Exclusive Semileptonic Decays of D Mesons Produced at Threshold

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- Introduction
- Overview of the data sample
- Overview of the technique
- Data plots for the tagging *D* side:
  - ✓ D^0 tags
  - ✓ D^+ tags
- Data plots for semileptonic decays:
  - ✓ D^0 semileptonic decays
  - ✓ D^+ semileptonic decay
- Sensitivity of the CLEO-c program to
  - ✓ *D* semileptonic decay branching fractions
  - ✓ *D* semileptonic decay form factors
  - ✓ CKM matrix elements V_{cs} and V_{cd}
- Summary and Outlook

Introduction

- The matrix element for a semileptonic D transition is

$$\mathcal{M}(M_i \to M_f l\nu) = -i\frac{G_F}{\sqrt{2}} V_{q_f Q_i} L^\mu H_\mu$$

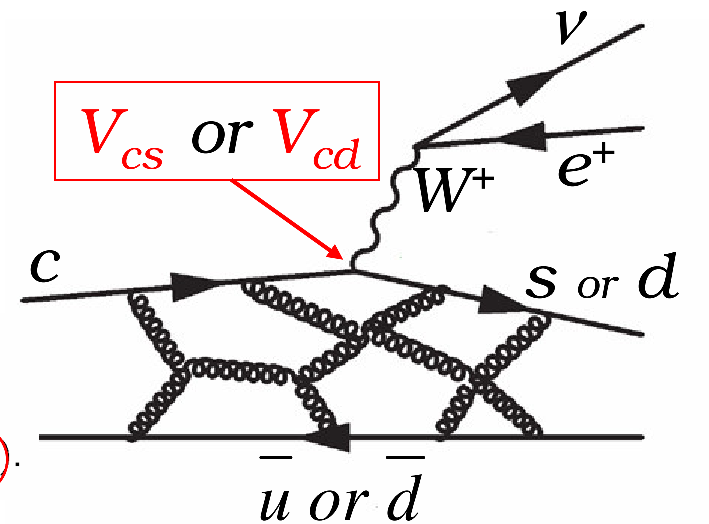
- Form Factors:

  - ✓ P to P transitions (1 FF):

$$\langle P'(p')|V^\mu - A^\mu|P(p)\rangle = f_+(q^2)(p+p')^\mu$$

  - ✓ P to V transitions (3 FFs):

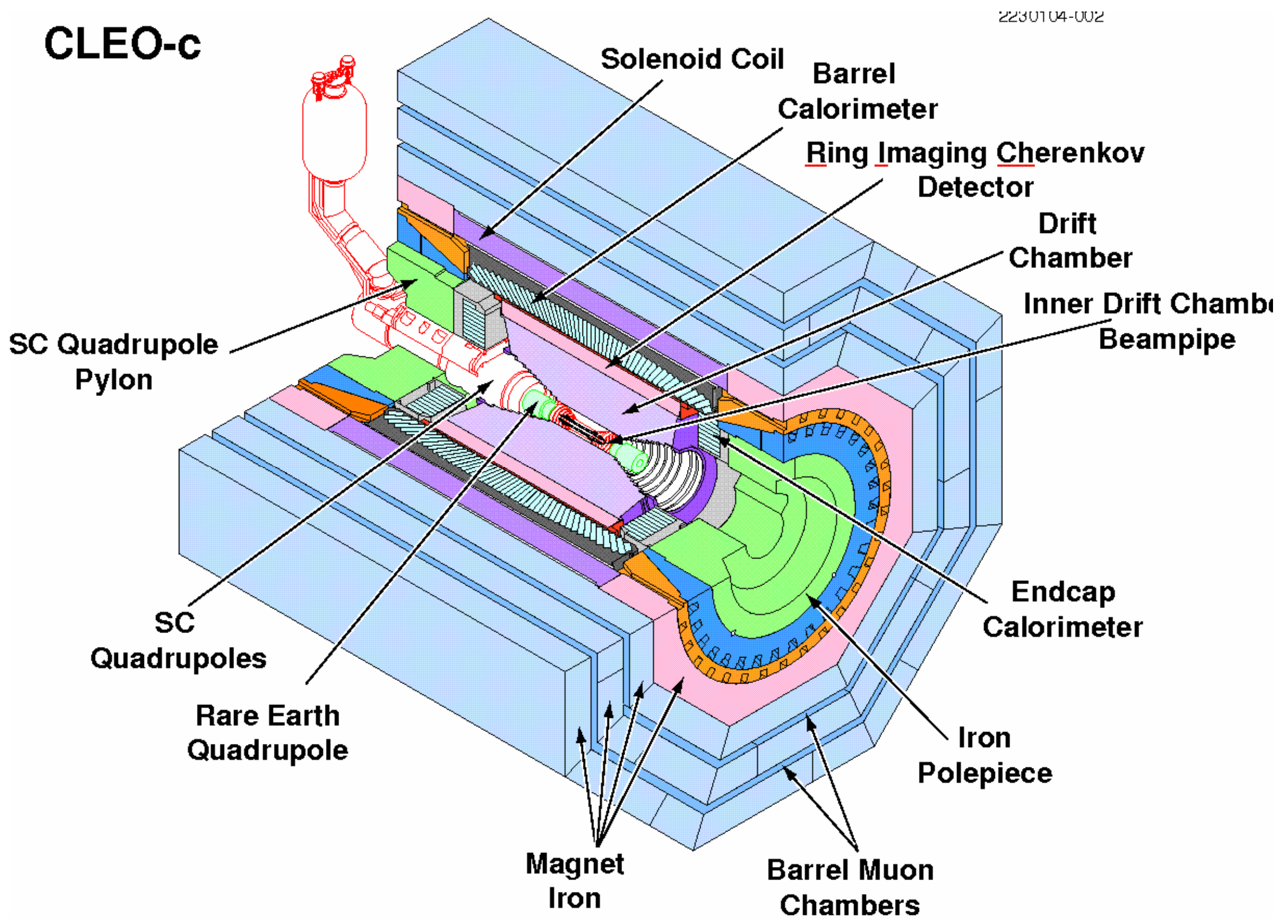
$$\langle V(p',\varepsilon)|V^\mu - A^\mu|P(p)\rangle = \frac{2i\epsilon^{\mu\nu\alpha\beta}}{M+m_V}\varepsilon^*_\nu p'_\alpha p_\beta V(q^2)$$
$$-(M+m_V)\varepsilon^{*\mu}A_1(q^2) + \frac{\varepsilon^*\cdot q}{M+m_V}(p+p')^\mu A_2(q^2).$$



- Measurements of the absolute branching fractions and form factors for semileptonic decays in the D system are important because they provide:
  - ✓ A test of theoretical form factor models
  - ✓ Input for validation and calibration of LQCD
  - ✓ Input on semileptonic form factors in the B system valuable for extraction of V_{ub} from, eg, $B\to\pi e\nu$
  - ✓ Direct measurements of V_{cs} and V_{cd}

The CLEO-c detector and data sample

- Data Sample: ~60/pb collected with the CLEO-c detector last fall/winter (October, 2003, through January, 2004) at $\psi(3770)$

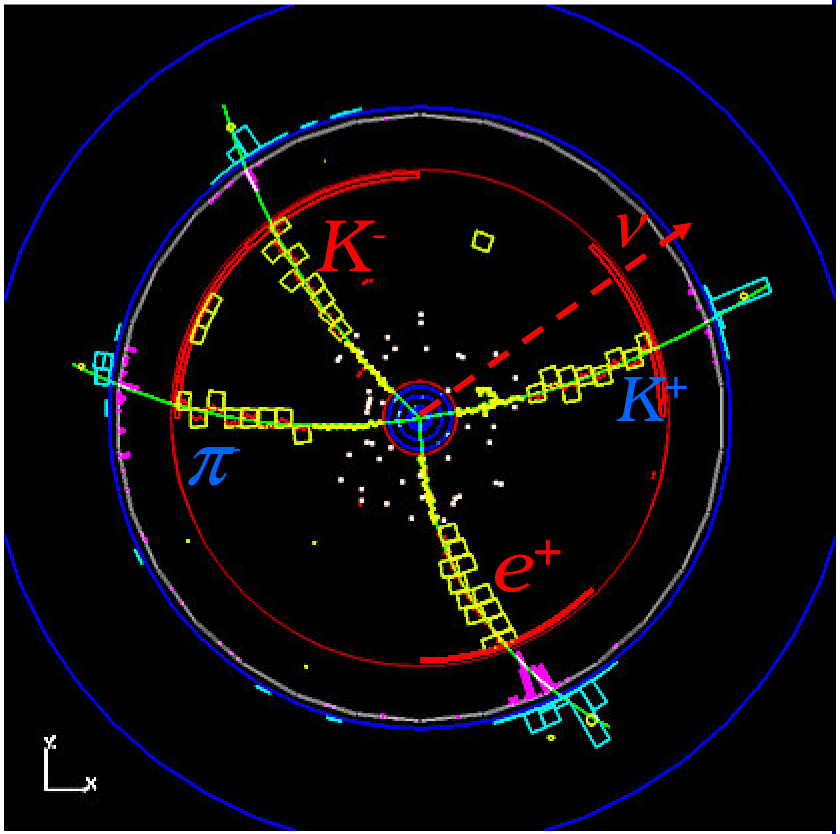


Overview of the technique

- Reconstruct one of the two *D*'s in a hadronic decay channel. It is called the tagging *D*. Two key variables in the tagging *D* reconstuction are:
  - ✓ $M_{bc} = \sqrt{E_{beam}^2 - P_{candidate}^2}$
  - ✓ $\Delta E = E_{beam} - E_{candidate}$
- Reconstruct from the remaining tracks and showers the observable particles in the final state of a semileptonic decay.
- Define an observable that can be used to separate signal and background as $U \equiv E_{miss} - |\boldsymbol{P}_{miss}|$, where E_{miss} and $\boldsymbol{P}_{miss}$ are the missing energy and momentum in the event, approximating the neutrino *E* and $\boldsymbol{P}$. The signal peaks at zero in *U*.
- Account for the background in the signal region of *U*.
- Account for the systematic effects.

$\psi(3770) \to D^0 \overline{D}^0$

$\overline{D}^0 \to K^+ \pi$, $D^0 \to K^- e^+ \nu$



The tagging D side of the event

D^0 Decay Mode	$\mathcal{B}$ (%) (PDG-02)
$D^0 \to K^-\pi^+$	(3.80 ± 0.09)
$D^0 \to K^-\pi^+\pi^0$	(13.1 ± 0.9)
$D^0 \to K^-\pi^+\pi^+\pi^-$	(7.46 ± 0.31)
$D^0 \to \overline{K^0}\pi^0$	(2.28 ± 0.22)
$D^0 \to \overline{K^0}\pi^+\pi^-$	(5.92 ± 0.35)
$D^0 \to \overline{K^0}\pi^+\pi^-\pi^0$	(10.8 ± 1.3)
$D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$	(4.0 ± 0.4)
$D^0 \to \overline{K^0}K^+K^-$	(1.0 ± 0.1)
$D^0 \to \pi^+\pi^-\pi^0$	(1.1 ± 0.4)
$D^0 \to K^+K^-$	(0.41 ± 0.01)
$D^0 \to \pi^+\pi^-$	(0.14 ± 0.01)
$D^0 \to K^-\pi^+\pi^0\pi^0$	

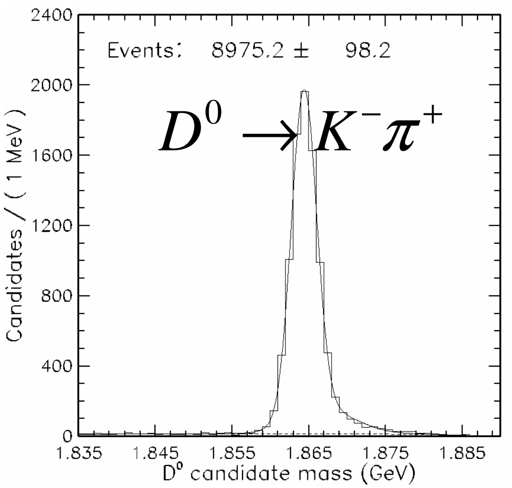
D^+ Decay Mode	$\mathcal{B}$ (%) (PDG-02)
$D^+ \to \overline{K^0}\pi^+$	(2.77 ± 0.18)
$D^+ \to K^-\pi^+\pi^+$	(9.1 ± 0.6)
$D^+ \to \overline{K^0}\pi^+\pi^0$	(9.7 ± 3.0)
$D^+ \to K^-\pi^+\pi^+\pi^0$	(6.4 ± 1.1)
$D^+ \to \overline{K^0}\pi^+\pi^+\pi^-$	(7.0 ± 0.9)
$D^+ \to K^+K^-\pi^+$	(0.9 ± 0.1)

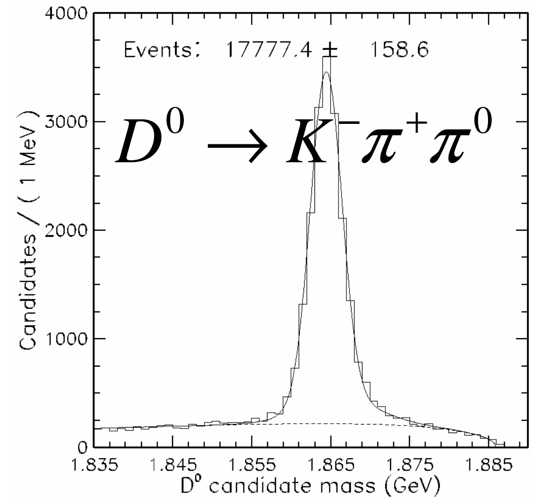
The total number of D^0 tags approximately is 62K in 60/pb

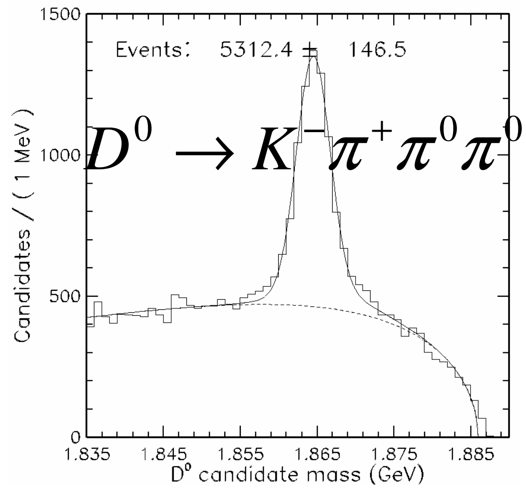
The total number of D^+ tags approximately is 30K in 60/pb

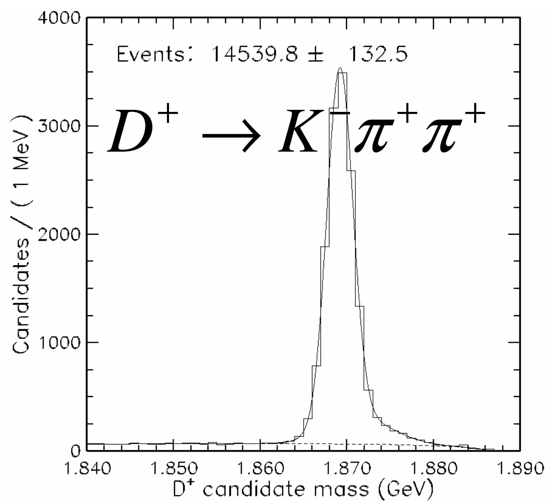
ALL PRELIMINARY

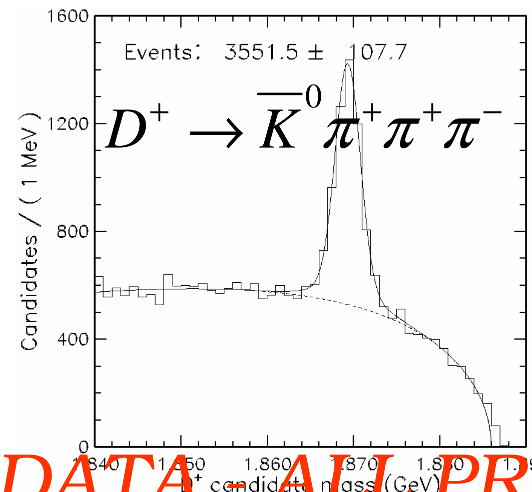
Representative plots of the *Mbc* distributions for D^0 and D^+ tags in 60/pb of DATA









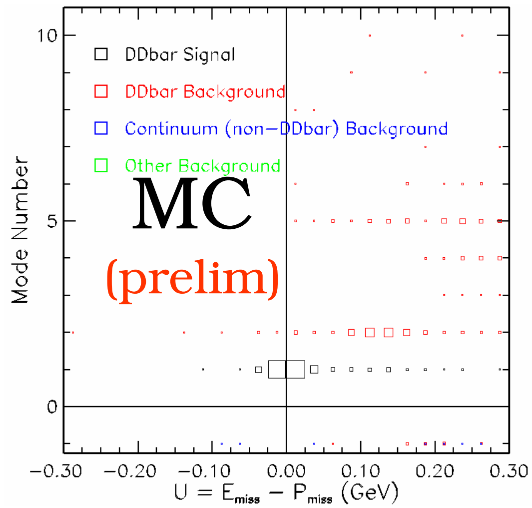


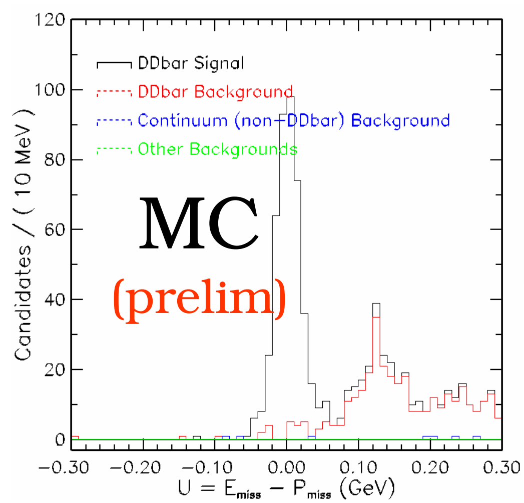
DATA - ALL PRELIMINARY

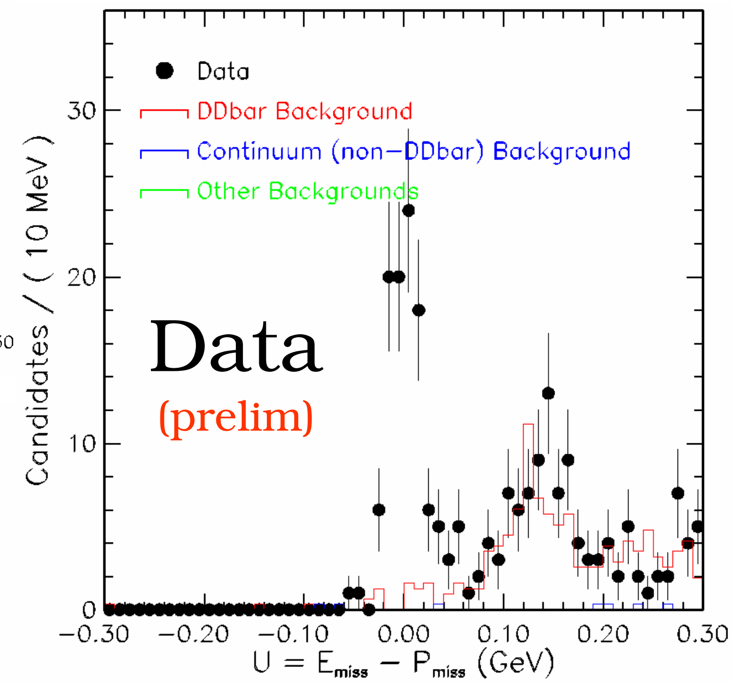
$D^0 \to \pi^- e^+ \nu$

Mode	Decay Mode
1.	$D^0 \to \pi^- e^+ \nu$
2.	$D^0 \to K^- e^+ \nu$
3.	$D^0 \to K^{*-}(K^- \pi^0) e^+ \nu$
4.	$D^0 \to K^{*-}(\overline{K^0} \pi^-) e^+ \nu$
5.	$D^0 \to \rho^-(\pi^- \pi^0) e^+ \nu$
6.	$D^+ \to \overline{K^0} e^+ \nu$
7.	$D^+ \to K^{*0}(K^- \pi^+) e^+ \nu$
8.	$D^+ \to \pi^0 e^+ \nu$
9.	$D^+ \to \rho^0(\pi^+ \pi^-) e^+ \nu$
10.	$D^+ \to \eta(\gamma\gamma) e^+ \nu$
-1.	all other decays

- Excess of around 100 events







ALL PRELIMINARY

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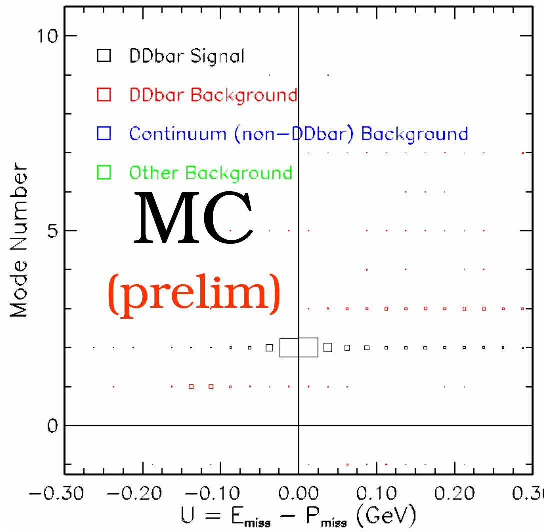
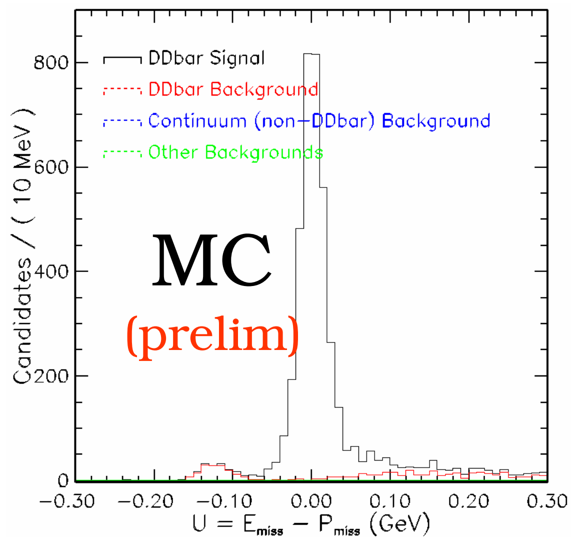
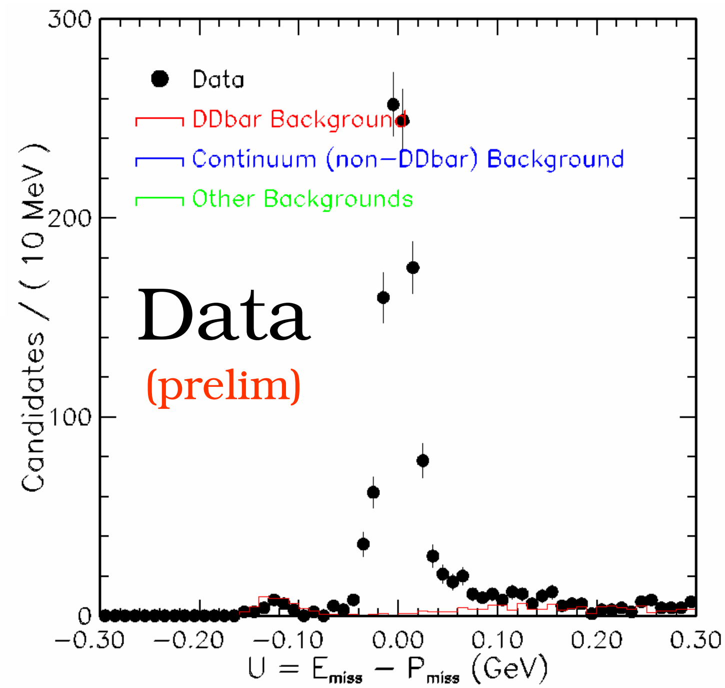




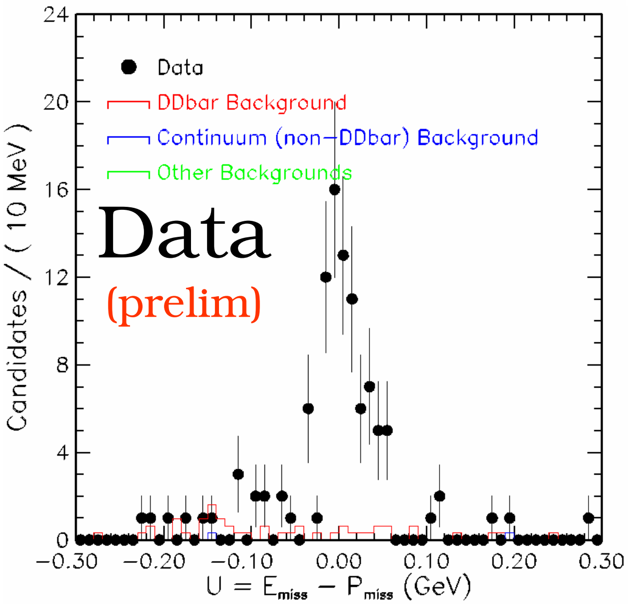


- Excess of around 1.1K events

ALL PRELIMINARY

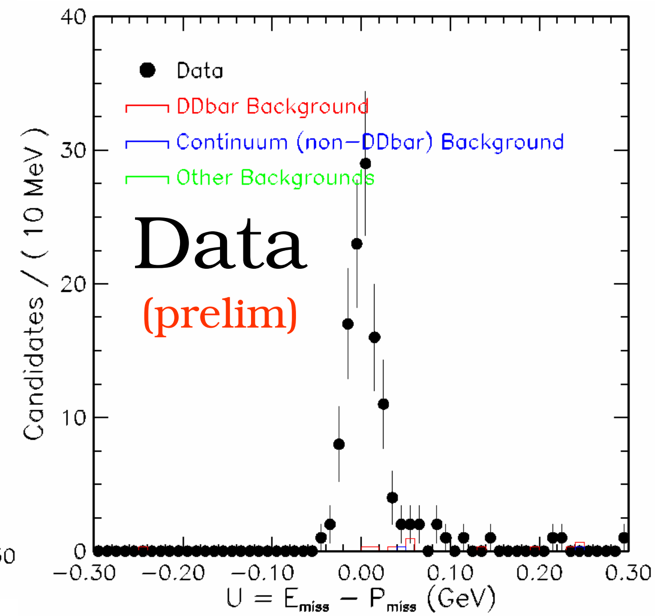
Other D^0 semileptonic modes

$D^0 \to K^{*-} e^+ \nu, \quad K^{*-} \to K^- \pi^0$



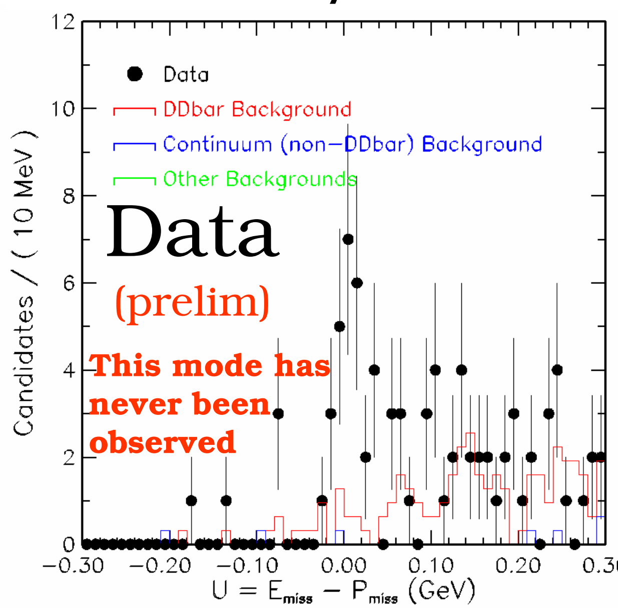
- Excess of around 80 events
- The nonresonant contribution is included in the yield

$D^0 \to K^{*-} e^+ \nu, \quad K^{*-} \to \overline{K^0} \pi^-$



- Excess of around 120 events
- The nonresonant contribution is included in the yield

$D^0 \to \rho^- e^+ \nu$

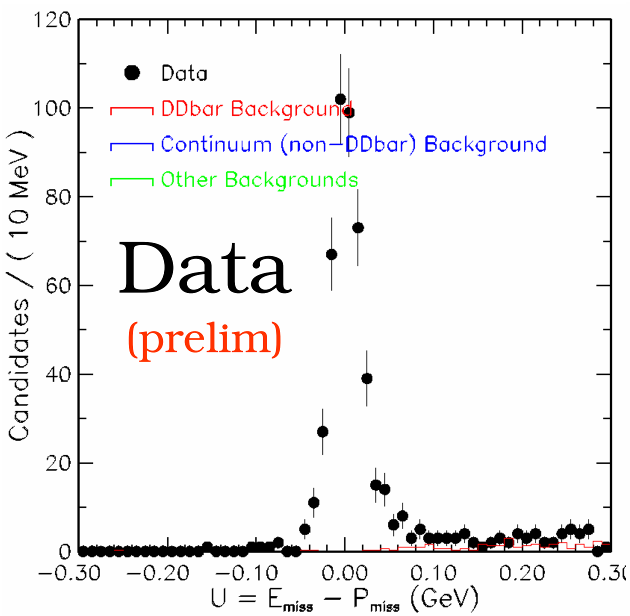


- Excess of around 25 events
- The nonresonant contribution is included in the yield
- This is a compelling evidence for this decay mode
- The background is mostly outside the signal box and can be easily reduced

ALL PRELIMINARY

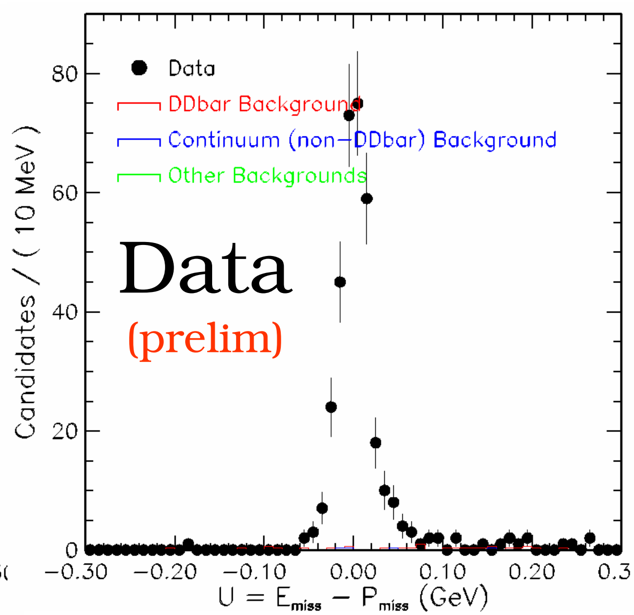
D^+ semileptonic modes (1)

$D^+ \to \overline{K}^0 e^+ \nu$



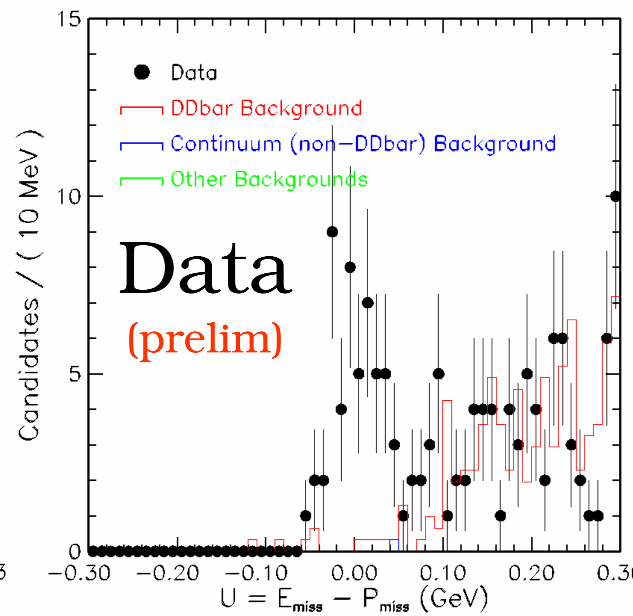
- Excess of around 400 events

$D^+ \to K^{*0} e^+ \nu, \quad K^{*0} \to K^- \pi^+$



- Excess of around 300 events
- The nonresonant contribution is included in the yield

$D^+ \to \pi^0 e^+ \nu$

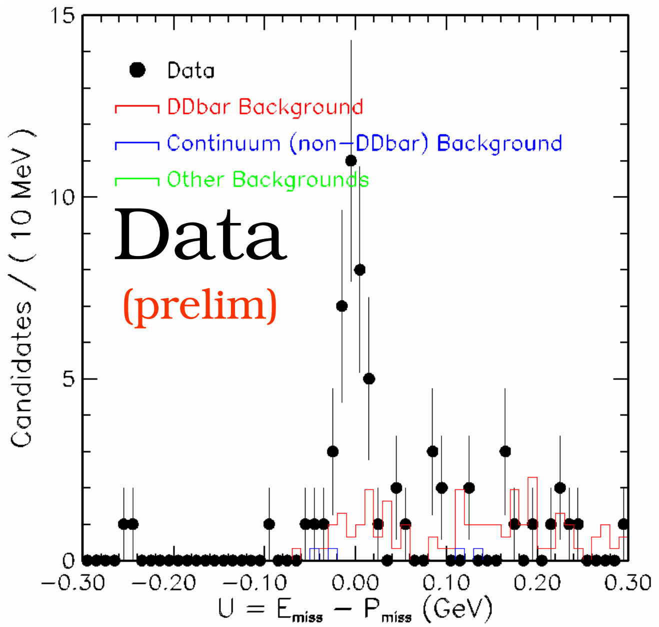


- Excess of around 50 events

ALL PRELIMINARY

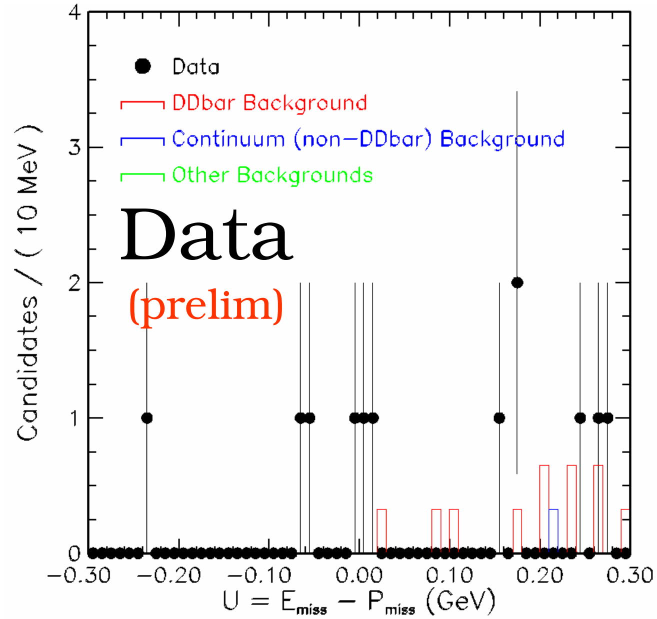
D^+ semileptonic modes (2)

$D^+ \to \rho^0 e^+ \nu$



- Excess of around 35 signal events
- The nonresonant contribution is included in the yield

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



- Too early to say anything

ALL PRELIMINARY

Systematic studies for BRs are ongoing

- Electron identification efficiency
- Hadron identification efficiency
- Track finding efficiency
- Tracking resolution and its effect on the U resolution

- Uncertainties in efficiencies from the form factor models

CLEO-c reach (1)

- The 60/pb data sample collected in fall-2003/winter-2004 by the CLEO-c detector already allows measurements of BRs for most or all of the modes considered today with statistical uncertainties comparable or smaller than those in PDG-2002.
- CLEO-c is expected to collect 50 times more (~3/fb) data on $\psi(3770)$ as well as ~3/fb of data at E_{cm} ~ 4140 MeV for studies of D_s mesons in the coming 2 years.
- The CLEO-c data will dramatically improve knowledge of the BRs of charm mesons:

$1: D^0 \to K^- e^+ \nu$

$2: D^0 \to K^{*-} e^+ \nu$

$3: D^0 \to \pi^- e^+ \nu$

$4: D^0 \to \rho^- e^+ \nu$

$5: D^+ \to \overline{K}^0 e^+ \nu$

$6: D^+ \to \overline{K}^{0*} e^+ \nu$

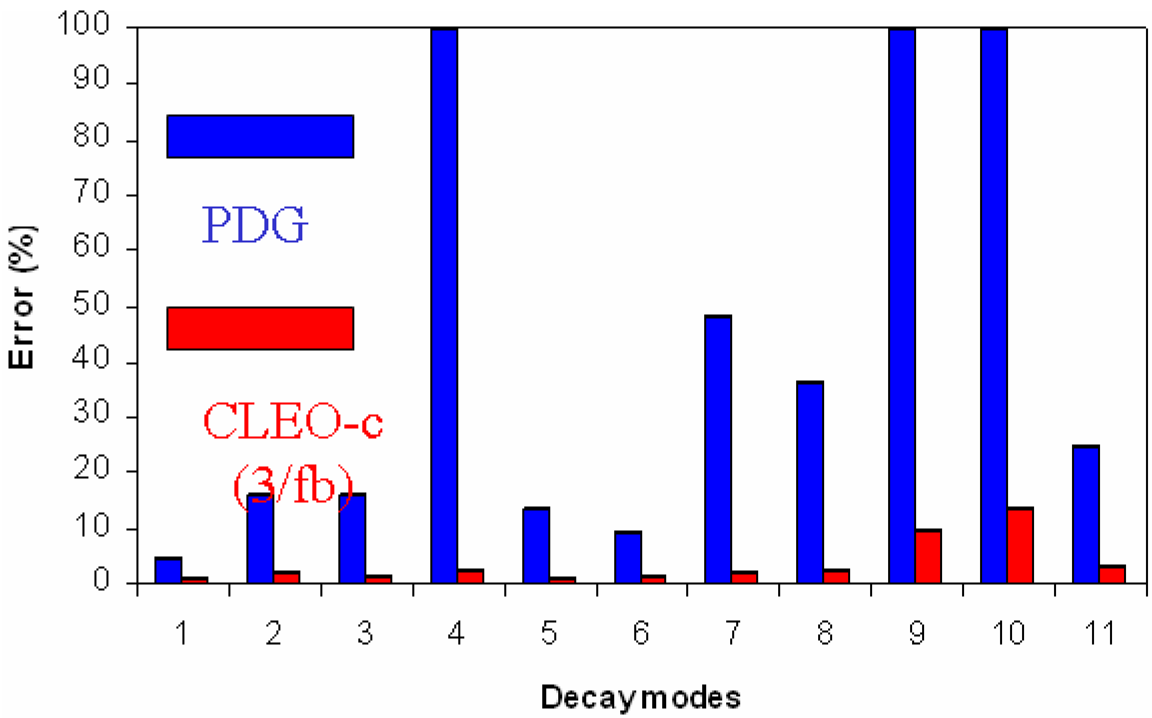
$7: D^+ \to \pi^0 e^+ \nu$

$8: D^+ \to \rho^0 e^+ \nu$

$9: D_s \to K^0 e^+ \nu$

$10: D_s \to K^{*0} e^+ \nu$

$11: D_s \to \phi e^+ \nu$



CLEO-c reach (2)

- CLEO-c semileptonic events allow precision studies of semileptonic decay form factors (predictions for 3/fb):
  - ✓ *P* to *P*: $f_+(q^2) = f_+(0)\, e^{\alpha q^2}, \quad \frac{\delta\alpha}{\alpha} \approx 2-3\%, \quad \textit{for both } D^0 \to K^- e^+ \nu \textit{ and } D^0 \to \pi^- e^+ \nu$
  - ✓ *P* to *V*: $R_V = \frac{V(0)}{A_1(0)} \approx 2-3\% \quad \textit{and} \quad R_2 = \frac{A_2(0)}{A_1(0)} \approx 2.5-3.5\% \quad \textit{for both } D^0 \to K^{*-} e^+ \nu \textit{ and } D^0 \to \rho^- e^+ \nu$
- The form factor measurements are essential for testing form factor models and calibrating LQCD, input from which is required for measurements of *Vcs* and *Vcd*:

$$\Gamma(D^0 \to K^- e^+ \nu) = \frac{B(D^0 \to K^- e^+ \nu)}{\tau(D^0)} = \gamma_s |V_{cs}|^2 \quad \Rightarrow \quad \frac{\delta V_{cs}}{V_{cs}} = \sqrt{\left(\frac{\delta\Gamma}{2\Gamma}\right)^2 + \left(\frac{\delta\gamma_s}{2\gamma_s}\right)^2}$$

theory

experiment

- Using the future CLEO-c measurements of BRs and the world average for *D* meson lifetimes (CLEO-c can *not* measure lifetimes directly), and assuming theory errors on γ_s and γ_d of 3%, the following uncertainties for *Vcs* and *Vcd* from a 3/fb data sample are within reach:

$$\frac{\delta V_{cs}}{V_{cs}} = 1.6\% \ (now\ 11\%) \quad and \quad \frac{\delta V_{cd}}{V_{cd}} = 1.7\% \ (now\ 7\%)$$

Summary and Outlook

- First exclusively reconstructed CLEO-c D^0 and D^+ semileptonic decays from the 60/pb data sample collected on $\psi(3770)$ have been presented. Expect first quantitative results this summer.
- The CLEO-c detector is functioning as expected.
- It is planned to collect 50 times more data on $\psi(3770)$ and the same amount of data at $E_{cm} \sim 4140$ MeV. This data sample will play an important role in particle physics as
  - ✓ validation and calibration data for LQCD - the first theory capable of solving strongly coupled field theory equations
  - ✓ input data to the *B*-factories and other experiments increasing their potential
- CLEO-c running resumes in September.

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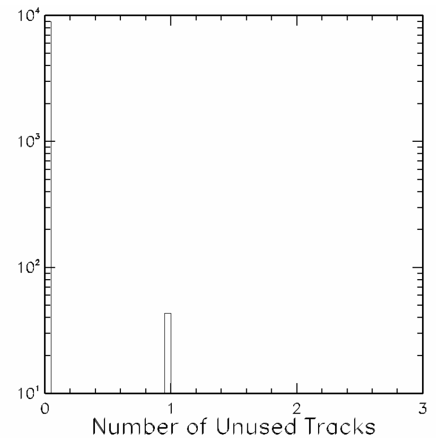
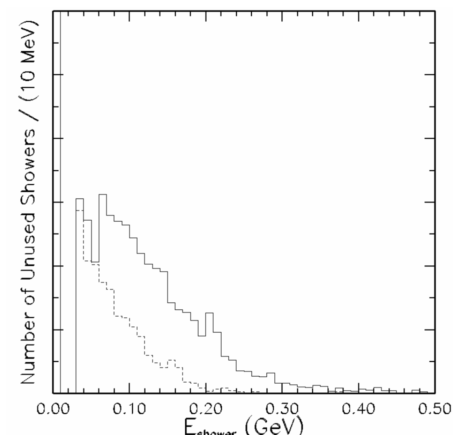
An overview of reconstruction

- Selection of tracks:
  - ✓ Track quality criteria
  - ✓ Hadronic PID criteria are based on
    - ➢ the dE/dX information
    - ➢ the RICH information
- Selection of showers and π^0:
  - ✓ unmatched to tracks showers
  - ✓ $E_{shower} > 30$ (50) *MeV*
  - ✓ hot crystals are excluded
  - ✓ $-3.5\sigma < |M(\pi^0)| < 3.0\sigma$
- Electron ID is based on a likelihood built from:
  - ✓ the ratio of *E/P*
  - ✓ the *dE/dX* information
  - ✓ the RICH information
- Bremsstrahlung photons for electrons are recovered

- Two important variables in the *D* tag reconstuction:
  - ✓ $\Delta E = E_{beam} - E_{cand}$
  - ✓ $M_{bc} = \mathrm{sqrt}(E^2_{beam} - P^2_{cand})$
- Require $|\Delta E| < 35\,MeV$ and $|M_{bc} - M_D| < 8\,MeV$
- All tracks found in the event must be used in reconstruction
- Require for unused showers $E_{shower} < 0.30$ (0.15) *GeV*
- Loose cuts on E_{miss} and P_{miss}





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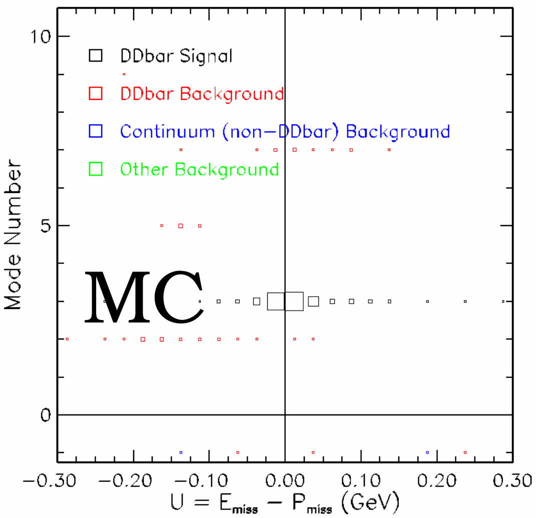

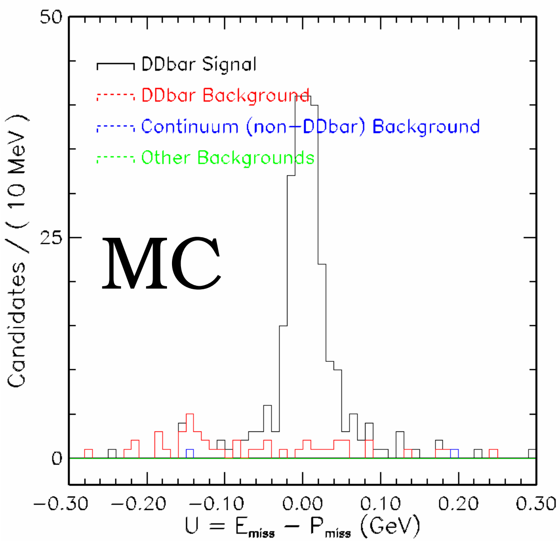

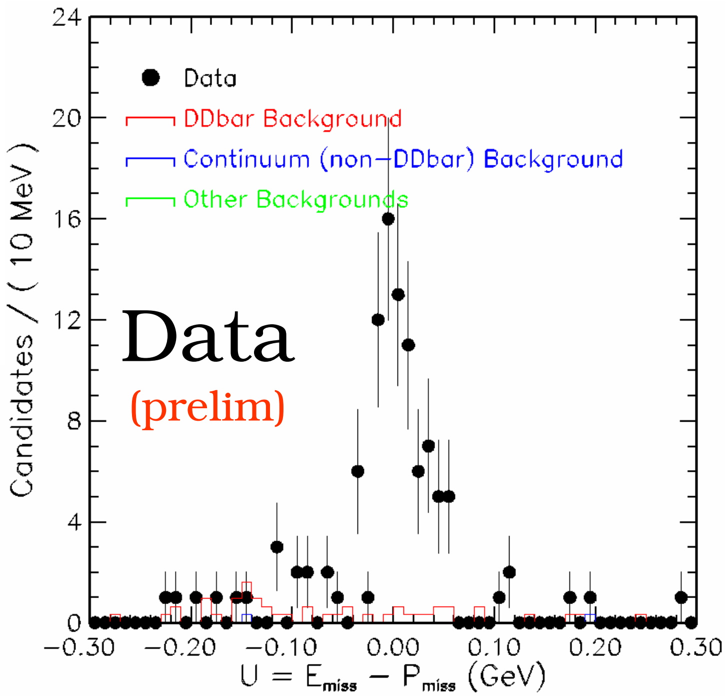

- Excess of around 80 signal events
- The nonresonant contribution is included in the yield

ALL PRELIMINARY

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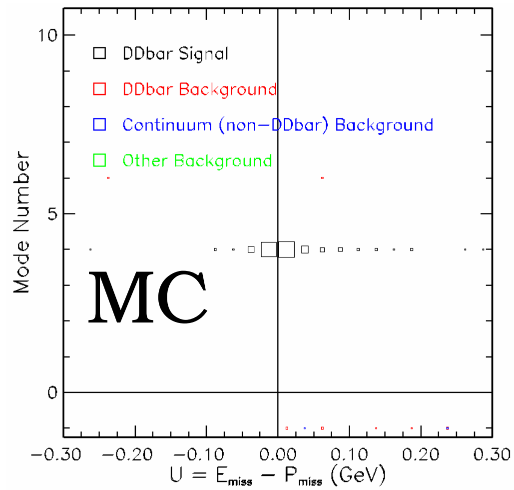

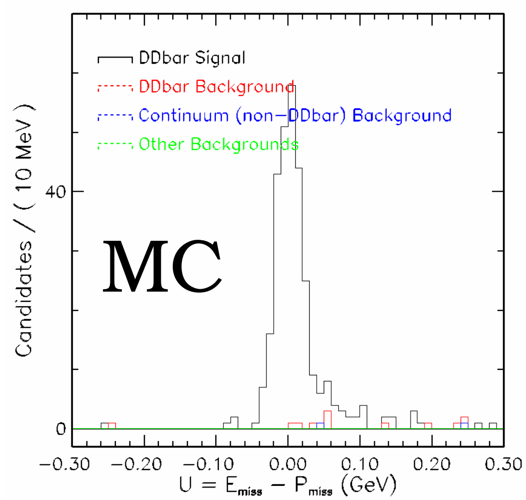

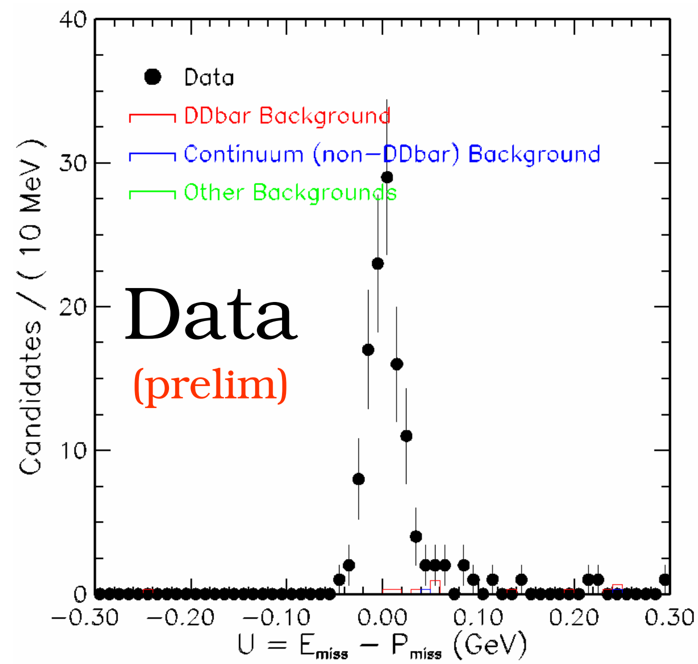

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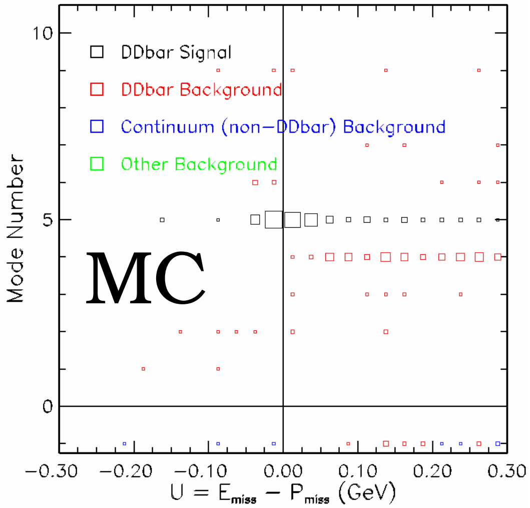
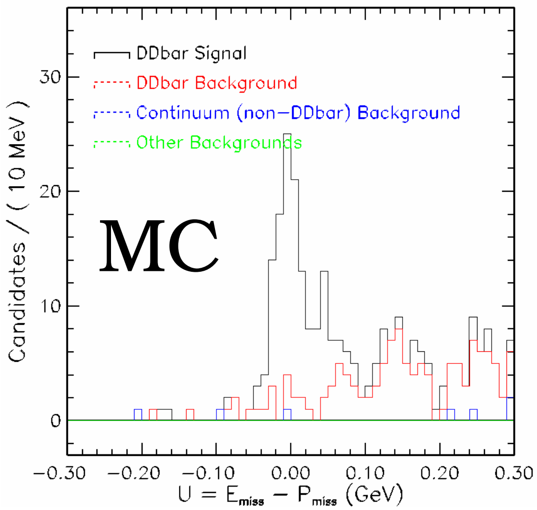
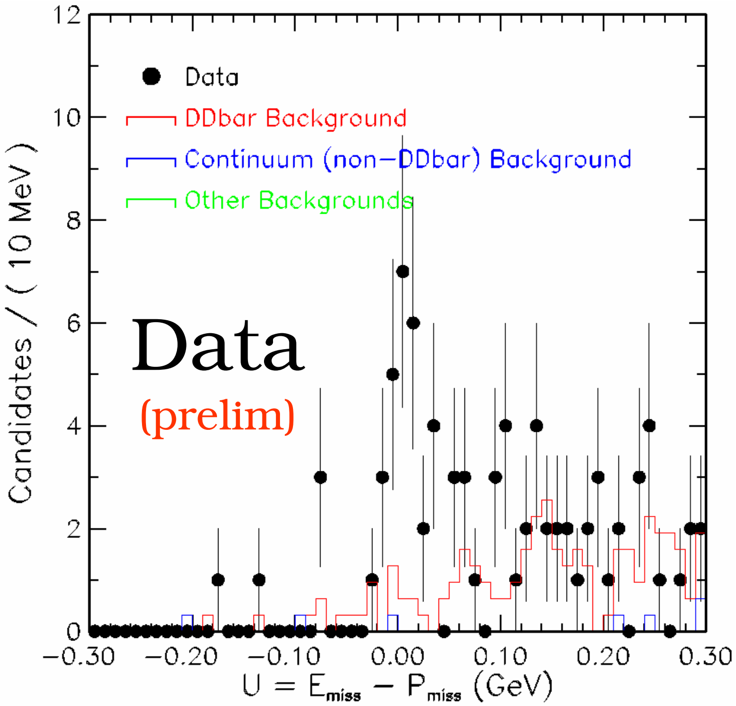
-1.	all other decays





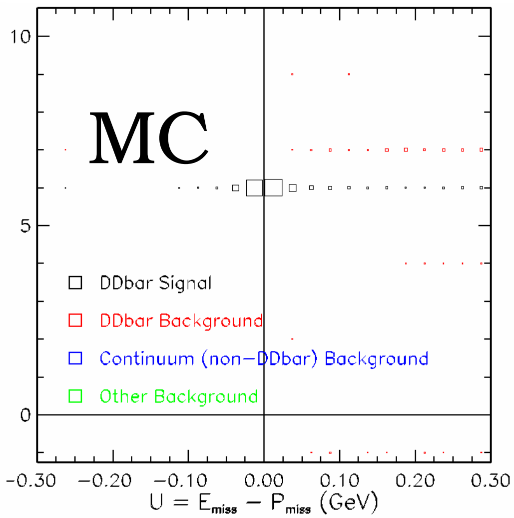


- Excess of around 25 events
- The nonresonant contribution is included in the yield

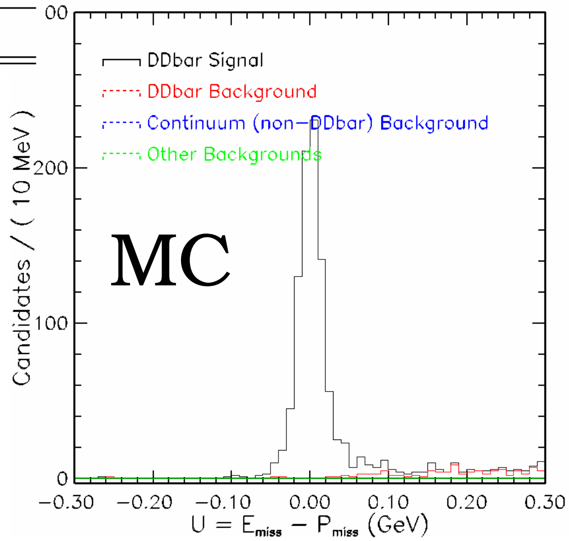
ALL PRELIMINARY

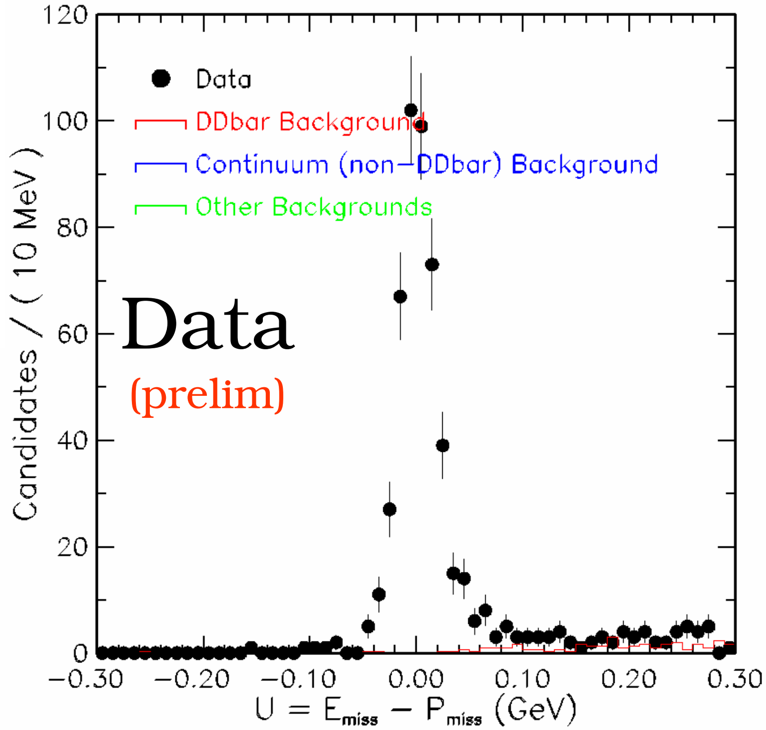
$D^+ \to \overline{K^0} e^+ \nu$

Mode	Decay Mode
1.	$D^0 \to \pi^- e^+ \nu$
2.	$D^0 \to K^- e^+ \nu$
3.	$D^0 \to K^{*-}(K^- \pi^0) e^+ \nu$
4.	$D^0 \to K^{*-}(\overline{K^0} \pi^-) e^+ \nu$
5.	$D^0 \to \rho^-(\pi^- \pi^0) e^+ \nu$
6.	$D^+ \to \overline{K^0} e^+ \nu$
7.	$D^+ \to K^{*0}(K^- \pi^+) e^+ \nu$
8.	$D^+ \to \pi^0 e^+ \nu$
9.	$D^+ \to \rho^0(\pi^+ \pi^-) e^+ \nu$
10.	$D^+ \to \eta(\gamma\gamma) e^+ \nu$
-1.	all other decays



- Excess of around 400 events

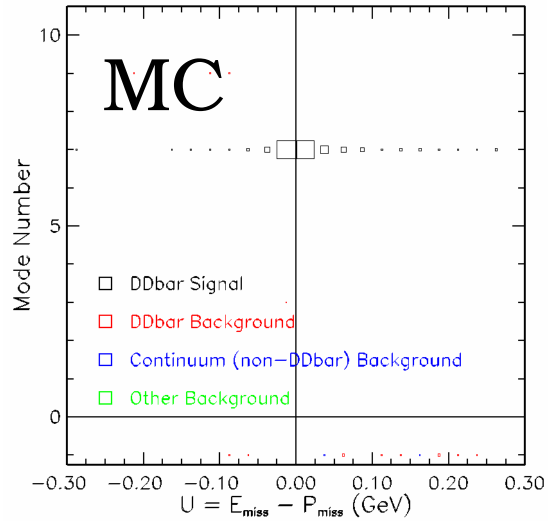


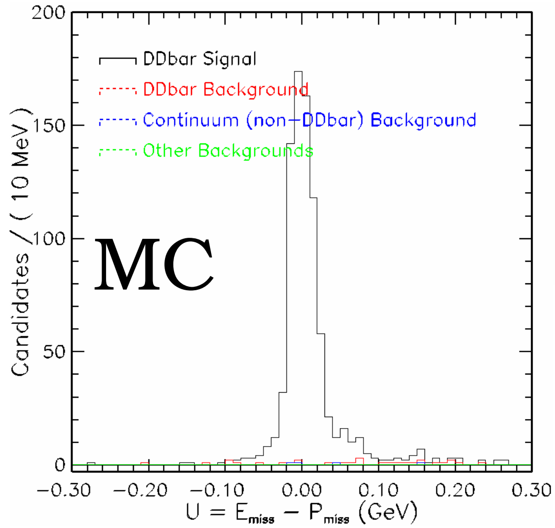


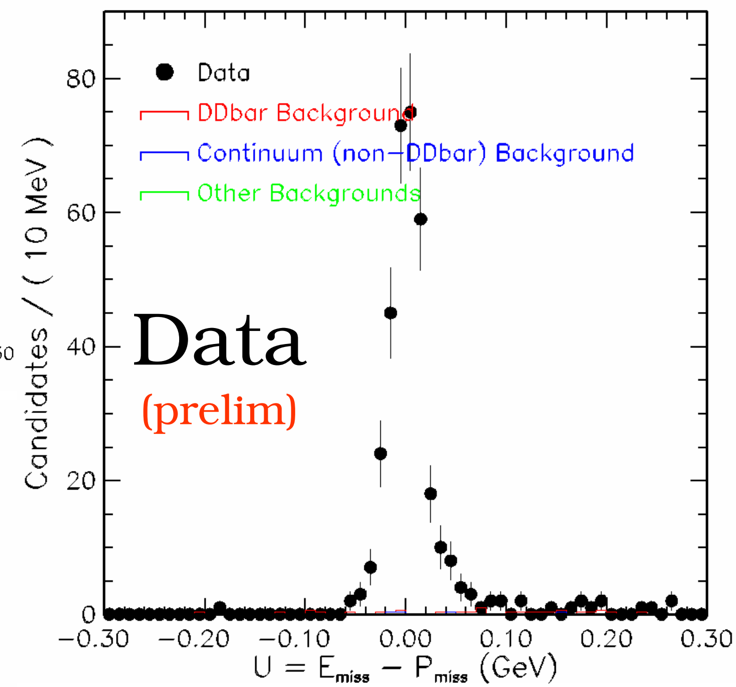
ALL PRELIMINARY

$D^+ \to K^{*0} e^+ \nu, \quad K^{*0} \to K^- \pi^+$

Mode	Decay Mode
1.	$D^0 \to \pi^- e^+ \nu$
2.	$D^0 \to K^- e^+ \nu$
3.	$D^0 \to K^{*-}(K^- \pi^0) e^+ \nu$
4.	$D^0 \to K^{*-}(\overline{K^0} \pi^-) e^+ \nu$
5.	$D^0 \to \rho^-(\pi^- \pi^0) e^+ \nu$
6.	$D^+ \to \overline{K^0} e^+ \nu$
7.	$D^+ \to K^{*0}(K^- \pi^+) e^+ \nu$
8.	$D^+ \to \pi^0 e^+ \nu$
9.	$D^+ \to \rho^0(\pi^+ \pi^-) e^+ \nu$
10.	$D^+ \to \eta(\gamma\gamma) e^+ \nu$
-1.	all other decays





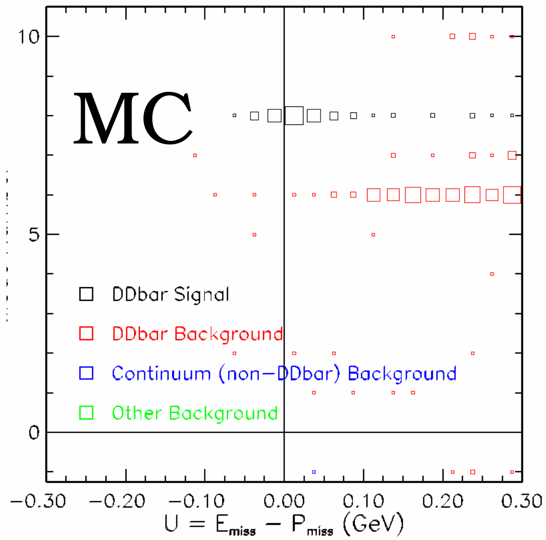


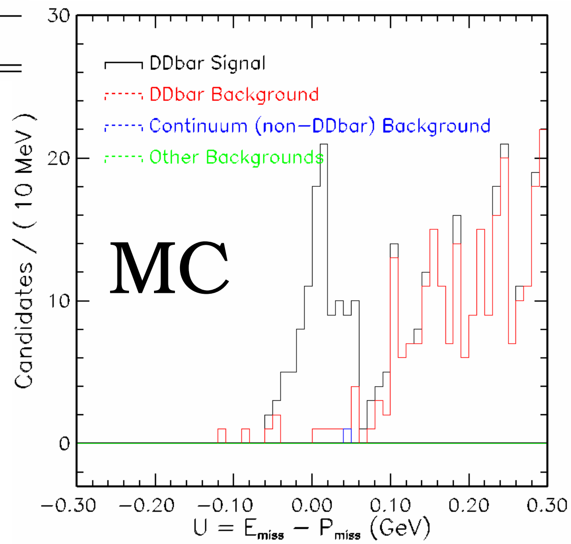
- Excess of around 300 events
- The nonresonant contribution is included in the yield

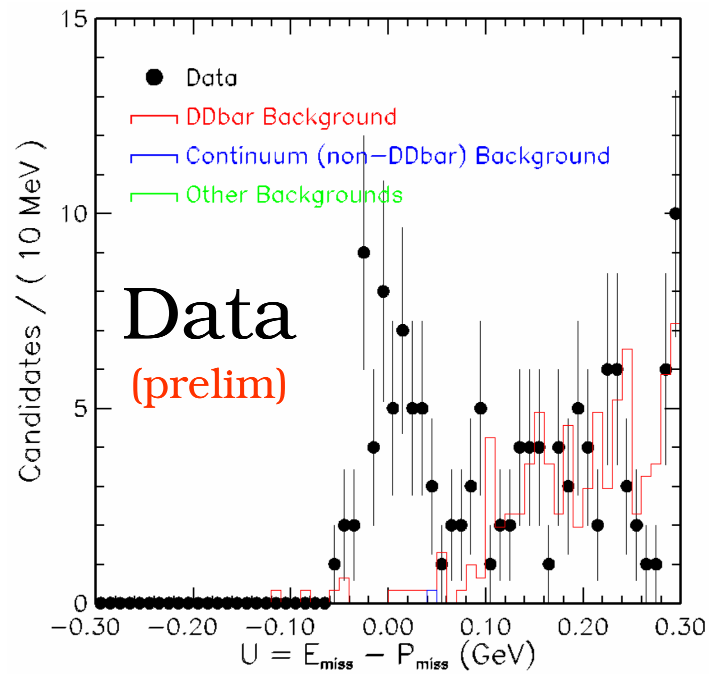
ALL PRELIMINARY

$D^+ \to \pi^0 e^+ \nu$

Mode	Decay Mode
1.	$D^0 \to \pi^- e^+ \nu$
2.	$D^0 \to K^- e^+ \nu$
3.	$D^0 \to K^{*-}(K^- \pi^0) e^+ \nu$
4.	$D^0 \to K^{*-}(\overline{K^0} \pi^-) e^+ \nu$
5.	$D^0 \to \rho^-(\pi^- \pi^0) e^+ \nu$
6.	$D^+ \to \overline{K^0} e^+ \nu$
7.	$D^+ \to K^{*0}(K^- \pi^+) e^+ \nu$
8.	$D^+ \to \pi^0 e^+ \nu$
9.	$D^+ \to \rho^0(\pi^+ \pi^-) e^+ \nu$
10.	$D^+ \to \eta(\gamma\gamma) e^+ \nu$
-1.	all other decays





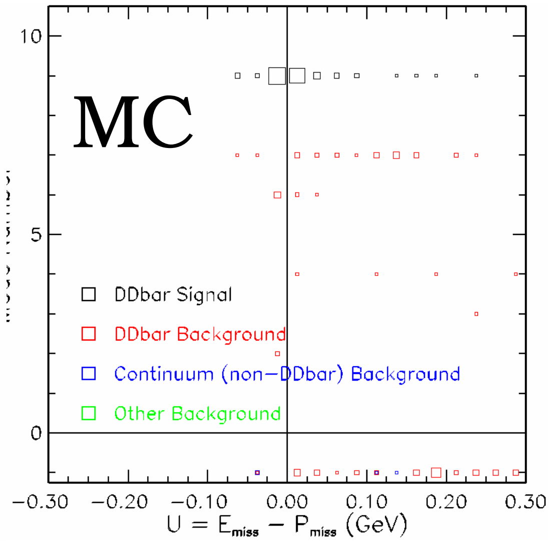


- Excess of around 50 events

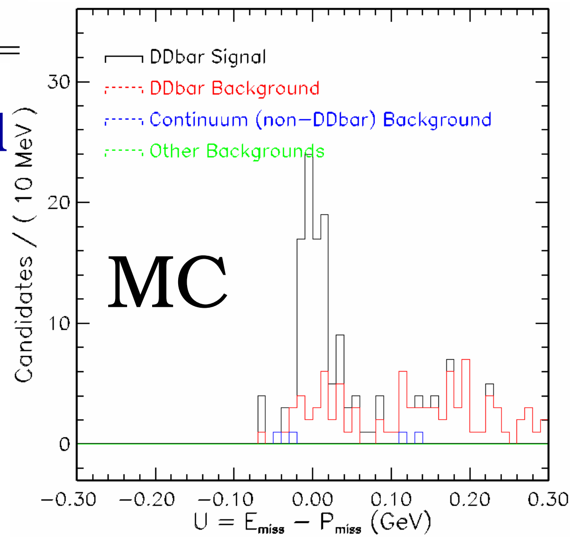
ALL PRELIMINARY

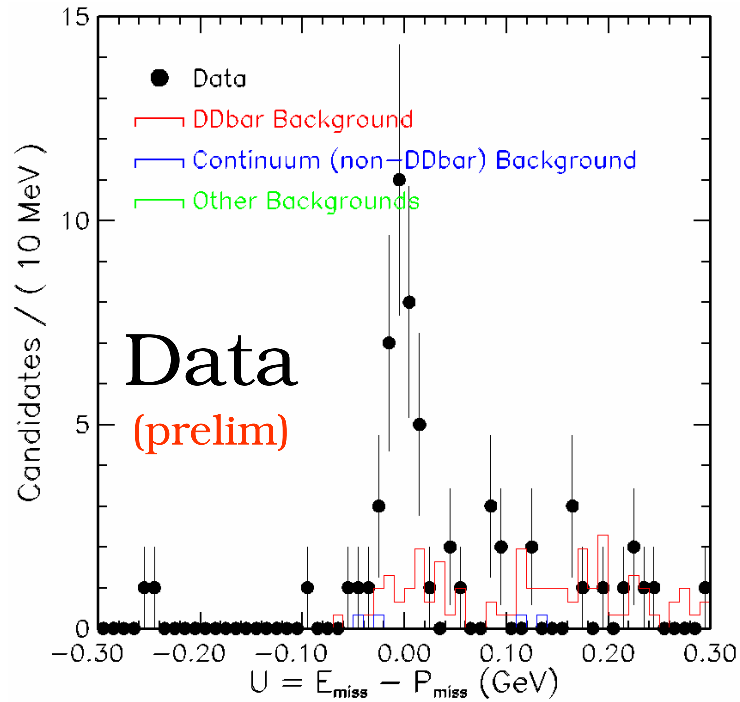
$D^{+} \to \rho^{0} e^{+} \nu$

Mode	Decay Mode
1.	$D^0 \to \pi^- e^+ \nu$
2.	$D^0 \to K^- e^+ \nu$
3.	$D^0 \to K^{*-}(K^- \pi^0) e^+ \nu$
4.	$D^0 \to K^{*-}(\overline{K^0} \pi^-) e^+ \nu$
5.	$D^0 \to \rho^-(\pi^- \pi^0) e^+ \nu$
6.	$D^+ \to \overline{K^0} e^+ \nu$
7.	$D^+ \to K^{*0}(K^- \pi^+) e^+ \nu$
8.	$D^+ \to \pi^0 e^+ \nu$
9.	$D^+ \to \rho^0(\pi^+ \pi^-) e^+ \nu$
10.	$D^+ \to \eta(\gamma\gamma) e^+ \nu$
-1.	all other decays



- Excess of around 35 signal events
- The nonresonant contribution is included in the yield

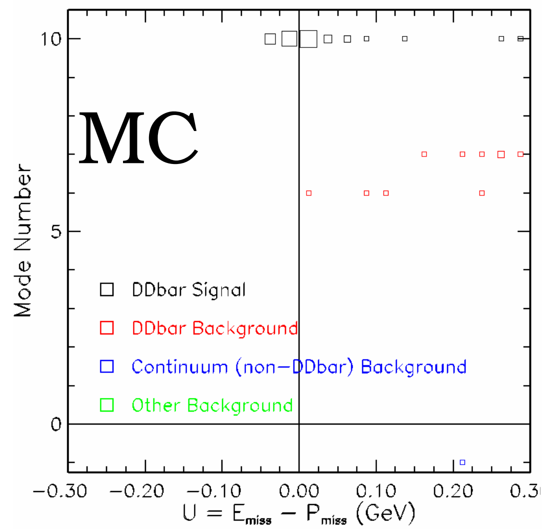


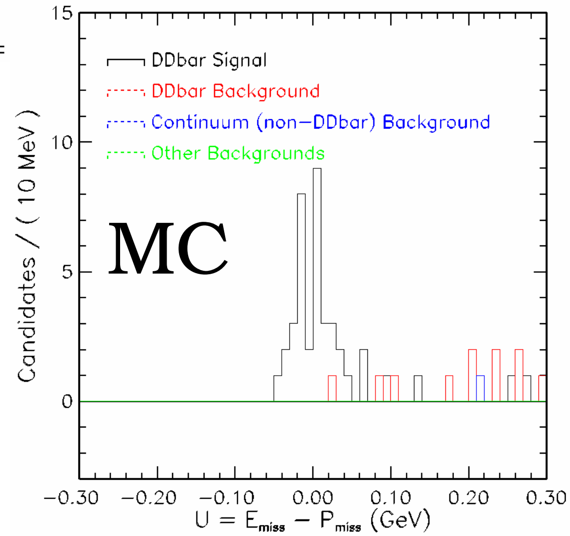


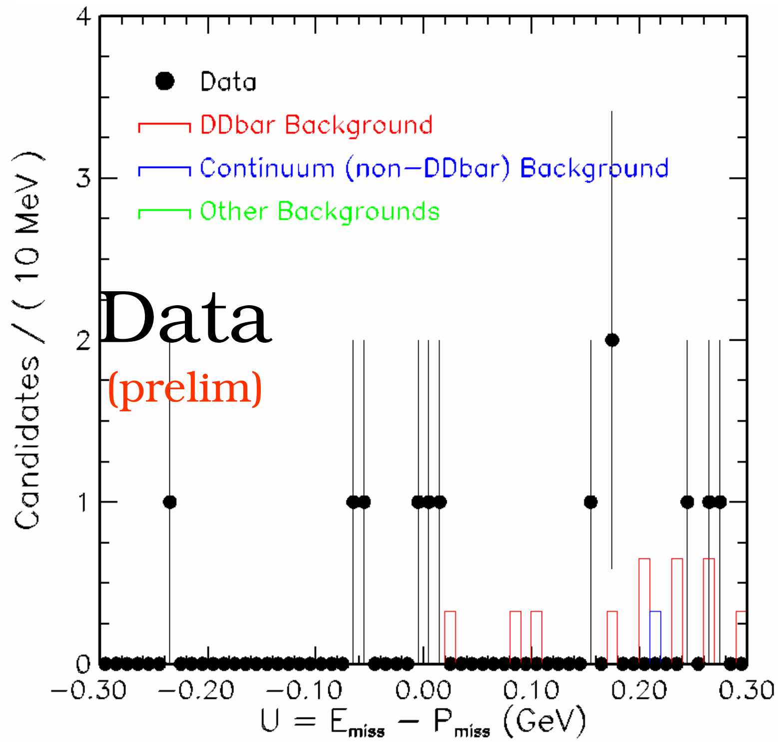
ALL PRELIMINARY

$D^+ \rightarrow \eta\, e^+ \nu$

Mode	Decay Mode
1.	$D^0 \to \pi^- e^+ \nu$
2.	$D^0 \to K^- e^+ \nu$
3.	$D^0 \to K^{*-}(K^- \pi^0) e^+ \nu$
4.	$D^0 \to K^{*-}(\overline{K^0} \pi^-) e^+ \nu$
5.	$D^0 \to \rho^-(\pi^- \pi^0) e^+ \nu$
6.	$D^+ \to \overline{K^0} e^+ \nu$
7.	$D^+ \to K^{*0}(K^- \pi^+) e^+ \nu$
8.	$D^+ \to \pi^0 e^+ \nu$
9.	$D^+ \to \rho^0(\pi^+ \pi^-) e^+ \nu$
10.	$D^+ \to \eta(\gamma\gamma) e^+ \nu$
-1.	all other decays



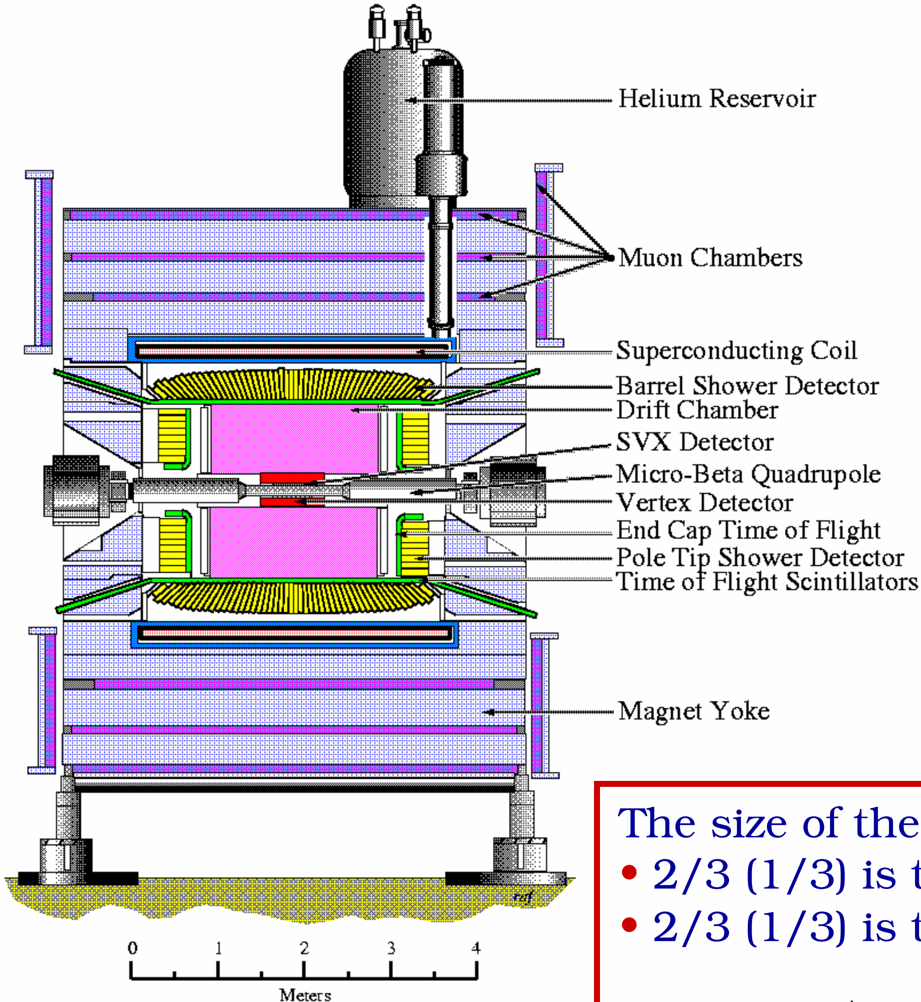




- Too early to say anything

ALL PRELIMINARY

The CLEO II and II.V detector



- **Tracking system:**
  SVX (3 layers) or Gas Vertex Detector,
  Vertex Detector, Drift Chamber
  (B=1.5T, $Ar_2+C_2H_6$ or $He_2+C_3H_8$)
  ($\delta p/p$ ~ 0.6% for a 2 GeV track)
- **Time of Flight system**
  Scintillating plastic (δt ~ 170ps)
- **Crystal Calorimeter**
  CsI crystals($\delta E/E$ ~ 2% for a 2 GeV photon
- **Muon chambers**
  Proportional chambers at 3, 5 and 7 λ_I

The size of the data sample is 13.7 fb^{-1}.
- 2/3 (1/3) is taken with CLEOII.V (CLEOII).
- 2/3 (1/3) is taken ON (50 MeV OFF) Y(4S).

~10M of $e^+e^- \rightarrow B\overline{B}$ and ~18M of $e^+e^- \rightarrow c\overline{c}$ events.