Charm Semileptonic Decays in FOCUS

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Outline

- Introduction to Semileptonic Decays
  - Importance
  - Applications to charm
    1. $D^0 \to \pi^- \mu^+ \nu$
    2. $D^+ \to \overline{K}^{*0} \mu^+ \nu$
- Introduction to the FOCUS experiment
  - Goals
  - Spectrometer
  - Selecting Charmed events
- Measurement of $\frac{\Gamma(D^+ \to \rho^0 \mu^+ \nu)}{\Gamma(D^+ \to \overline{K}^{*0} \mu^+ \nu)}$

Semileptonic Decays: $M_{Q\overline{q}} \longrightarrow m_{q'\overline{q}}\ell^+\nu_\ell$

- Can be used to extract CKM matrix elements with input from theory.
- Since there is no interaction between hadrons and leptons in final state, the matrix element can be factorized into a leptonic part and hadronic part. This provides an ideal environment for the study of hadronic current.

$$\mathcal{M}(P_{Q\overline{q}} \to X_{q'\overline{q}}\ell\nu) = \frac{G_F}{\sqrt{2}} V_{Qq'} L^\mu H_\mu$$

$$L^\mu = \overline{u}_\nu \gamma^\mu (1-\gamma_5) v_\ell, \;\; H^\mu = \langle k | J^\mu_{had} | P \rangle$$

- The hadronic current can be expressed in terms of Form Factors (calculable with different theoretical methods) and the available four-vectors in the decay.
  - Because the charmed CKM matrix elements are well constrained, testing these methods will lead to better constraints on the CKM matrix element of the b–sector.

Form Factors

- Describe the modification to the weak current transforming the heavy meson into a lighter meson due to the hadronization process.
- Invariant functions of $q^2 = M^2_{W^*}$.
- $q^2_{\mathrm{max}} = (M - m)^2$ is known as the zero-recoil configuration; $q^2_{\mathrm{min}} \sim 0$ except for $\ell = \tau$.
- In LQCD the FF are easiest to calculate near q^2_{max}; Data are taken near q^2_{min}.
- An *ansatz* pole form can be used to compare theory with experiment, e.g.,

$$f(q^2) = \frac{f(0)}{1 - q^2/m^2_{\mathrm{pole}}}$$

- m_{pole} is the mass of the lowest lying meson composed of the two quarks involved in the weak decay with the same J^P Quantum Numbers.

Pseudoscalar to pseudoscalar: $D \rightarrow P'\ell\nu$

- Daughter meson has no spin. Only available four-vectors four-momenta are $(p - p')^\mu$ and $(p + p')^\mu$.
- Only vector part of the V-A plays a role. The hadronic current can be written as:

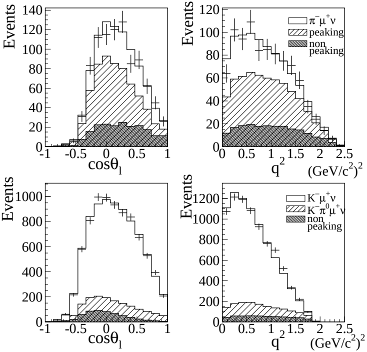
$$< P'|V^\mu|D >= f_+(q^2)(p + p')^\mu + f_-(q^2)(p - p')^\mu$$

- In the limit of zero lepton mass (valid for e and μ) the differential decay can be approximated as

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{q'Q}|^2 p_{p'}^3}{24\pi^3} |f_+(q^2)|^2$$

- Integrating over the available q^2 range and using the pole equation it is possible to determine $f_+(0)$.
- Measurement of $\frac{\Gamma(D^0 \rightarrow \pi^- \mu^+ \nu)}{\Gamma(D^0 \rightarrow K^- \mu^+ \nu)}$ can be used to extract $\left|\frac{V_{\rm cd}}{V_{\rm cs}}\right|^2 \left|\frac{f_+^{D\rightarrow\pi}(0)}{f_+^{D\rightarrow K}(0)}\right|$.

- D^0 mesons decaying from charged D^* were selected.
- Look for a muon and a hadron (K or π) forming a good decay vertex. Look for a soft pion consistent with being in the production vertex.
- Used a binned likelihood fit to two–dimensional distribution q^2 vs. $\cos\theta_\ell$.
- Assumed standard pole form for Form Factor.



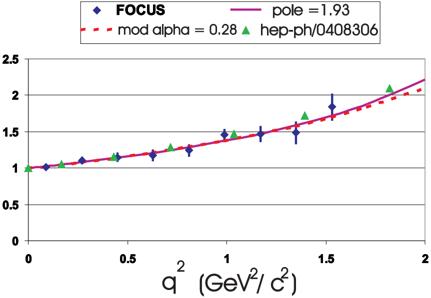
Results (Phys.Lett.B607:233-242)

$$\frac{\Gamma(D^0 \to \pi^-\mu^+\nu)}{\Gamma(D^0 \to K^-\mu^+\nu)} = 0.074 \pm 0.008\ (\mathrm{stat}) \pm 0.007\ (\mathrm{syst})$$

$$\left|\frac{V_{\mathrm{cd}}}{V_{\mathrm{cs}}}\right|^2 \left|\frac{f_+^\pi(0)}{f_+^K(0)}\right| = 0.037 \pm 0.004\ (\mathrm{stat}) \pm 0.004\ (\mathrm{syst})$$

Non–parametric approach: $f_+^K(q^2)$

- The pole form $f_+(q^2) = \frac{f_+(0)}{1-q^2/m^2_{\mathrm{pole}}}$ is simplest parametrization.
- Other q^2 dependence, e.g., $f_+(q^2) = \frac{f_+(0)}{(1-\frac{q^2}{m^2_{\mathrm{pole}}})(1-\alpha\frac{q^2}{m^2_{\mathrm{pole}}})}$ have been proposed.
- Measurement of this dependence needed to compare to LQCD predictions.



Result (Phys.Lett.B607:233-242)

$$m_{\mathrm{pole}} = 1.93 \pm 0.05 \pm 0.03\ \mathrm{GeV}/c^2$$

- LQCD predictions for the Form Factor $f_+^K(q^2)$ are consistent with data.
- Weighted average of m_{pole} measurements is 5.1σ lower than the spectroscopic mass ($m_{D_s^*} = 2.11\ \mathrm{GeV}/c^2$).

Pseudoscalar to vector: $D \to V'\ell\nu$

- Available four-vectors: four-momentum $(p-p')^\mu$ and $(p+p')^\mu$, and polarization vector ε^μ.
- General form of the current is:

$$
\begin{aligned}
< V(p',\varepsilon)|V^\mu - A^\mu|D(p) >= & \frac{2i\epsilon^{\mu\nu\alpha\beta}}{M_D+m_V}\varepsilon^*_\nu p'_\alpha p_\beta V(q^2) \\
& -(M_D+m_V)\varepsilon^{*\mu}A_1(q^2) \\
& +\frac{\varepsilon^*\cdot q}{M_D+m_V}(p+p')^\mu A_2(q^2) \\
& +2m_V\frac{\varepsilon^*\cdot q}{q^2}q^\mu(A_3(q^2)-A_0(q^2))
\end{aligned}
$$

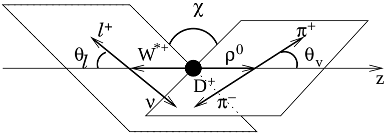
where

$$A_3(q^2)=\frac{M_D+m_V}{2m_V}A_1(q^2)-\frac{M_D-m_V}{2m_V}A_2(q^2)$$

- Terms proportional to q^μ are negligible for $\ell=e$ and $\ell=\mu$ cases.

$$\mathrm{V}(q^2)=\frac{\mathrm{V}(0)}{1-q^2/m_{\mathrm{V}}^2},\ A_i(q^2)=\frac{A_i(0)}{1-q^2/m_{\mathrm{A}}^2}$$

- If the vector decays strongly into two pseudoscalars (e.g.; $\rho \rightarrow \pi\pi$) four kinematic variables describe the decay, $\theta_\ell, \theta_v,$ and χ, and q^2.



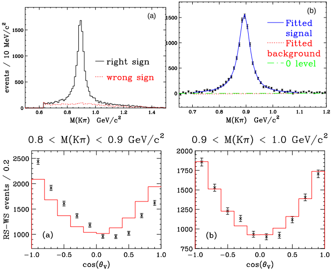
- The decay rate (in terms of helicity amplitudes) becomes:

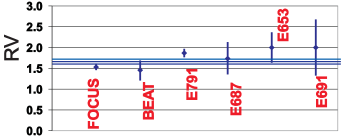
$$\frac{d\Gamma(D \rightarrow V\ell\nu, V \rightarrow P_1P_2)}{dq^2 d\cos\theta_\ell d\cos\theta_{\rm V} d\chi} = \frac{3G_F|V_{q'Q}|^2}{8(4\pi)^4}\frac{p_{\rm V} q^2}{M_D^2}\Gamma(V \rightarrow P_1P_2)\times$$
$$\Big[(1+\cos\theta_\ell)^2\sin^2\theta_{\rm V}|H_+(q^2)|^2$$
$$+(1-\cos\theta_\ell)^2\sin^2\theta_{\rm V}|H_-(q^2)|^2$$
$$+4\sin^2\theta_\ell\cos^2\theta_{\rm V}|H_0(q^2)|^2$$
$$+\text{cross terms}\Big]$$

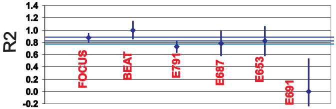
- $H_0(q^2)$ is a combination of $A_1(q^2)$ and $A_2(q^2)$, while $H_\pm$ is a combination of $A_1(q^2)$ and $V(q^2)$.

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

- $D^+ \to \overline{K}^{*0} \mu^+ \nu$ provides the cleanest example of a semileptonic vector decay.
- Wrong Sign used to modeled non–charm background.
- There is a strong forward–backward asymmetry in $\cos\theta_V$ distribution for events below the $\overline{K}^*$ pole.
- FOCUS modeled this as a non–resonant s–wave interference (Phys.Lett.B535:43-51).
- Non–resonant component is $\sim 5\%$.







Result (Phys.Lett.B544:89-96)

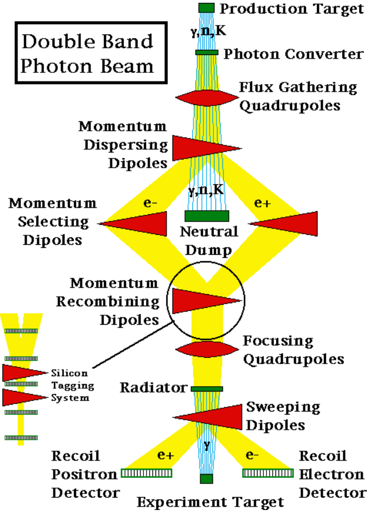
$$r_v = 1.504 \pm 0.057 \pm 0.039$$
$$r_2 = 0.875 \pm 0.049 \pm 0.064$$

The FOCUS Experiment

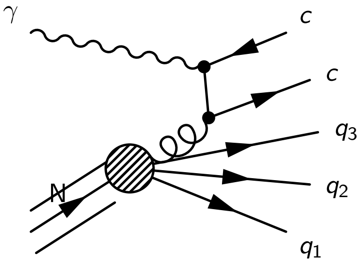
- FNAL–E831 is a fixed target experiment that took data during the 1996–1997 fixed target run at Fermilab.
- FOCUS stands for Photoproduction Of Charm with an Upgraded Spectrometer.

FOCUS Goals

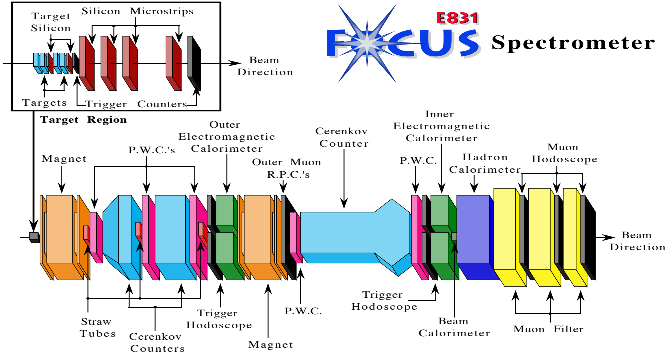
- More than 1 million *Golden Modes* (i.e.; $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$) fully reconstructed.
- Studies include:
  - Branching fractions and Form Factors of charmed semileptonic decays.
  - Lifetime measurements of all weakly decaying singly charmed particles.
  - Branching fractions and Dalitz analyzes of charmed hadronic decays.
  - Spectroscopy of exited charmed baryons and mesons.
  - Searches and upper limits for Mixing, CP/CPT violations, rare, and forbidden decays, doubly charmed baryons, and $D_{sJ}(2632)$.
  - Charm production asymmetry.
  - Upper limits on pentaquarks.



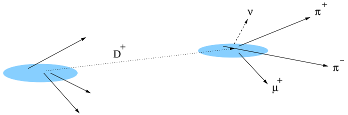
- Photon beam with average energy $\sim$ 180 GeV.
- Segmented Beryllium Oxide used as experimental target.
- Photon–Gluon fusion is the main mechanism for the production of charm.

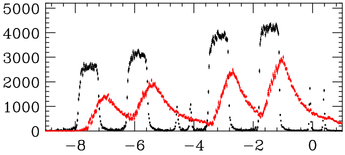


The FOCUS Spectrometer



- Particle ID
  - 3 Čerenkov for e, π, K, and p
  - 2 Muon Detectors (IMU, OMU)
- Momentum
  - 2 Oppositely polarized magnets
- Tracking & Vertexing
  - Target Silicon Detector
  - Silicon Microstrips
  - 5 PWC stations
- Calorimetry
  - 2 EM (IE, OE), HC



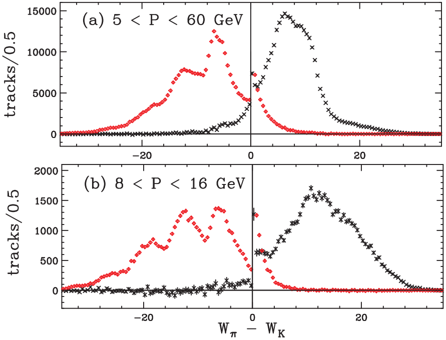


Some details of the FOCUS vertexing

- L/σ_L: significance of separation (signature for weak decays).
- OoT: Significance of decay being out of target material. OoT events are cleaner. Avoids confusing detached vertices with secondary hadronic interaction inside target.
- CL_{prim}, CL_{sec}: Conf. Levels of production and decay vertices.
- Iso1: CL that tracks from decay vertex are consistent with production vertex.
- Iso2: CL that other tracks (incl. from production vertex) are consistent with decay vertex.

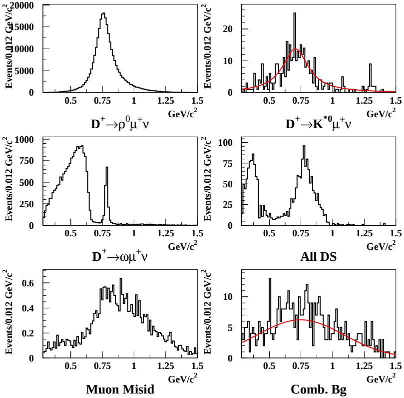
Selecting Charm: Hadron ID

- Three multi-cell threshold Čerenkov detectors
- Gives positive particle ID over limited momentum ranges
- We use an ID method based on log-likelihoods
  - For each particle hypothesis, find probability of observing the given light pattern.
  - Calculate differences between particle hypotheses e.g., $W_\pi - W_K > 0$ favors Kaon hypothesis
  - Gives a continuum of particle ID values



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

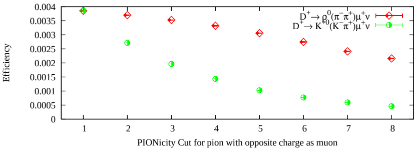
- Cabibbo suppressed decay $c \to dW^*$.
- Due to lack of statistics, previous measurements have large errors. PDG avg. $\frac{\Gamma(D^+ \to \rho^0 \mu^+ \nu)}{\Gamma(D^+ \to \overline{K}^{*0} \mu^+ \nu)} = 0.061 \pm 0.014$
- Theoretical predictions for ratio range from 0.018 to 0.045.
- Reconstruction is hard because of the large amount of peaking backgrounds present.
  - Semileptonic modes with two pions and neutrals in final state.
  - Combinatorial background.
  - Muon misid

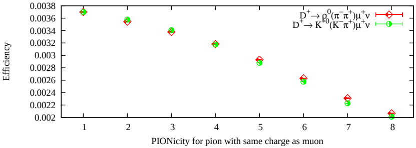


$D^+ \to \rho^0 \mu^+ \nu$ Selection

- Vertexing
  - Good secondary vertex with two oppositely charged pions and a muon: $\mathrm{CL}_{\mathrm{sec}} > 5\%$
  - Significance of vertex detachment: $L/\sigma_L > 15$
  - Secondary vertex outside of target: OoT $> 1\sigma$; primary inside target
  - No tracks extra tracks compatible with the secondary vertex: Iso2< 0.01;
  - Primary vertex: Used all remaining tracks to find highest multiplicity, most upstream. $\mathrm{CL}_{\mathrm{prim}} > 1\%$; tracks in secondary incompatible with primary vertex: Iso1 < 0.01
- Particle ID
  - π track with opposite charge wrt muon: $W_{\mathrm{K}} - W_\pi > 5$
  - π track with same charge wrt muon: $W_{\mathrm{K}} - W_\pi > 1$
  - Muon track: $\mathrm{CL}_\mu > 1\%$, $p_\mu > 10\ \mathrm{GeV}/c$, missing planes < 2
- Mass Cuts
  - $1.2 < M(\pi^+\pi^-\mu^+) < 1.8$
  - $(\pi^+\pi^-\mu^+) - M(\pi^-\mu^+) > 0.20$

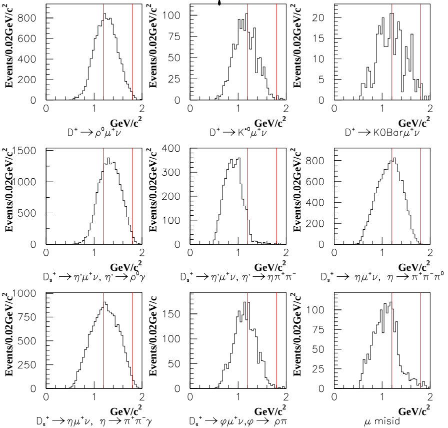
- Different requirements for the two pions.
  - Loose pion requirement: Effect is uniform for all semileptonic backgrounds
  - Strong pion requirement: Minimizes contribution from $D^+ \to K^- \pi^+ \mu^+ \nu$ reflection when the K is misid as π

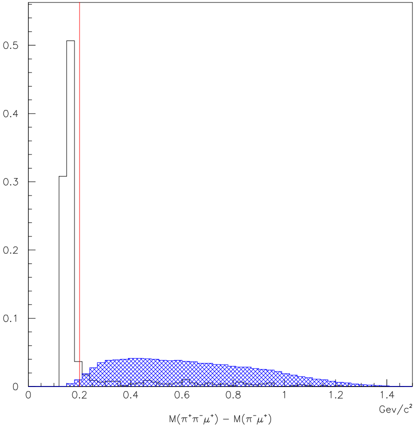




Mass Cuts

$\pi^+\pi^-\mu^+$ Mass





- $1.2 < M(\pi^+\pi^-\mu^+) < 1.8\ \mathrm{GeV}/c^2$ Cuts high multiplicity events; allows for missing ν
- $M(\pi^+\pi^-\mu^+) - M(\pi^-\mu^+) > 0.20\ \mathrm{GeV}/c^2$ Eliminates background from $D^{*+} \to D^0(\pi^-\mu^+\nu)\pi^+$

$D^+ \to \rho^0 \mu^+ \nu$ Fit

- Fit $M_{\pi\pi}$ with a binned max. log likelihood fit

$$\mathcal{L} = \prod_{i=1}^{\#\text{bins}} \frac{n_i^{s_i} e^{-n_i}}{s_i!} \times \text{penalty}$$

  - n_i = Number of events in bin i of data histogram
  - s_i = Number of events in bin i of fit histogram

What is included

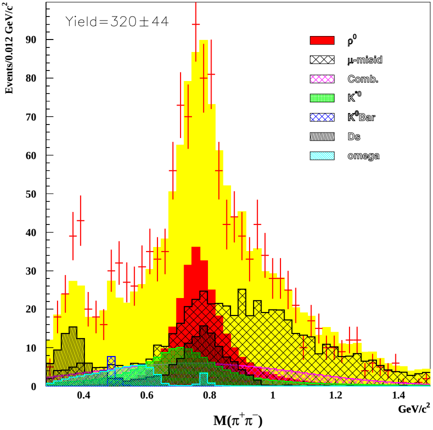
$$n_i = Y_{D^+ \to \rho^0 \mu^+ \nu} S_{\rho^0 \mu^+ \nu} + \text{ECY}_{D^+ \to K^- \pi^+ \mu^+ \nu} \epsilon(K\pi\mu\nu \to \rho\mu\nu) S_{K\pi\mu\nu} + Y_{D^+ \to K_S^0 \mu^+ \nu} S_{K_S^0 \mu^+ \nu} + Y_{D^+ \to \omega \mu^+ \nu} S_{\omega \mu^+ \nu} + Y_{D_s^+} S_{D_s^+} + Y_{\mathcal{C}} S_{\mathcal{C}} + Y_{\mathcal{M}} S_{\mathcal{M}}$$

$$\text{penalty} = \exp\left[-\frac{1}{2} \left(R_{\omega/\overline{K}^{*0}} \text{ECY}_{\overline{K}^{*0} \mu^+ \nu} - Y_{D^+ \to \omega \mu^+ \nu} \right)^2 / \sigma^2_{D^+ \to \omega e \nu} \right]$$

$$R_{\omega/\overline{K}^{*0}} = \frac{\text{BR}(D^+ \to \omega e^+ \nu)}{\text{BR}(D^+ \to \overline{K}^{*0} e^+ \nu)}$$

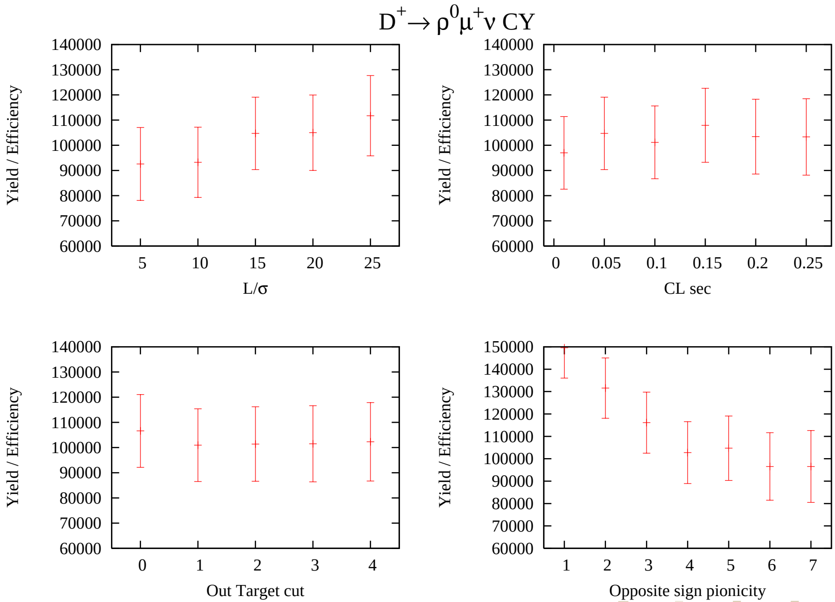
- Use Cleo results for electronic mode $D^+ \to \omega e^+ \nu$

Fit Results



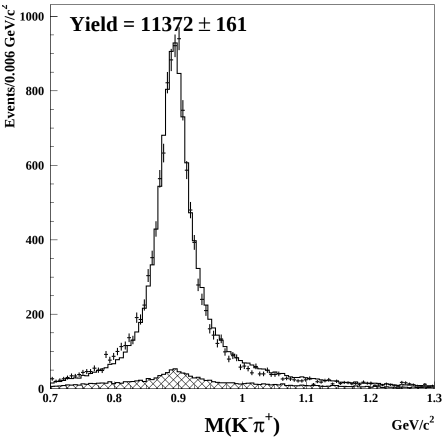
Decay Mode	Yield
$D^+ \to \rho^0 \mu^+ \nu$	320 ± 44
$\overline{K}^{*0}, K/\pi$ Mis-id	68
$D^+ \to \overline{K}^0 \mu^+ \nu$	7 ± 6
D_s^+ modes total	181 ± 39
$D^+ \to \omega \mu^+ \nu$	51 ± 22
Muon Mis-Id	554 ± 43
Combinatorial	233 ± 50

Efficiency Corrected Yield



Normalization: $D^+ \to \overline{K}^{*0} \mu^+ \nu$

- Selection
  - Good secondary vertex with a Kaon, pion, and muon
  - Same requirements as for $D^+ \to \rho^0 \mu^+ \nu$ sample for vertexing and muon ID
  - Hadron ID:
    - Kaon track: $W_\pi - W_\mathrm{K} > 1$
    - Pion track: $W_\mathrm{K} - W_\pi > 0$
- Fit
  - Fit $M_{K^-\pi^+}$ with a binned max. log likelihood fit using signal and non–$D^+ \to K^- \pi^+ \mu^+ \nu$ bg from CCbar Monte Carlo

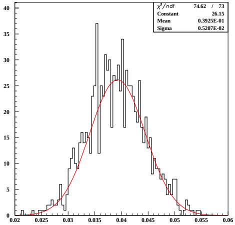


Branching Ratio Results

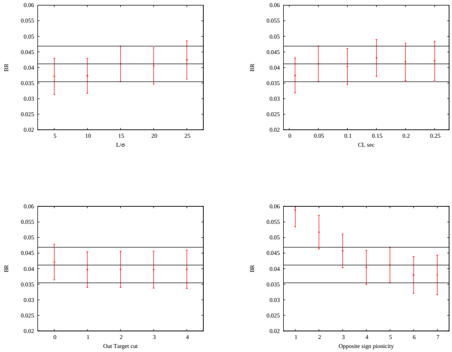
$$\frac{\Gamma(D^+ \to \rho^0 \mu^+ \nu)}{\Gamma(D^+ \to \overline{K}^{*0} \mu^+ \nu)} = \frac{Y_{D^+ \to \rho^0 \mu^+ \nu} / \epsilon_{D^+ \to \rho^0 \mu^+ \nu}}{Y_{D^+ \to K^- \pi^+ \mu^+ \nu} / \epsilon_{D^+ \to K^- \pi^+ \mu^+ \nu}} \, \frac{BR(\overline{K}^{*0} \to K^- \pi^+)}{1 - f_{\text{s-wave}}}$$

Result

$$\frac{\Gamma(D^+ \to \rho^0 \mu^+ \nu)}{\Gamma(D^+ \to \overline{K}^{*0} \mu^+ \nu)} = 0.0412 \pm 0.0057$$



Rho BR MiniMC results

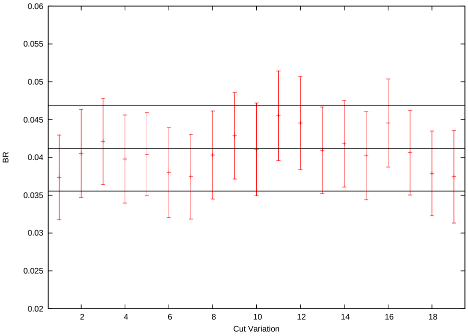


Systematic Uncertainties

- Most systematic uncertainty cancel when taking ratio.
- We identified three possible sources of systematic uncertainties.
  1. Selection requirements
     - Final cut set was among 1260 cut combination tested; Could it be an outlier? How sensitive is the BR to the cut selection?
  2. Fit choices
     - Shapes used, BR of background modes, fit to $D^+ \to K^-\pi^+\mu^+\nu$, binning...
  3. Split Samples
     - Detector simulation & charm production mechanism in MC. Are there any internal inconsistencies in the data?

Cut Variations

Cut	Variation
L/σ	10, 20
OoT	0, 2
OoM	1, 2
CL_{sec}	0.01, 0.10
Iso2	0.10, 0.001
Mispl (IMU)	1
p_μ (IMU)	15, 20
CL_μ (IMU)	0.05, 0.10
$W_K - W_\pi$	4, 6
$M(\pi^+\pi^-\mu^+) - M(\pi^-\mu^+)$	No cut

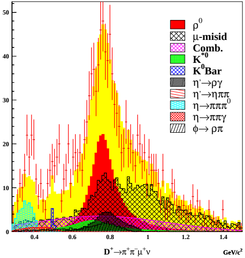


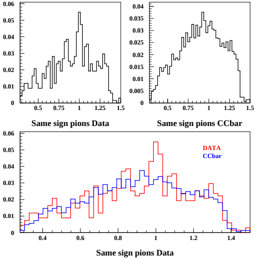
- Use variant of results as an estimate of systematic uncertainty due to selection

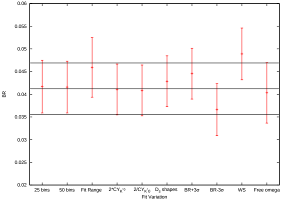
Cut systematic

$$\sigma_{cut} = 0.0023$$

Fit Variations







- Shapes: Different shape for combinatorial bg; individual shapes for D_s contribution
- BR: Double/half the contribution of $D^+ \to K^-\pi^+\mu^+\nu$ reflection; change BR's for D_s modes by $\pm 3\sigma$; free $D^+ \to \omega\mu^+\nu$ contribution

Fit systematic

$$\sigma_{\text{fit}} = 0.0033$$

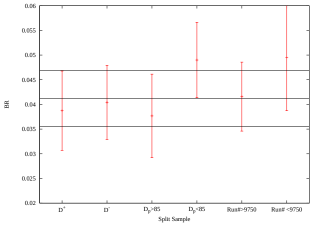
Split Samples

- 3 sets of pairs of independent sub–samples split according to
  1. Run Number: Before and after installation of TSSD
  2. D momentum: Tests trigger, production model, and detector simulation
  3. $D^{\pm}$: Tests production model
- Use method based on PDG's S–factor to separate systematics from statistical effects. If $\chi^2/(\mathrm{N}-1) > 1$

$$\widetilde{\sigma} = <\sigma> \sqrt{\chi^2/(\mathrm{N}-1)}$$

$$\sigma_{syst} = \sqrt{\widetilde{\sigma}^2 - \sigma^2} \quad \text{if} \quad \widetilde{\sigma} > \sigma$$

$$\sigma_{syst} = 0 \quad \text{if} \quad \widetilde{\sigma} \leq \sigma$$



Result

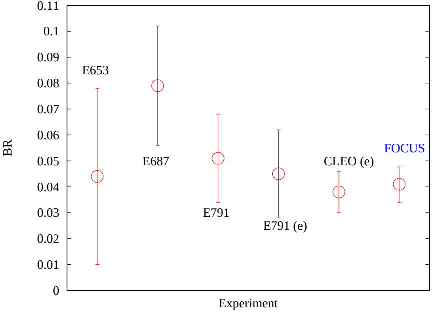
No sizable systematic effect revealed by test

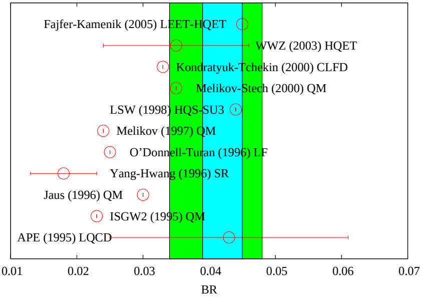
Systematic Source	Error
Cut Variations	0.0023
Fit Variations	0.0033
Split Sample	negligible
Total	0.0040

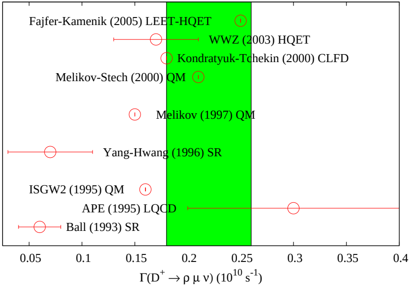
Final Results & Comparison

Adding stat & syst in quadrature (Phys.Lett.B637:32-38)

$$\frac{\Gamma(D^+ \to \rho^0 \mu^+ \nu)}{\Gamma(D^+ \to \overline{K}^{*0} \mu^+ \nu)} = 0.041 \pm 0.007$$







Conclusions

- Semileptonic decays provide a clean environment for the understanding of the hadronic current.
- The FOCUS experiment fully reconstructed more than 1 million *Golden Modes* providing large charmed samples for precision studies.
- FOCUS has made substantial contributions to the understanding of charmed semileptonic decays with measurements of form factors and branching ratios with reduced statistical and systematic uncertainties that will help in the discrimination among theoretical models.