

Fermilab E791 Collaboration

# Rare and Forbidden Decays of $D$ Mesons

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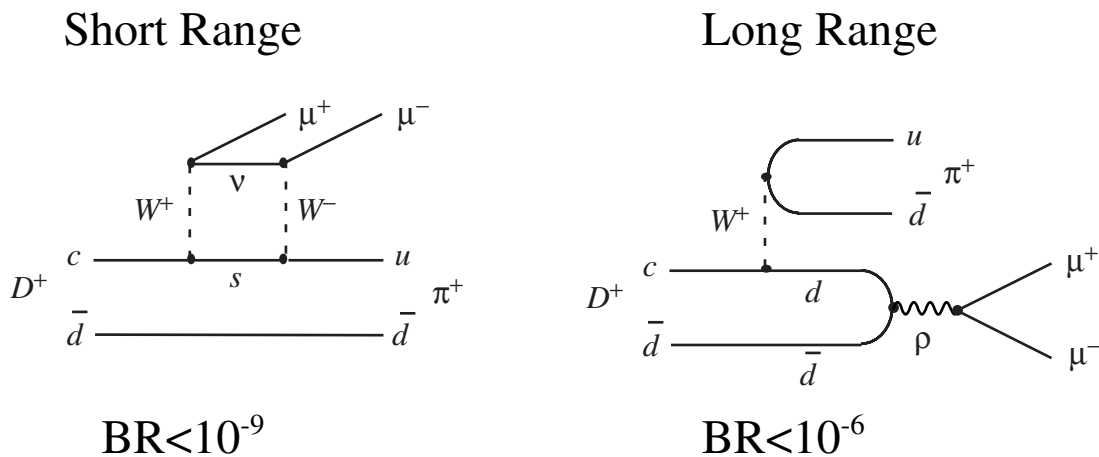
**University of Mississippi**

- **Introduction**
- **Physics Motivation — Search for New Mediators**
- **Detector Description — Fixed Target**
- **Method — Blind Analysis**
- **Results**
- **Conclusion**

XXXVI<sup>th</sup> Rencontres de Moriond — Electroweak Interactions and  
Unified Theories — Les Arcs, France, March 10-17, 2001

# Why Search for Rare and Forbidden decays?

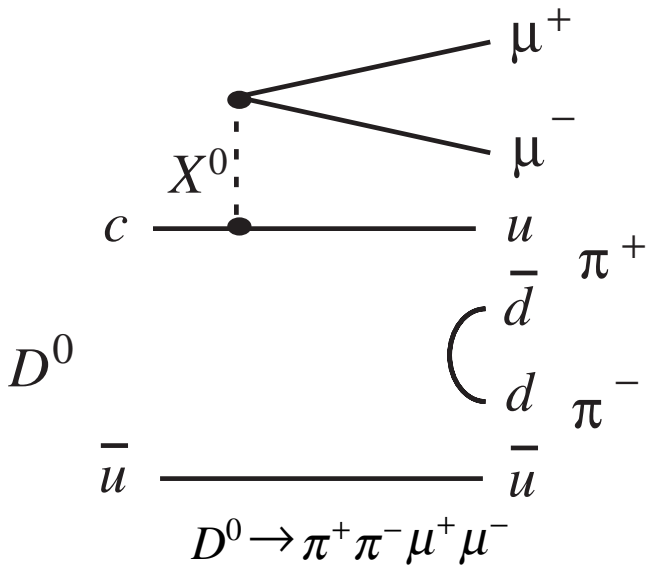
- Tests Standard Model and allows investigation of phenomena in mass ranges beyond those available to current accelerators
- Standard Model predicts Branching Ratio  $<10^{-9}$ – $10^{-6}$



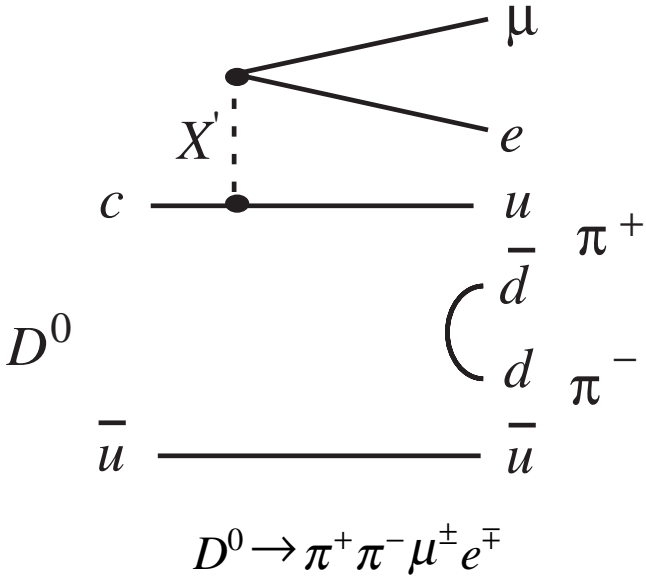
- Search for violations from Flavor Changing Neutral Currents, Lepton Number and/or Flavor Violations (via Leptoquark, Horizontal Gauge Bosons, etc.?)

# New Mediators

Flavor Changing Neutral Current

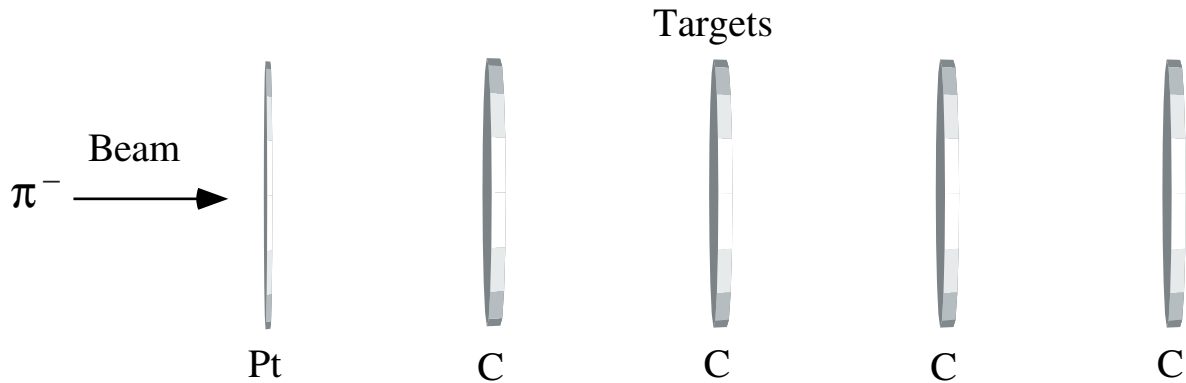


Horizontal Gauge Boson



# Detector Description

The E791 experiment used a 500 GeV  $\pi^-$  beam hitting a target



The E791 Spectrometer consisted of the following detectors:

## Particle Tracking Detectors

- 23 planes of Silicon Microstrip Detectors (SMDs)
- 45 planes of wire chambers (PWCs and DCs)

## Momentum Measurement

- 2 dipole magnets

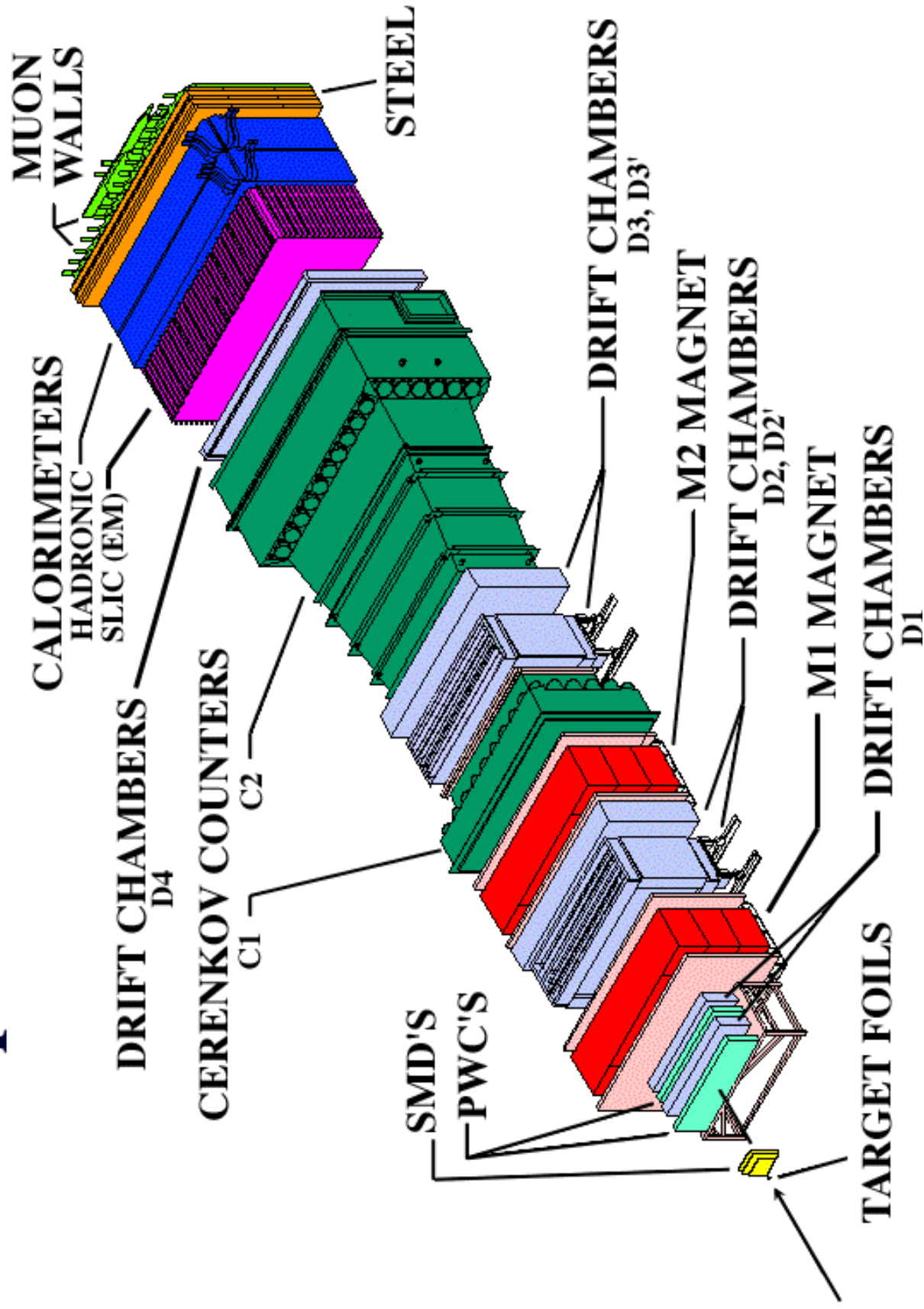
## Particle Identification

- 2 multi-cell Čerenkov counters
- Muon detector

## Energy Measurement

- Electromagnetic and hadronic calorimeters

# E-791 Spectrometer



# Blind Analysis Method

Method:

- Cover signal region with a “box”
- Optimize ALL cuts before opening “box”

Maximize Monte Carlo Signal/ $\sqrt{\text{Data Wings}}$

- Open “box” covering signal region

Blind Analysis Closed mass “box” widths:

$$D^+ \rightarrow h\mu\mu \quad 60 \text{ MeV}/c^2$$

$$D^+ \rightarrow hee(\text{or } h\mu e) \quad 120 \text{ MeV}/c^2$$

$$D_s^+ \rightarrow h\mu\mu \quad 40 \text{ MeV}/c^2$$

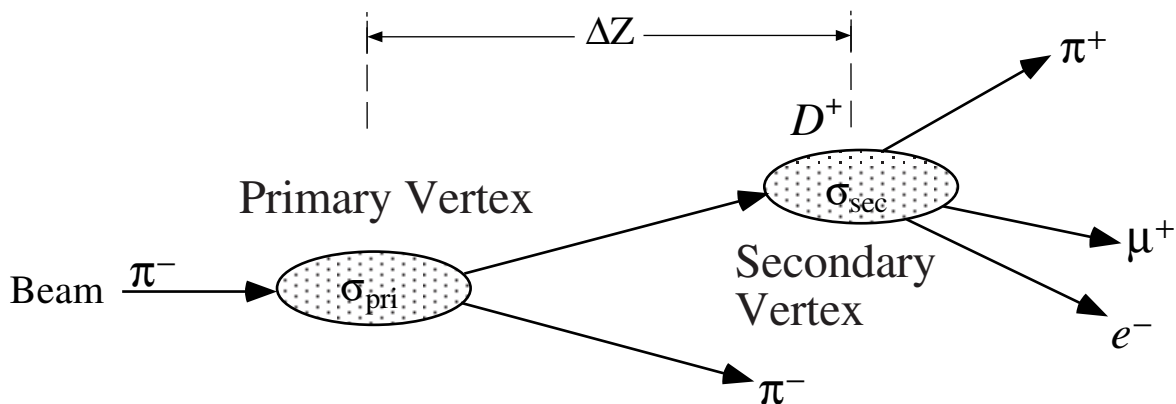
$$D_s^+ \rightarrow hee(\text{or } h\mu e) \quad 80 \text{ MeV}/c^2$$

$$D^0 \rightarrow \mu\mu, hh\mu\mu, V\mu\mu \quad 70 \text{ MeV}/c^2$$

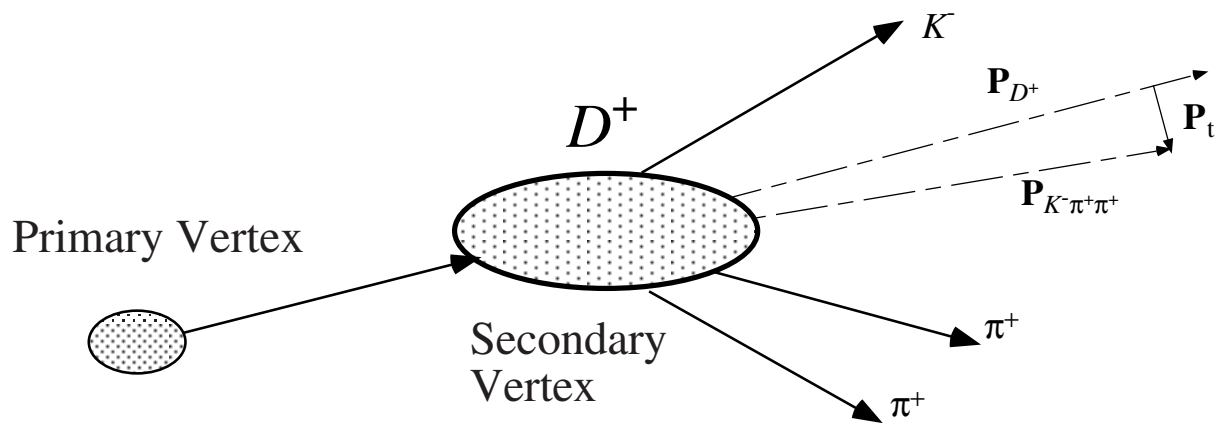
$$D^0 \rightarrow ee, hhee, Vee (\text{or } \mu e, hh\mu e, V\mu e) \quad 140 \text{ MeV}/c^2$$

# Description of the Kinematics Variables

- Vertex Separation (SDZ)



- Transverse Momentum Balance (PTB)



## Kinematics Cuts

	$D^+$	$D_s^+$	$D^0$
Separation of Vertices	$> 20 \sigma$	$> 12 \sigma$	$> 12 \sigma$
Vertex separation from Target	$> 5 \sigma$	$> 5 \sigma$	$> 5 \sigma$
Lifetime	$< 5 \text{ ps}$	$< 3 \text{ ps}$	$< 3 \text{ ps}$
Impact parameter	$< 0.040 \text{ mm}$	$< 0.040 \text{ mm}$	$< 0.040 \text{ mm}$
Transverse momentum balance	$< 0.20 \text{ GeV}/c$	$< 0.25 \text{ GeV}/c$	$< 0.30 \text{ GeV}/c$

Cuts were determined to maximize Monte Carlo signal  $/\sqrt{\text{Background}}$ . (Background is data outside the signal region.)

Other cuts:

- Removal of “reflections” due to particle misidentification
- Particle ID cuts



# Upper Limit Branching Ratio Calculation

$$BR_X < \frac{N_X/\epsilon_X}{N_{norm}/\epsilon_{norm}} \cdot BR_{norm}$$
$$< \frac{N_X}{N_{norm}} \cdot \frac{\epsilon_{norm}}{\epsilon_X} \cdot BR_{norm}$$

Where  $\frac{\epsilon_{norm}}{\epsilon_X} = \frac{N_{norm}^{MC}}{N_X^{MC}}$  and

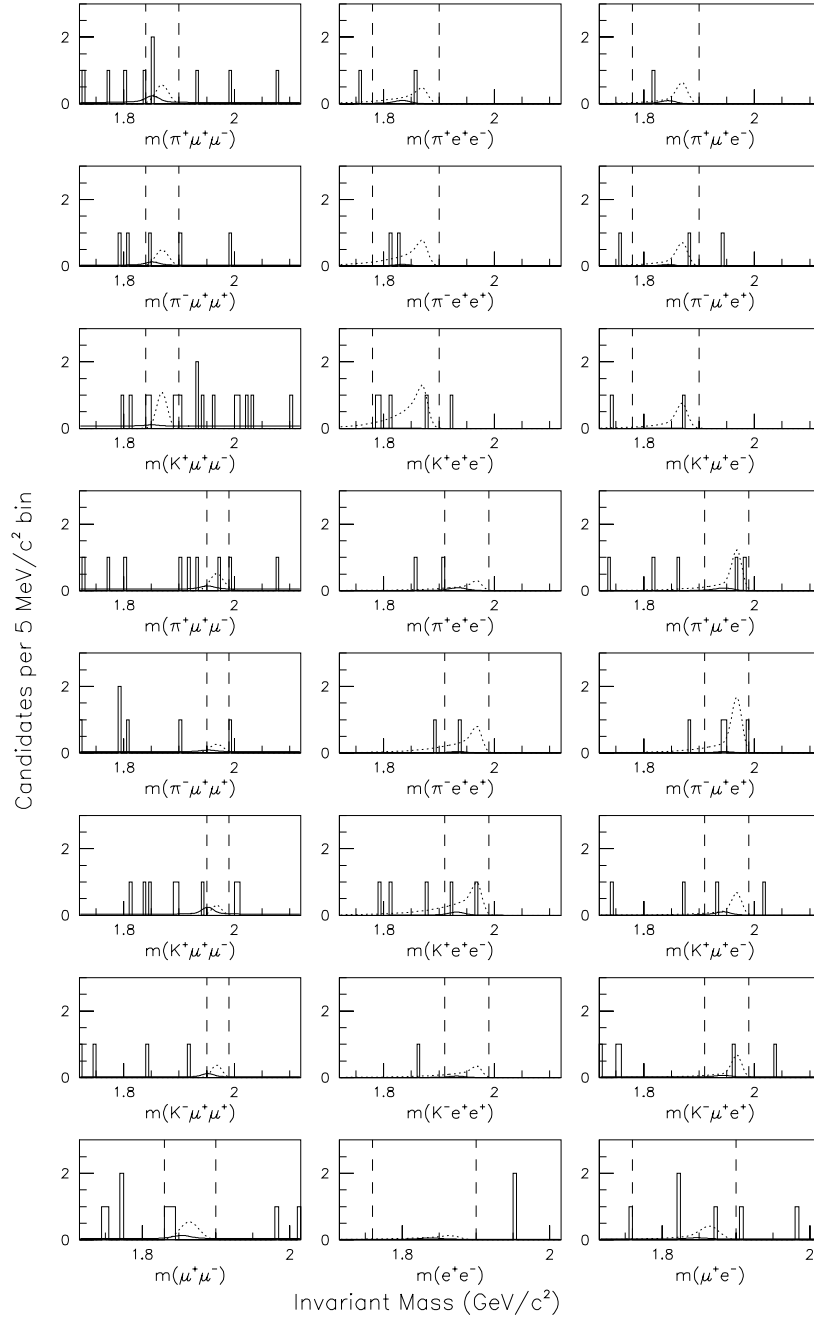
$N_X$  is now the 90% CL upper limit prediction on the number of events.

Since there was some background,  $N_X$  is calculated using the method of Feldman and Cousins. One also has to correct  $N_X$  for systematic errors. This was done using the method of Cousins and Highland.

# 2 and 3-Body Rare and Forbidden Decays

<b>Decay Modes Examined</b>		
<b>Flavor Changing Neutral Currents</b>	<b>Lepton Flavor Violating</b>	<b>Lepton Number Violating</b>
$D^+ \rightarrow \pi^+ \mu^+ \mu^-$	$D^+ \rightarrow \pi^+ \mu^\pm e^\mp$	$D^+ \rightarrow \pi^- \mu^+ \mu^+$
$D^+ \rightarrow \pi^+ e^+ e^-$	$D^+ \rightarrow \pi^- \mu^+ e^+$	$D^+ \rightarrow \pi^- e^+ e^+$
$D^+ \rightarrow K^+ \mu^+ \mu^-$	$D^+ \rightarrow K^+ \mu^\pm e^\mp$	$D_s \rightarrow K^- \mu^+ \mu^+$
$D^+ \rightarrow K^+ e^+ e^-$	$D_s \rightarrow K^+ \mu^\pm e^\mp$	$D_s \rightarrow K^- e^+ e^+$
$D_s \rightarrow K^+ \mu^+ \mu^-$	$D_s \rightarrow K^- \mu^+ e^+$	$D_s \rightarrow \pi^- \mu^+ \mu^+$
$D_s \rightarrow K^+ e^+ e^-$	$D_s \rightarrow \pi^+ \mu^\pm e^\mp$	$D_s \rightarrow \pi^- e^+ e^+$
$D_s \rightarrow \pi^+ \mu^+ \mu^-$	$D_s \rightarrow \pi^- \mu^+ e^+$	
$D_s \rightarrow \pi^+ e^+ e^-$	$D^0 \rightarrow \mu^\pm e^\mp$	
$D^0 \rightarrow \mu^+ \mu^-$		
$D^0 \rightarrow e^+ e^-$		

# 2 and 3-Body Data



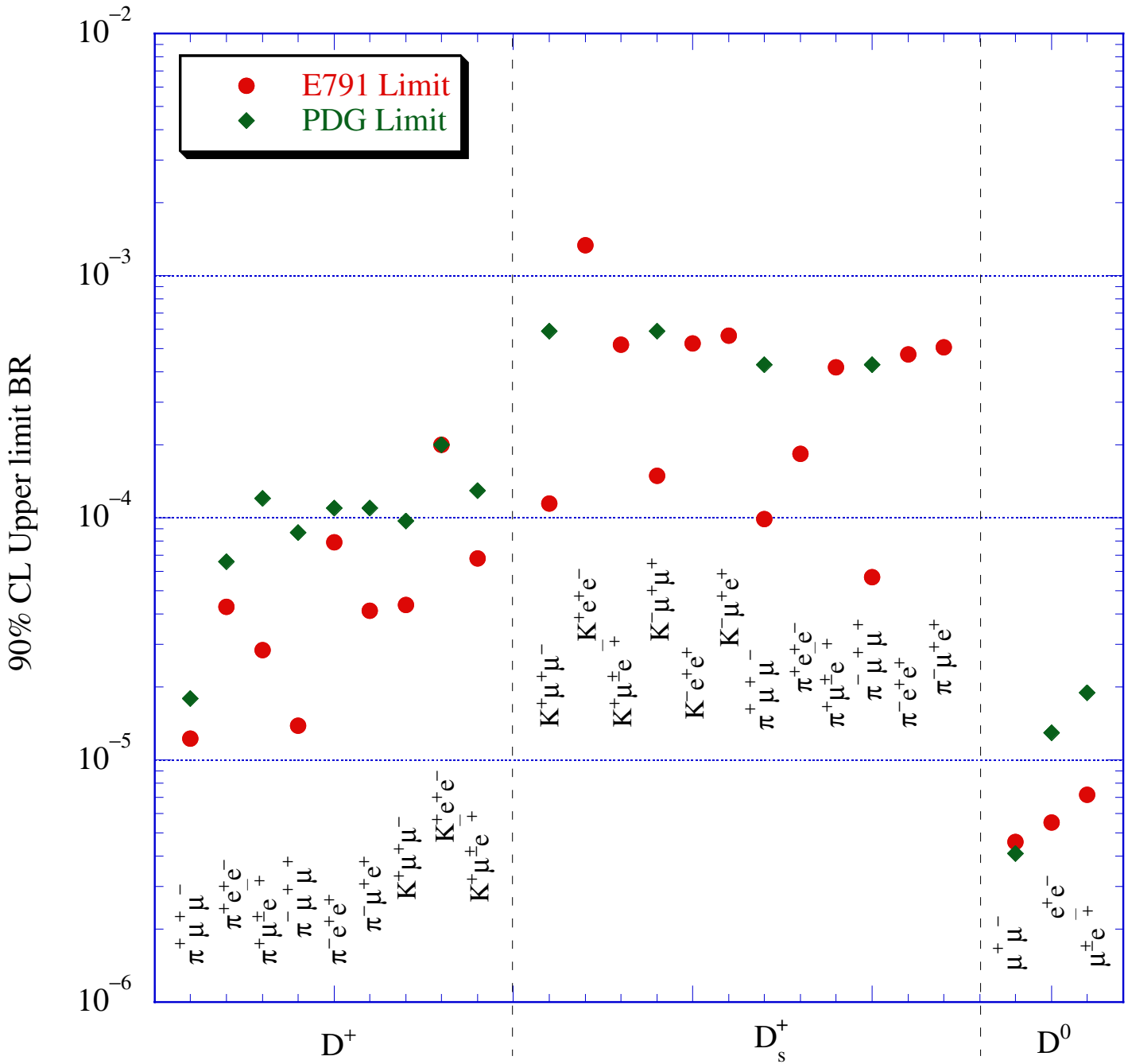
The solid line is the predicted background shape. The dotted line is the expected shape of the 90% CL upper limit number of events. The dashed lines are the “box” boundaries.

# Final Results<sup>1</sup> – 90% CL upper limit

Mode	E791 BR	BR (1998 PDG)	Previous Results
$D^+ \rightarrow \pi^+ \mu^+ \mu^-$	$1.48 \times 10^{-5}$	$1.8 \times 10^{-5}$	E791
$D^+ \rightarrow \pi^+ e^+ e^-$	$5.17 \times 10^{-5}$	$6.6 \times 10^{-5}$	E791
$D^+ \rightarrow \pi^+ \mu^\pm e^\mp$	$3.42 \times 10^{-5}$	$1.2 \times 10^{-4}$	E687
$D^+ \rightarrow \pi^- \mu^+ \mu^+$	$1.67 \times 10^{-5}$	$8.7 \times 10^{-5}$	E687
$D^+ \rightarrow \pi^- e^+ e^+$	$9.56 \times 10^{-5}$	$1.1 \times 10^{-4}$	E687
$D^+ \rightarrow \pi^- \mu^+ e^+$	$4.96 \times 10^{-5}$	$1.1 \times 10^{-4}$	E687
$D^+ \rightarrow K^+ \mu^+ \mu^-$	$4.38 \times 10^{-5}$	$9.7 \times 10^{-5}$	E687
$D^+ \rightarrow K^+ e^+ e^-$	$2.00 \times 10^{-4}$	$2.0 \times 10^{-4}$	E687
$D^+ \rightarrow K^+ \mu^\pm e^\mp$	$6.80 \times 10^{-5}$	$1.3 \times 10^{-4}$	E687
$D_s^+ \rightarrow K^+ \mu^+ \mu^-$	$1.38 \times 10^{-4}$	$5.9 \times 10^{-4}$	E653
$D_s^+ \rightarrow K^+ e^+ e^-$	$1.61 \times 10^{-3}$		
$D_s^+ \rightarrow K^+ \mu^\pm e^\mp$	$6.25 \times 10^{-4}$		
$D_s^+ \rightarrow K^- \mu^+ \mu^+$	$1.80 \times 10^{-4}$	$5.9 \times 10^{-4}$	E653
$D_s^+ \rightarrow K^- e^+ e^+$	$6.34 \times 10^{-4}$		
$D_s^+ \rightarrow K^- \mu^+ e^+$	$6.82 \times 10^{-4}$		
$D_s^+ \rightarrow \pi^+ \mu^+ \mu^-$	$1.43 \times 10^{-4}$	$4.3 \times 10^{-4}$	E653
$D_s^+ \rightarrow \pi^+ e^+ e^-$	$2.66 \times 10^{-4}$		
$D_s^+ \rightarrow \pi^+ \mu^\pm e^\mp$	$6.05 \times 10^{-4}$		
$D_s^+ \rightarrow \pi^- \mu^+ \mu^+$	$8.22 \times 10^{-5}$	$4.3 \times 10^{-4}$	E653
$D_s^+ \rightarrow \pi^- e^+ e^+$	$6.86 \times 10^{-4}$		
$D_s^+ \rightarrow \pi^- \mu^+ e^+$	$7.34 \times 10^{-4}$		
$D^0 \rightarrow \mu^+ \mu^-$	$5.18 \times 10^{-6}$	$4.1 \times 10^{-6}$	BEATRICE, E771
$D^0 \rightarrow e^+ e^-$	$6.23 \times 10^{-6}$	$1.3 \times 10^{-5}$	CLEO
$D^0 \rightarrow \mu^\pm e^\mp$	$8.12 \times 10^{-6}$	$1.9 \times 10^{-5}$	CLEO

<sup>1</sup> “Search for Rare and Forbidden Dilepton Decays of the  $D^+$ ,  $D_s^+$ , and  $D^0$  Charmed Mesons”, E. M. Aitala, *et al.*, *Phys. Lett.* **B462** (1999) 401-409.

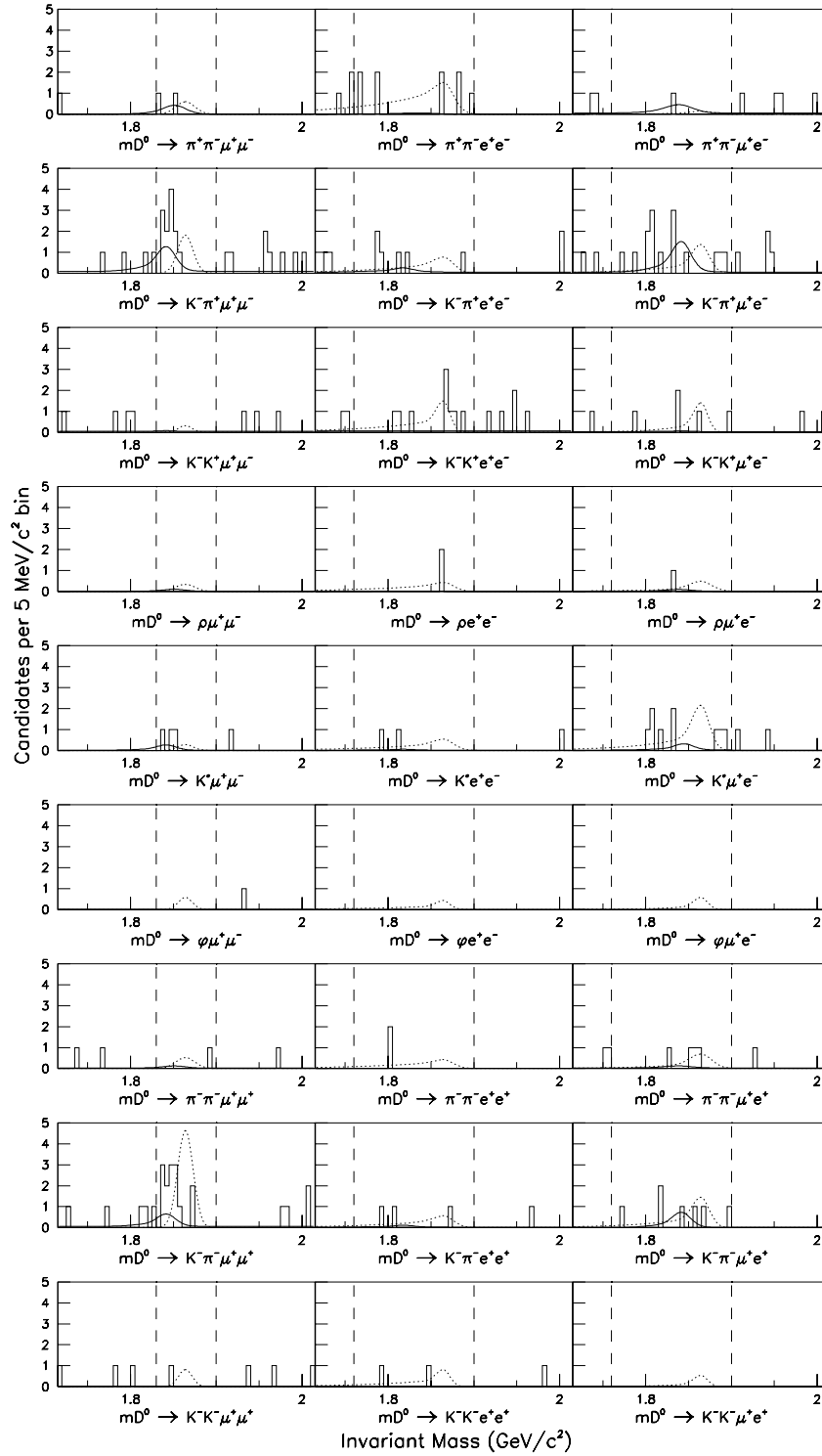
# Final 90% CL Results



# 3 and 4-Body Rare and Forbidden Decays

<b>Decay Modes Examined</b>		
<b>Flavor-Changing Neutral-Current</b>	<b>Lepton Flavor Violating</b>	<b>Lepton Number Violating</b>
$D^0 \rightarrow \rho^0 \mu^+ \mu^-$	$D^0 \rightarrow \rho^0 \mu^\pm e^\mp$	$D^0 \rightarrow \pi^- \pi^- \mu^+ \mu^+$
$D^0 \rightarrow \rho^0 e^+ e^-$	$D^0 \rightarrow \bar{K}^{*0} \mu^\pm e^\mp$	$D^0 \rightarrow \pi^- \pi^- e^+ e^+$
$D^0 \rightarrow \bar{K}^{*0} \mu^+ \mu^-$	$D^0 \rightarrow \phi \mu^\pm e^\mp$	$D^0 \rightarrow K^- \pi^- \mu^+ \mu^+$
$D^0 \rightarrow \bar{K}^{*0} e^+ e^-$	$D^0 \rightarrow \pi^+ \pi^- \mu^\pm e^\mp$	$D^0 \rightarrow K^- \pi^- e^+ e^+$
$D^0 \rightarrow \phi \mu^+ \mu^-$	$D^0 \rightarrow K^- \pi^+ \mu^\pm e^\mp$	$D^0 \rightarrow K^- K^- \mu^+ \mu^+$
$D^0 \rightarrow \phi e^+ e^-$	$D^0 \rightarrow K^+ K^- \mu^\pm e^\mp$	$D^0 \rightarrow K^- K^- e^+ e^+$
$D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$	$D^0 \rightarrow \pi^- \pi^- \mu^+ e^+$	
$D^0 \rightarrow \pi^+ \pi^- e^+ e^-$	$D^0 \rightarrow K^- \pi^- \mu^+ e^+$	
$D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-$	$D^0 \rightarrow K^- K^- \mu^+ e^+$	
$D^0 \rightarrow K^- \pi^+ e^+ e^-$		
$D^0 \rightarrow K^+ K^- \mu^+ \mu^-$		
$D^0 \rightarrow K^+ K^- e^+ e^-$		

# 3 and 4-Body Data



The solid line is the predicted background shape. The dotted line is the expected shape of the 90% CL upper limit number of events. The dashed lines are the “box” boundaries.

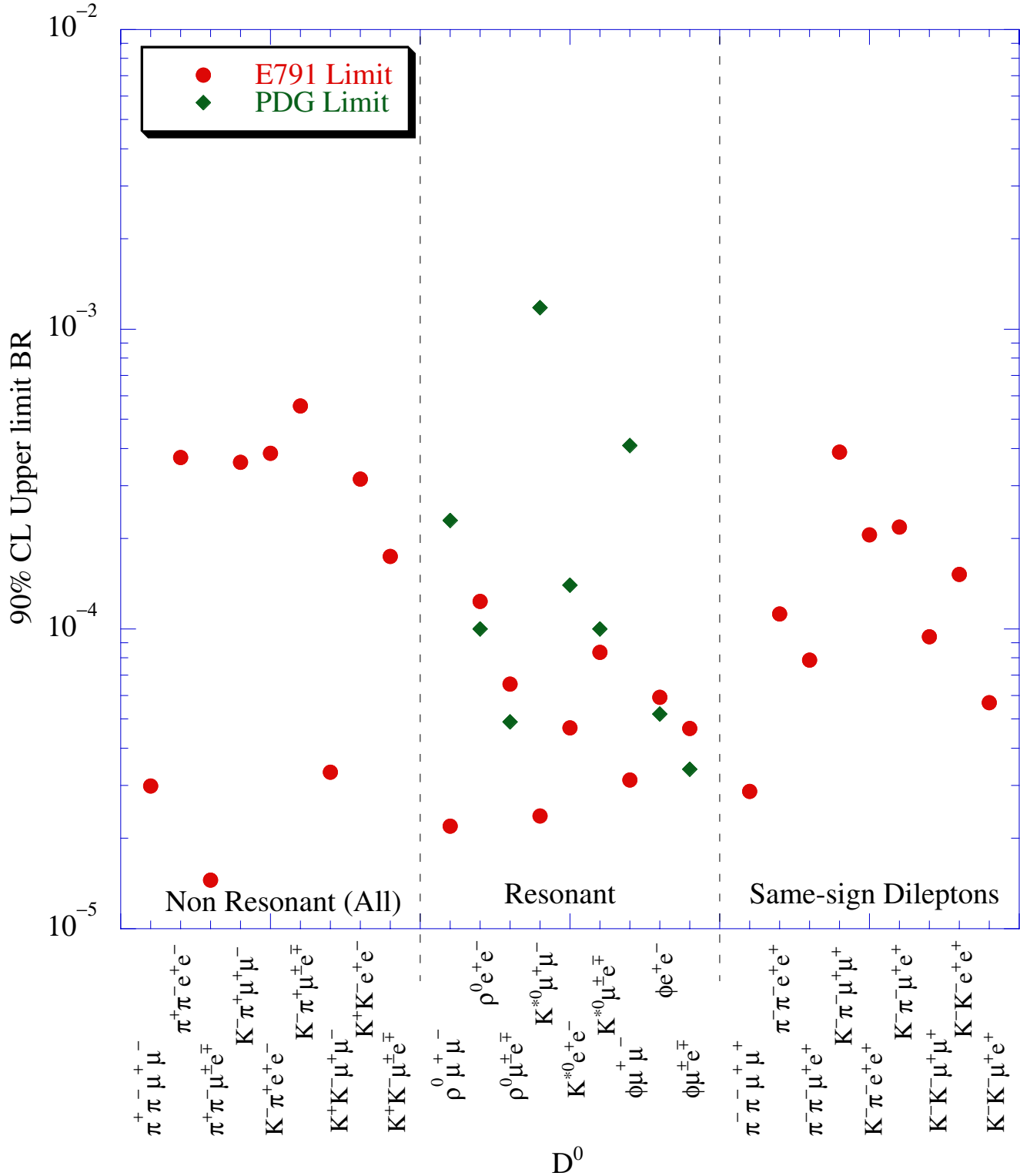
## Final Results<sup>2</sup> – 90% CL upper limit

Mode	E791 BR	2000 PDG BR	Previous Results
$D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$	$2.99 \times 10^{-5}$		
$D^0 \rightarrow \pi^+ \pi^- e^+ e^-$	$3.73 \times 10^{-4}$		
$D^0 \rightarrow \pi^+ \pi^- \mu^\pm e^\mp$	$1.45 \times 10^{-5}$		
$D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-$	$1.68 \times 10^{-4}$		
$D^0 \rightarrow K^- \pi^+ e^+ e^-$	$2.88 \times 10^{-4}$		
$D^0 \rightarrow K^- \pi^+ \mu^\pm e^\mp$	$2.38 \times 10^{-4}$		
$D^0 \rightarrow K^+ K^- \mu^+ \mu^-$	$3.59 \times 10^{-4}$		
$D^0 \rightarrow K^+ K^- e^+ e^-$	$3.85 \times 10^{-4}$		
$D^0 \rightarrow K^+ K^- \mu^\pm e^\mp$	$5.53 \times 10^{-4}$		
$D^0 \rightarrow \rho^0 \mu^+ \mu^-$	$2.20 \times 10^{-5}$	$2.3 \times 10^{-4}$	E653
$D^0 \rightarrow \rho^0 e^+ e^-$	$1.24 \times 10^{-4}$	$1.0 \times 10^{-4}$	CLEO
$D^0 \rightarrow \rho^0 \mu^\pm e^\mp$	$6.56 \times 10^{-5}$	$4.9 \times 10^{-5}$	CLEO
$D^0 \rightarrow \bar{K}^{*0} \mu^+ \mu^-$	$2.38 \times 10^{-5}$	$11.8 \times 10^{-4}$	CLEO
$D^0 \rightarrow \bar{K}^{*0} e^+ e^-$	$4.68 \times 10^{-5}$	$1.4 \times 10^{-4}$	CLEO
$D^0 \rightarrow \bar{K}^{*0} \mu^\pm e^\mp$	$8.34 \times 10^{-5}$	$1.0 \times 10^{-4}$	CLEO
$D^0 \rightarrow \phi \mu^+ \mu^-$	$3.13 \times 10^{-5}$	$4.1 \times 10^{-4}$	CLEO
$D^0 \rightarrow \phi e^+ e^-$	$5.92 \times 10^{-5}$	$5.2 \times 10^{-5}$	CLEO
$D^0 \rightarrow \phi \mu^\pm e^\mp$	$4.66 \times 10^{-5}$	$3.4 \times 10^{-5}$	CLEO
$D^0 \rightarrow \pi^- \pi^- \mu^+ \mu^+$	$2.88 \times 10^{-5}$		
$D^0 \rightarrow \pi^- \pi^- e^+ e^+$	$1.12 \times 10^{-4}$		
$D^0 \rightarrow \pi^- \pi^- \mu^+ e^+$	$7.86 \times 10^{-5}$		
$D^0 \rightarrow K^- \pi^- \mu^+ \mu^+$	$3.90 \times 10^{-4}$		
$D^0 \rightarrow K^- \pi^- e^+ e^+$	$2.06 \times 10^{-4}$		
$D^0 \rightarrow K^- \pi^- \mu^+ e^+$	$2.18 \times 10^{-4}$		
$D^0 \rightarrow K^- K^- \mu^+ \mu^+$	$9.40 \times 10^{-5}$		
$D^0 \rightarrow K^- K^- e^+ e^+$	$1.52 \times 10^{-4}$		
$D^0 \rightarrow K^- K^- \mu^+ e^+$	$5.68 \times 10^{-5}$		

<sup>2</sup> “Search for Rare and Forbidden Charm Mesons Decays  $D^0 \rightarrow V \ell^+ \ell^-$  and  $hh\ell\ell$ ”, E. M. Aitala, *et al.*, Accepted by *Phys. Rev. Lett.*, hep-ex/0011077.



# Final 90% CL Results



# Summary

## $D^+ \rightarrow hll$ , $D_s^+ \rightarrow hll$ and $D^0 \rightarrow \ell^+ \ell^-$ Analysis

- Examined 24 decay modes.
- 8 Results never before published.
- 14 Improvements on published results, some by an order of magnitude.

## $D^0 \rightarrow Vll$ and $D^0 \rightarrow hll$ Analysis

- Examined 27 decay modes.
- 18 Results never before published.
- 5 Improvements on published results, some by 1-2 orders of magnitude.

## Future Plans

- Normalize  $D^0 \rightarrow \rho^0 \ell^+ \ell^-$  to  $\text{BR}(D^0 \rightarrow \rho^0 \pi^+ \pi^-)$  once we measure it.