Gamma(D^{\pm} \to \pi^0 e\ \nu)}$	$2.00 \pm 0.15 \pm 0.09$
$\frac{D^{\pm} \to \pi^0 e\ \nu}{D^{\pm} \to K^0 e\ \nu}$	$4.38 \pm 0.29 \pm 0.13$ %	$\frac{\Gamma(D^0 \to K^{\pm} e\ \nu)}{\Gamma(D^{\pm} \to K^0 e\ \nu)}$	$1.04 \pm 0.02 \pm 0.04$

PRELIMINARY

Form Factor Results

Simp. Pole

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

Decay Mode	$\lvert V_{cx}\rvert f^+(0)$	m_{pole}
$D^0 \to \pi^{\pm} e\nu$	$0.146 \pm 0.004 \pm 0.003$	$1.87 \pm 0.03 \pm 0.01$
$D^0 \to K^{\pm} e\nu$	$0.736 \pm 0.005 \pm 0.010$	$1.98 \pm 0.03 \pm 0.02$
$D^{\pm} \to \pi^0 e\nu$	$0.152 \pm 0.007 \pm 0.004$	$1.97 \pm 0.07 \pm 0.02$
$D^{\pm} \to K^0 e\nu$	$0.719 \pm 0.009 \pm 0.012$	$1.97 \pm 0.05 \pm 0.02$

Mod. Pole

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

Decay Mode	$\lvert V_{cx}\rvert f^+(0)$	α
$D^0 \to \pi^{\pm} e\nu$	$0.142 \pm 0.005 \pm 0.003$	$0.37 \pm 0.09 \pm 0.03$
$D^0 \to K^{\pm} e\nu$	$0.734 \pm 0.006 \pm 0.010$	$0.19 \pm 0.05 \pm 0.03$
$D^{\pm} \to \pi^0 e\nu$	$0.151 \pm 0.008 \pm 0.004$	$0.12 \pm 0.17 \pm 0.05$
$D^{\pm} \to K^0 e\nu$	$0.718 \pm 0.009 \pm 0.012$	$0.20 \pm 0.08 \pm 0.04$

PRELIMINARY

V_{cs} and V_{cd} Results

Combine $|V_{cx}|f(0)$ with LQCD value for $f(0)$

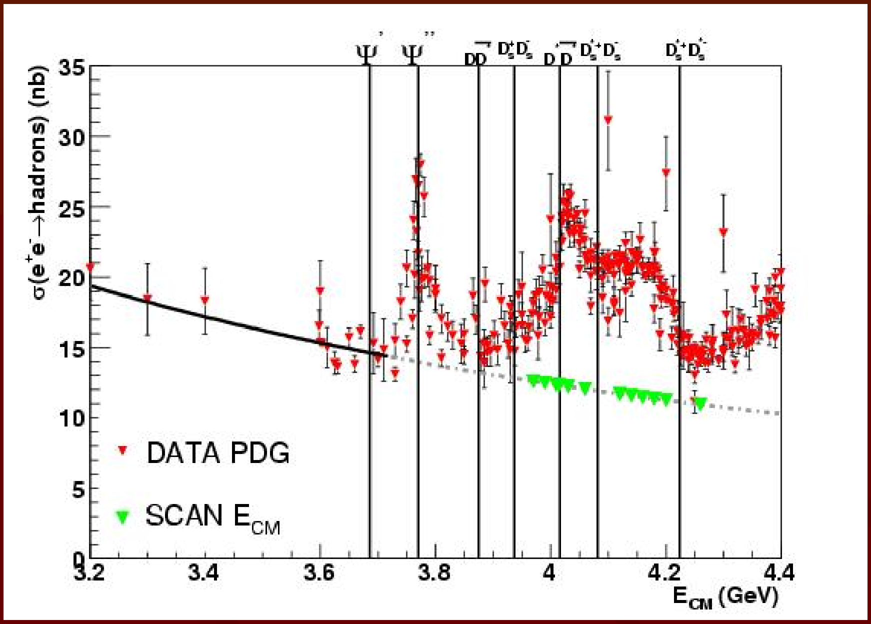
PRL **94**, 011601 (2005)

Decay Mode	$|V_{cx}| \pm (stat) \pm (syst) \pm (theory)$	PDG (HF) Value
$D^0 \to \pi^{\pm} e \nu$	$0.221 \pm 0.013 \pm 0.004 \pm 0.028$	0.224 ± 0.012
$D^0 \to K^{\pm} e \nu$	$1.006 \pm 0.042 \pm 0.013 \pm 0.103$	0.996 ± 0.013 (0.976 ± 0.014)
$D^{\pm} \to \pi^0 e \nu$	$0.235 \pm 0.016 \pm 0.006 \pm 0.029$	0.224 ± 0.012
$D^{\pm} \to K^0 e \nu$	$0.984 \pm 0.042 \pm 0.017 \pm 0.101$	0.996 ± 0.013 (0.976 ± 0.014)

Precision comparable to exclusives with tags; much independent information. Combined results will give best precision.

Open Charm and Charmonium Production in e^+e^- Annihilations E_{CM} = 3970-4260 GeV

- Primary CLEO-c Motivations:
  - Determine optimal energy for D_s studies.
  - Assess capabilities for D physics above $\psi(3770)$.
- Additional Objectives:
  - Detailed study of “intricate behavior” of hadronic cross section in the region above open-charm threshold.
  - $Y(4260)$: confirmation, more details.



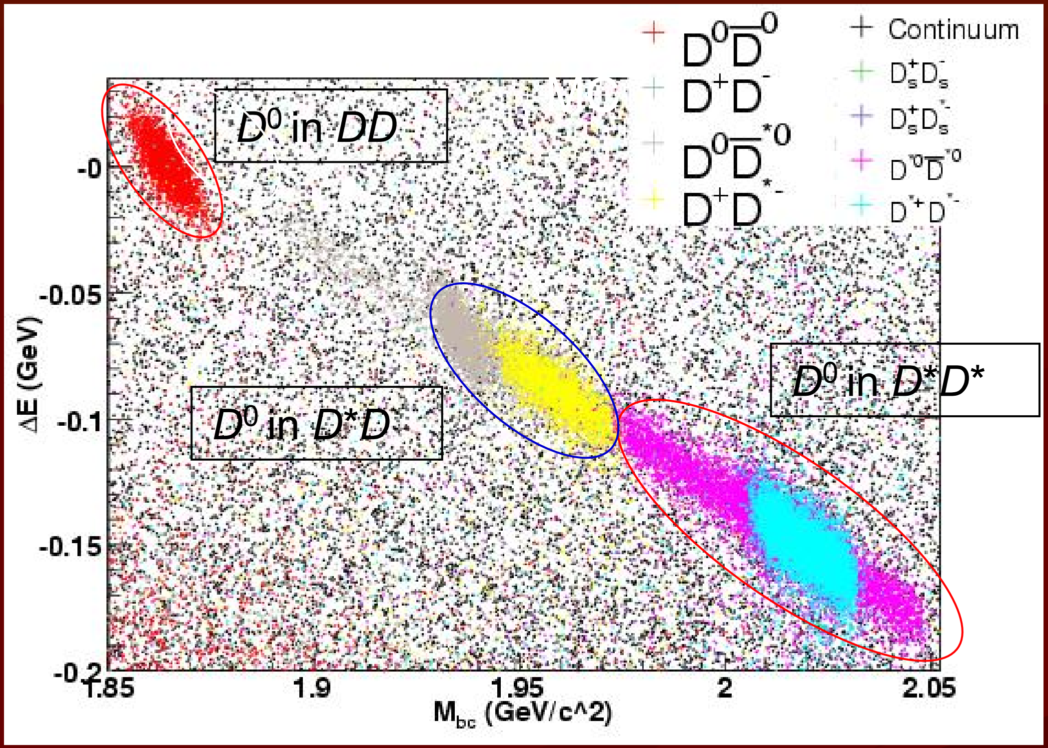
- Scan Data Sample:
  - 12 energies, 60 pb^{-1}
- First real D_s Run at 4170 MeV:
  - Part 1: 76 pb^{-1} (results at FPCP)
  - Part 2: under way, expected total >150 pb^{-1}

Objective: Determine Optimal Energy for D_s Physics
Procedure: Measure Cross Sections for 8 Event Types

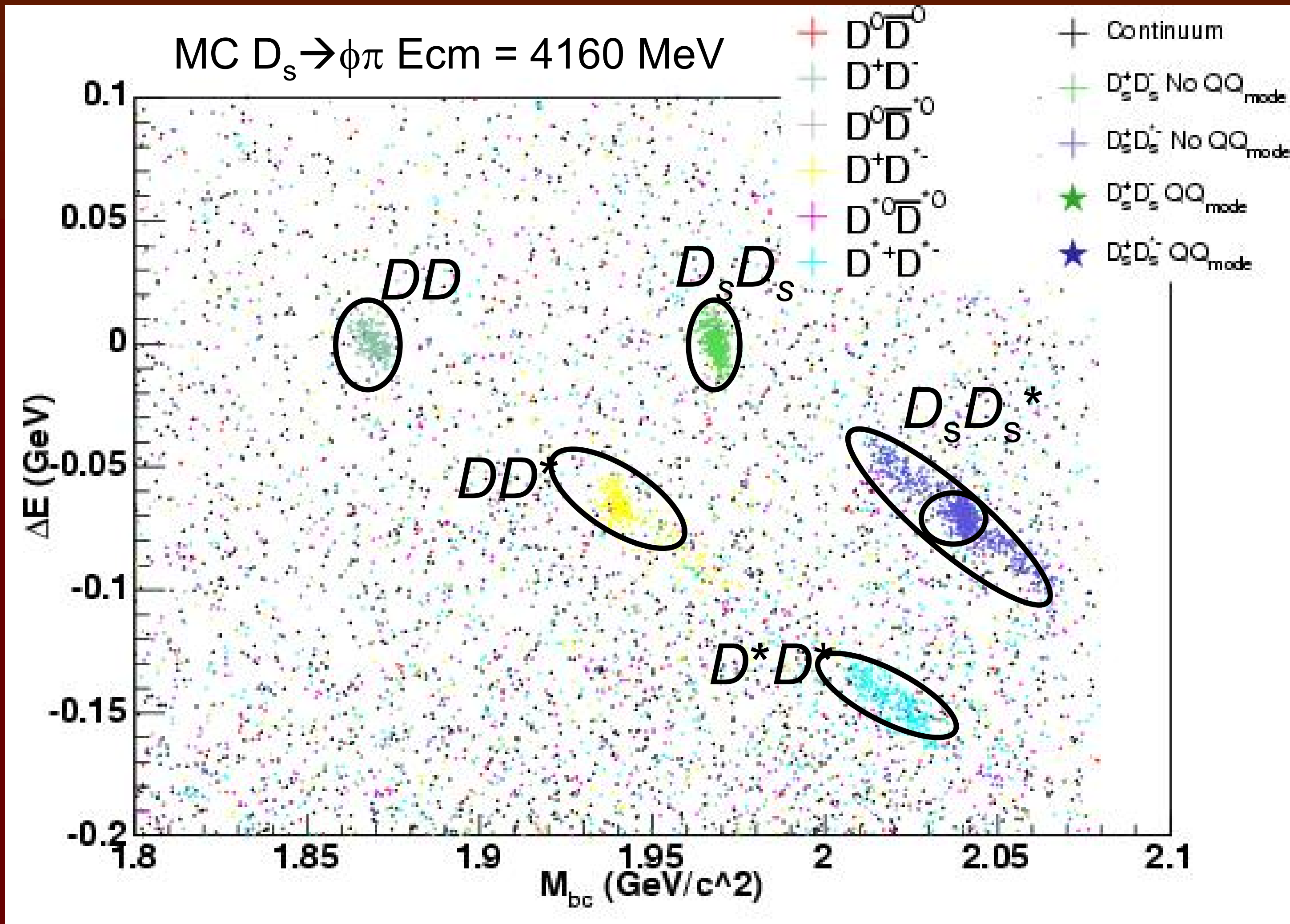
$D_{(s)}^{(*)}\overline{D}_{(s)}^{(*)}$

- Use 3 D^0, 5 D^+, and 8 D_s^+ modes to select charmed mesons.
- Do not reconstruct D^*, since momentum (or M_{bc}), differentiates event types.
- For DD and D_sD_s cut on ΔE and use M_{bc} to extract yields.
- For other event types cut on M_{bc} and use invariant mass to extract yield.
- Cut values determined by kinematics – no double counting allowed, cross-feed small and calculable.

MC $D^0 \rightarrow K\pi$ at E_{cm}=4160 MeV



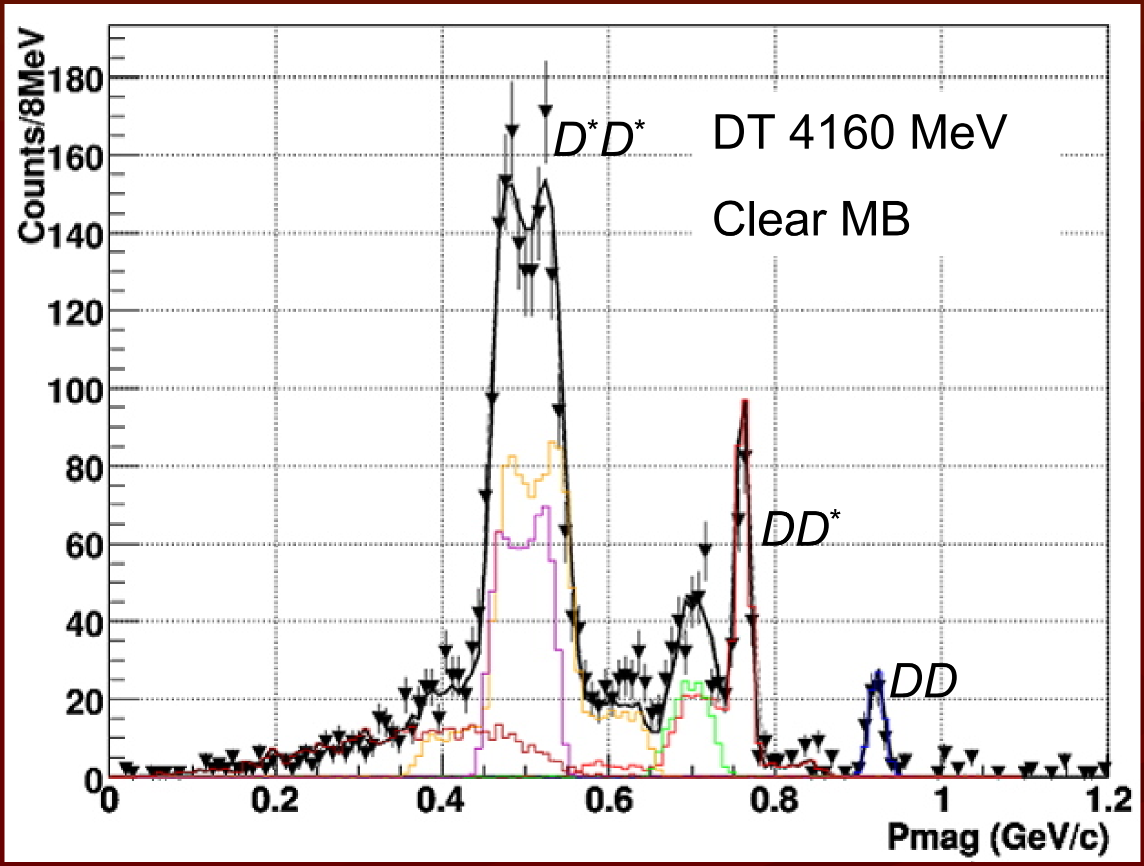
Closer look: selecting D_s



Complication: Not all charm events fall into one of the 8 final states, with two charmed mesons and nothing else!

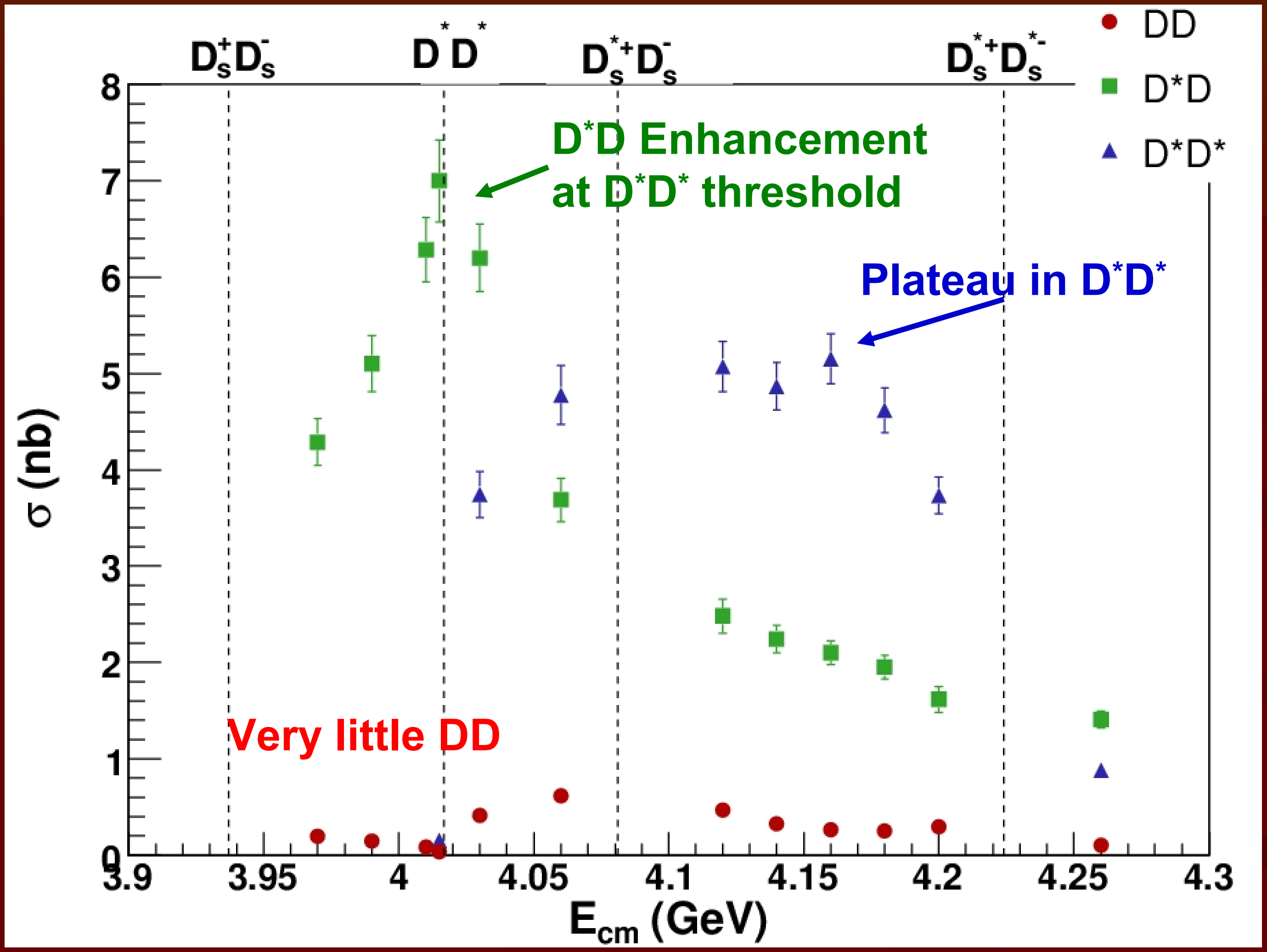
Evidence for "multibody" (MB) events, e.g. $e^+e^- \to DD^*\pi$:

D^0 Momenta



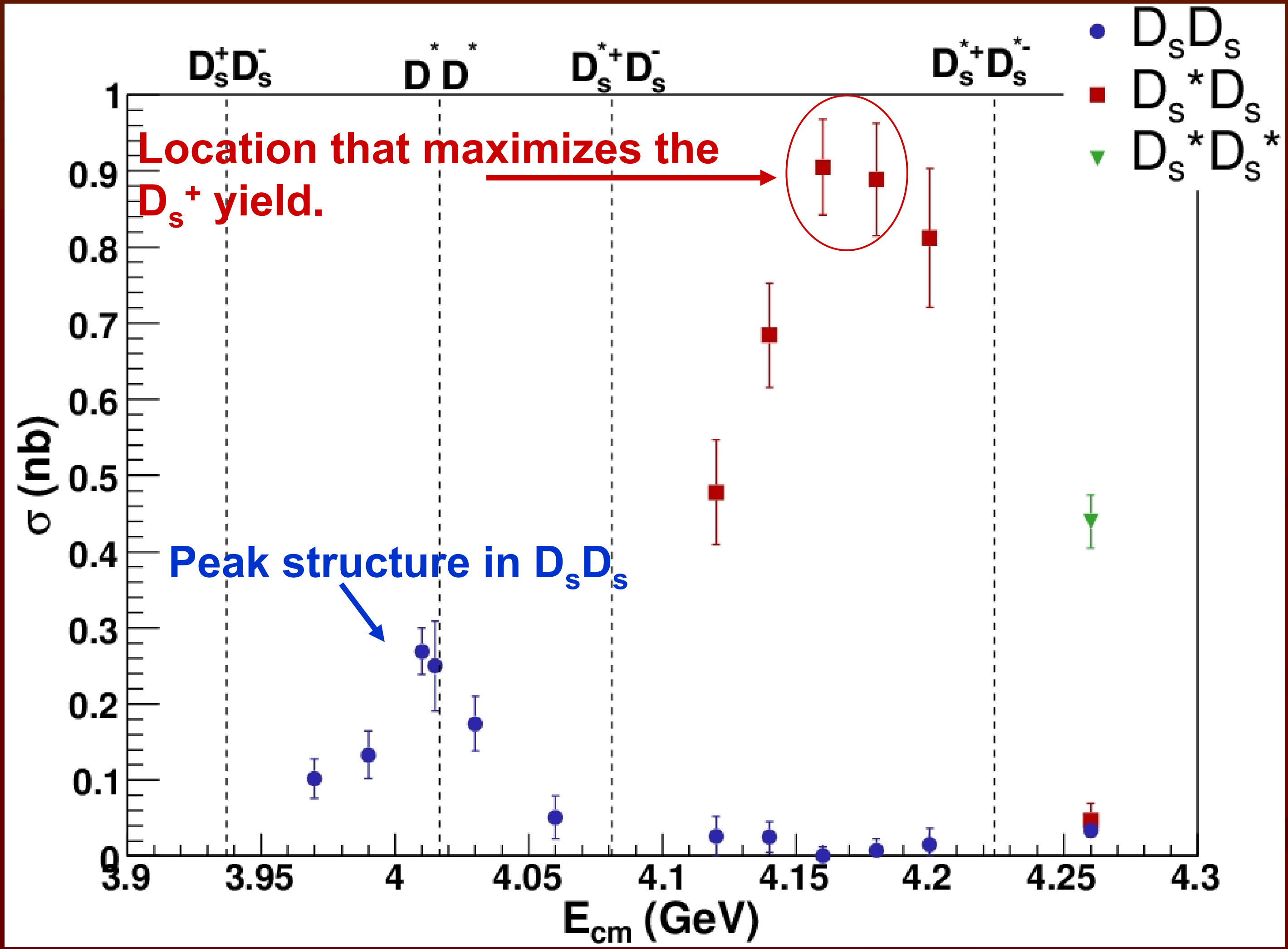
PRELIMINARY

Partial systematic uncertainties
Multibody correction not applied
Not radiatively corrected



PRELIMINARY

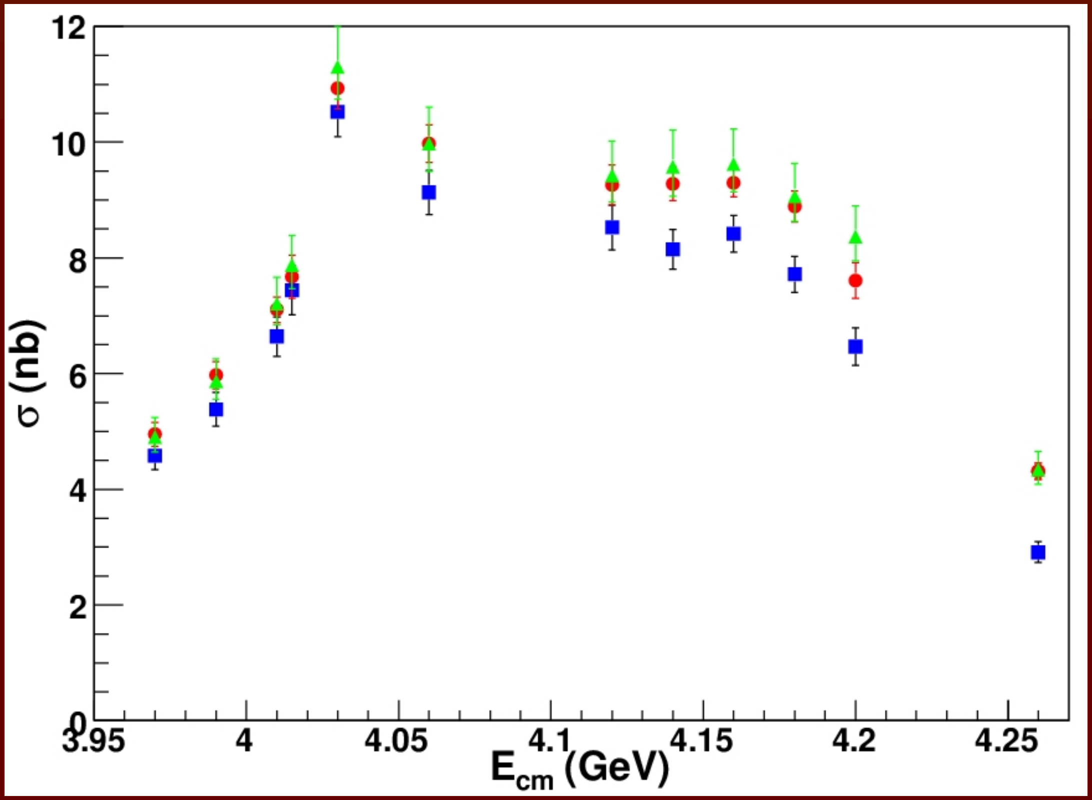
Partial systematic uncertainties
Not radiatively corrected



Cross-Check: Inclusive vs. Exclusive

PRELIMINARY

Partial systematic uncertainties
Not radiatively corrected



- **Exclusive:**
  Sum of (up to) 8 modes with two charmed mesons (no MB)
- **Inclusive charm:**
  $D^0 + D^+ + D_s$
- **Inclusive Hadrons:**
  Excess over *uds*

Good agreement between two inclusives.

Excess of inclusive over exclusive reaffirms MB.

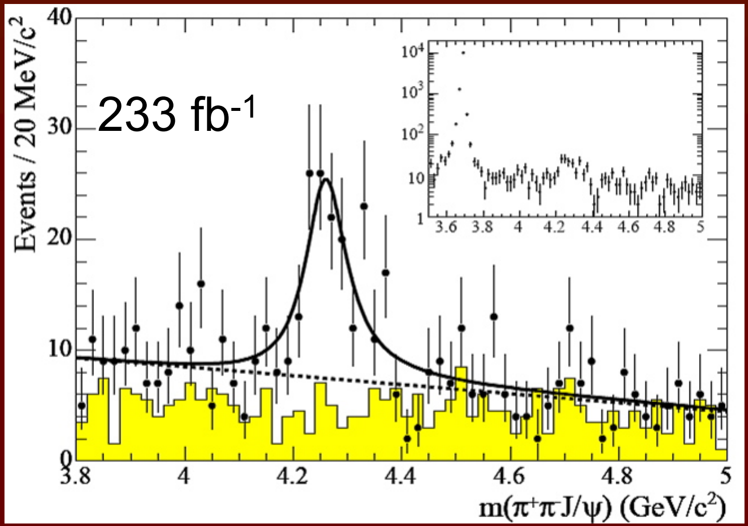
Scan Conclusion

- D_s "Mini-Factory" at E_{CM}=4170 MeV has been selected and is in operation.
- $\sigma(D_s D_s^*) \approx 1$ nb
  - Precise value depends on D_s branching fractions.
- Analysis is under way of the first 76 pb^{-1} for the D_s program. Some preliminary results on hadronic D_s decays will be presented by Sheldon Stone on Tuesday morning.

CLEO Investigations of Y(4260)

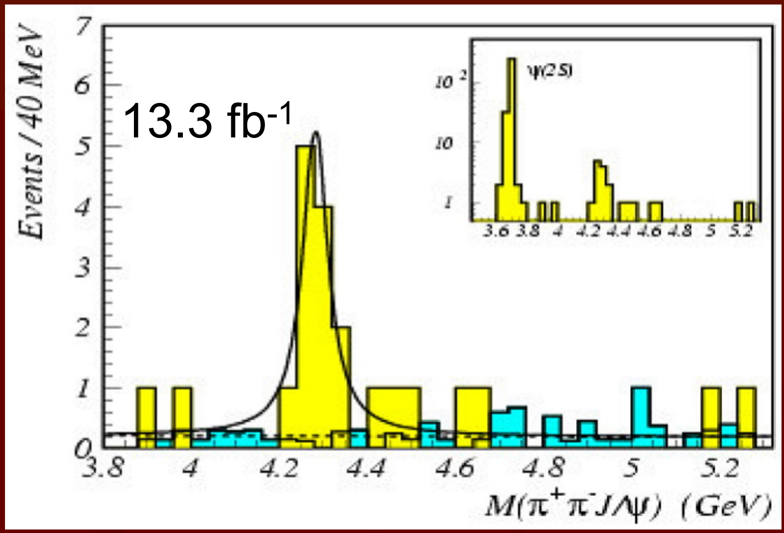
BaBar discovery

PRL **95**, 142001 (2005)



CLEO III Confirmation

PRELIMINARY – 4.9σ



$e^+e^-\to\gamma(\pi^+\pi^- J/\psi)$ $J^{PC}=1^{--}$

…at a minimum in the

cross section for $e^+e^-\to$hadrons

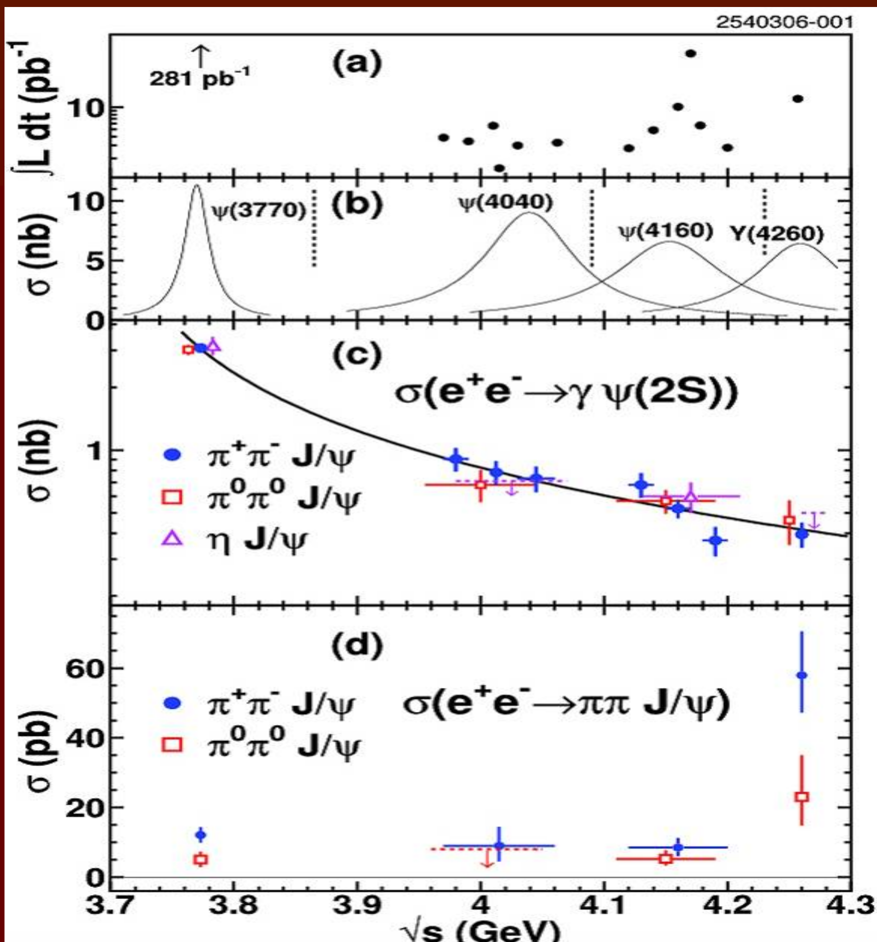
Many possible explanations: hybrids, tetraquarks, molecular states, conventional ψ(4S)+QM

What can CLEO-c say?

Charmonium Decays of $\psi(4040)$, $\psi(4160)$, and $Y(4260)$

CLEO-c hep-ex/0602034

Submitted to PRL



Search for 16 final states with J/ψ, $\psi(2S)$, χ_{cJ}, ϕ

Use $e^+e^-\to\gamma\psi(2S)$ to verify efficiency, background, luminosity.

- $Y(4260)\to\pi^+\pi^- J/\psi$ confirmed (11σ)
- First observation of $Y(4260)\to\pi^0\pi^0 J/\psi$ (5.1σ) and first evidence for $Y(4260)\to K^+K^- J/\psi$ (3.7σ), plus in-progress open-charm studies should narrow the explanations.

CLEO-c: Summary and Prospects

- CLEO-c is already having major impact on our knowledge of charm, with broader implications for all of flavor physics.
  - Measurements of leptonic *D* decays, hadronic *D* decays, semileptonic *D* decays (including exclusive form factors), charm prcharm production, *Y*(4260),….
- Excellent prospects for much more:
  - Scheduled to run through April, 2008; plan designed to achieve maximum physics returns on the likely luminosity budget.
  - 750 pb^{-1} at 3770 for *D* physics, 750 pb^{-1} at 4170 for D_s (and *D*) physics and ≥30 million psi(2S).

Quantity	Exp. Precision
$BF(D^0 \to K^- \pi^+)$	±1.25%
$BF(D^+ \to K^- \pi^+ \pi^+)$	±1.4%
$BF(D_s \to \phi \pi^+)$	±4%
$BF(D^+ \to \mu\nu)$	±9%
$BF(D_s \to \mu\nu)$	±9%
$BF(D^0 \to \pi^- e^+ \nu)$	±2.3%
$\lvert V_{cd} \rvert$	±2%
FF param. α	±0.05