Rare Open Charm Decays (CLEO-c/BESIII)

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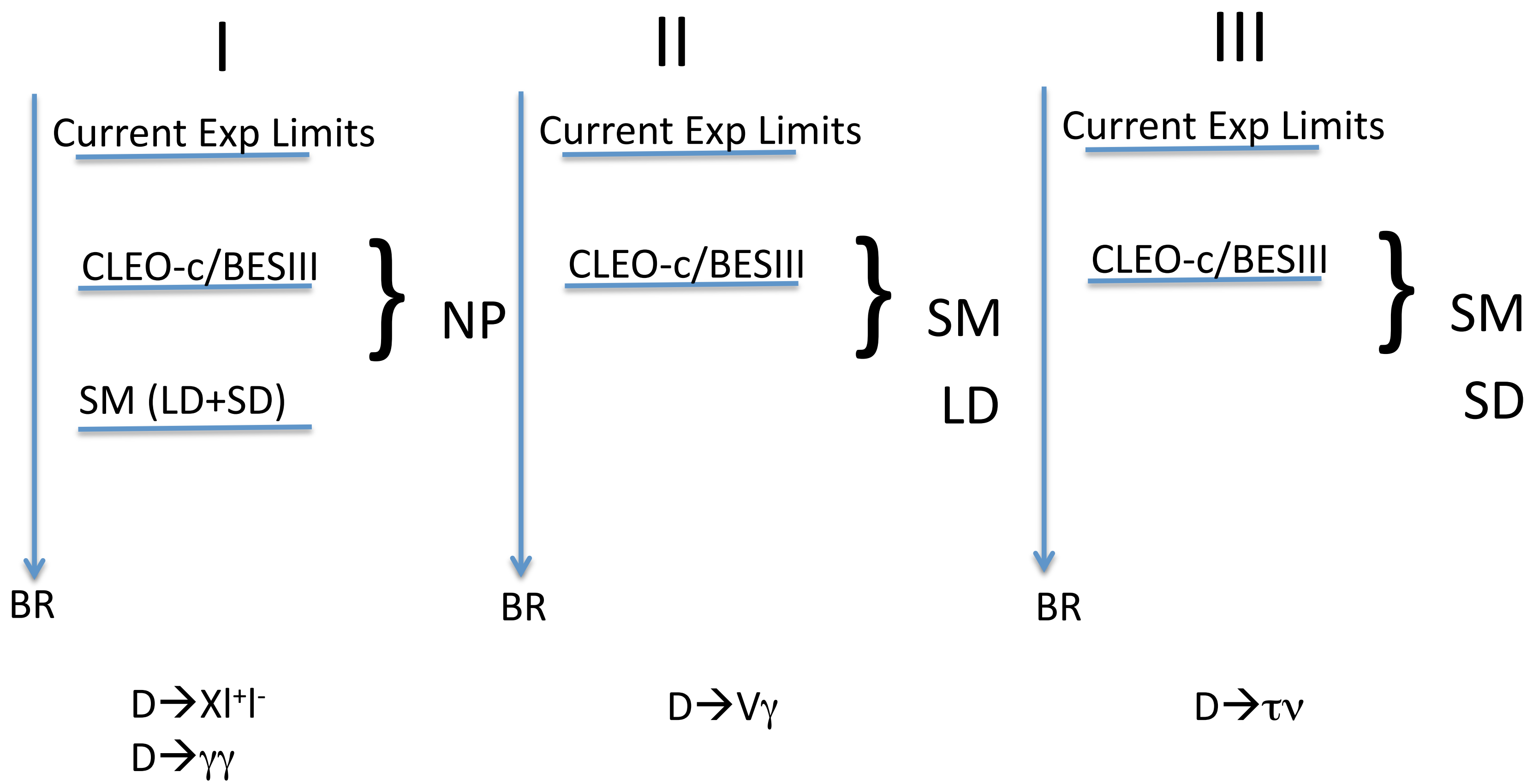
Outline

- Overview
- Results from CLEO-c
- Prospects
- Conclusions and Summary

What is Rare?

- Suppressed or Forbidden by SM
  - FCNC ($c \rightarrow u$) GIM suppressed:
    - $D^+ \rightarrow \pi^+ e^+ e^-$, $D \rightarrow X \gamma$
  - LNV/LFV:
    - $D^+ \rightarrow \pi^- e^+ e^+$, $D^+ \rightarrow \pi^+ e^+ \mu^-$
  - BNV:
    - $D \rightarrow X\ p$
- Not so exotic but interesting (BESIII targets)
  - $D \rightarrow \tau\nu$ (SM consistency)
  - $D \rightarrow l\nu\gamma$ (Validate radiative contributions, $\times 10^{-5}$)
- Small Deviations rather than small rates (BESIII target)
  - Lepton Universality ($D \rightarrow Xe\nu$ versus $D \rightarrow X\mu\nu$)
- D-mixing and CPV

Rare Charm Decays at Charm Factories



IV: Forbidden($Xe\mu$, Xl^+l^+)

D^0-Status of measurements

Process	Decay type	Upper limit
$\gamma\gamma$	FCNC	$< 2.7 \times 10^{-5}$
e^+e^-	FCNC	$< 1.2 \times 10^{-6}$
$\mu^+\mu^-$	FCNC	$< 1.3 \times 10^{-6}$
$\pi^0\, e^+e^-$	FCNC	$< 4.5 \times 10^{-5}$
$\pi^0\, \mu^+\mu^-$	FCNC	$< 1.8 \times 10^{-4}$
ηe^+e^-	FCNC	$< 1.1 \times 10^{-4}$
$\eta\mu^+\mu^-$	FCNC	$< 5.3 \times 10^{-4}$
$\pi^+\pi^-\, e^+e^-$	FCNC	$< 3.73 \times 10^{-4}$
$\rho^0 e^+e^-$	FCNC	$< 1.0 \times 10^{-4}$
$\pi^+\pi^-\, \mu^+\mu^-$	FCNC	$< 3.0 \times 10^{-5}$
$\rho^0\mu^+\mu^-$	FCNC	$< 2.2 \times 10^{-5}$
ωe^+e^-	FCNC	$< 1.8 \times 10^{-4}$
$\omega\mu^+\mu^-$	FCNC	$< 8.3 \times 10^{-4}$
$K^+K^-\, e^+e^-$	FCNC	$< 3.15 \times 10^{-4}$
ϕe^+e^-	FCNC	$< 5.2 \times 10^{-5}$
$K^+K^-\, \mu^+\mu^-$	FCNC	$< 3.3 \times 10^{-5}$
$\phi\mu^+\mu^-$	FCNC	$< 3.1 \times 10^{-5}$
$\overline{K}^0\, e^+e^-$	N/A[a]	$< 1.1 \times 10^{-4}$
$\overline{K}^0\, \mu^+\mu^-$	N/A[a]	$< 2.6 \times 10^{-4}$
$K^-\, \pi^+\, e^+e^-$	FCNC	$< 3.85 \times 10^{-4}$
$\overline{K}^{*0}\, e^+e^-$	N/A[a]	$< 4.7 \times 10^{-5}$
$K^+\, \pi^+\, \mu^+\mu^-$	FCNC	$< 3.59 \times 10^{-4}$

Process	Decay type	Upper limit
$\overline{K}^{*0}\, \mu^+\mu^-$	N/A[a]	$< 2.4 \times 10^{-5}$
$\pi^+\pi^-\, \pi^0\, \mu^+\mu^-$	FCNC	$< 8.1 \times 10^{-4}$
$e^\pm\, \mu^\mp$	LFV	$< 8.1 \times 10^{-7}$
$\pi^0\, e^\pm\, \mu^\mp$	LFV	$< 8.6 \times 10^{-5}$
$\eta e^\pm\, \mu^\mp$	LFV	$< 1.0 \times 10^{-4}$
$\pi^+\pi^-\, e^\pm\, \mu^\mp$	LFV	$< 1.5 \times 10^{-5}$
$\rho^0 e^\pm\, \mu^\mp$	LFV	$< 4.9 \times 10^{-5}$
$\omega e^\pm\, \mu^\mp$	LFV	$< 1.2 \times 10^{-4}$
$K^-K^+\, e^\pm\, \mu^\mp$	LFV	$< 1.8 \times 10^{-4}$
$\phi e^\pm\, \mu^\mp$	LFV	$< 3.4 \times 10^{-5}$
$\overline{K}^0\, e^\pm\, \mu^\mp$	LFV	$< 1.0 \times 10^{-4}$
$K^-\, \pi^+\, e^\pm\, \mu^\mp$	LFV	$< 5.53 \times 10^{-4}$
$\overline{K}^{*0}\, e^\pm\, \mu^\mp$	LFV	$< 8.3 \times 10^{-5}$
$\pi^-\, \pi^-\, e^+\, e^+ + \mathrm{c.c}$	LV	$< 1.12 \times 10^{-4}$
$\pi^-\, \pi^-\, \mu^+\, \mu^+ + \mathrm{c.c}$	LV	$< 2.9 \times 10^{-5}$
$K^-\, \pi^-\, e^+\, e^+ + \mathrm{c.c}$	LV	$< 2.06 \times 10^{-4}$
$K^-\, \pi^-\, \mu^+\, \mu^+ + \mathrm{c.c}$	LV	$< 3.9 \times 10^{-4}$
$K^-\, K^-\, e^+\, e^+ + \mathrm{c.c}$	LV	$< 1.52 \times 10^{-4}$
$K^-\, K^-\, \mu^+\, \mu^+ + \mathrm{c.c}$	LV	$< 9.4 \times 10^{-5}$
$\pi^-\, \pi^-\, e^+\, \mu^+ + \mathrm{c.c}$	LV	$< 7.9 \times 10^{-5}$
$K^-\, \pi^-\, e^+\, \mu^+ + \mathrm{c.c}$	LV	$< 2.18 \times 10^{-4}$
$K^-\, K^-\, e^+\, \mu^+ + \mathrm{c.c}$	LV	$< 5.7 \times 10^{-5}$

Charm Factory D^0s

CLEO-c 5×10^6

BESIII $> 10^7$

From **Flavor Physics in the Quark Sector**: hep-ph 0907.5386

Charged $D_{(s)}$:Status of measurements

Process	Decay type	Upper limit
$\pi^+ e^+e^-$	FCNC	$< 7.4 \times 10^{-6}$
$\pi^+ \mu^+\mu^-$	FCNC	$< 3.9 \times 10^{-6}$
$\rho^+\mu^+\mu^-$	FCNC	$< 5.6 \times 10^{-4}$
$K^+ e^+e^-$	N/A [a]	$< 6.2 \times 10^{-6}$
$K^+ \mu^+\mu^-$	N/A [a]	$< 9.2 \times 10^{-6}$
$\pi^+ e^\pm \mu^\mp$	LFV	$< 3.4 \times 10^{-5}$
$K^+ e^\pm \mu^\mp$	LFV	$< 6.8 \times 10^{-5}$
$\pi^- e^+ e^+$	LV	$< 3.6 \times 10^{-6}$
$\pi^- \mu^+ \mu^+$	LV	$< 4.8 \times 10^{-6}$
$\pi^- e^+ \mu^+$	LV	$< 5.0 \times 10^{-5}$
$\rho^-\mu^+ \mu^+$	LV	$< 5.6 \times 10^{-4}$
$K^- e^+ e^+$	LV	$< 4.5 \times 10^{-6}$
$K^- \mu^+ \mu^+$	LV	$< 1.3 \times 10^{-5}$
$K^- e^+ \mu^+$	LV	$< 1.3 \times 10^{-4}$
$K^{*-} \mu^+ \mu^+$	LV	$< 8.5 \times 10^{-4}$

Process	Decay type	Upper limit
$\pi^+ e^+e^-$	N/A [a]	$< 2.7 \times 10^{-4}$
$\pi^+ \mu^+\mu^-$	N/A [a]	$< 2.6 \times 10^{-5}$
$K^+ e^+e^-$	FCNC	$< 1.6 \times 10^{-3}$
$K^+ \mu^+\mu^-$	FCNC	$< 3.6 \times 10^{-5}$
$K^{*-} \mu^+\mu^-$	FCNC	$< 1.4 \times 10^{-3}$
$\pi^+ e^\pm \mu^\mp$	LFV	$< 6.1 \times 10^{-4}$
$K^+ e^\pm \mu^\mp$	LFV	$< 6.3 \times 10^{-4}$
$\pi^- e^+ e^+$	LV	$< 6.9 \times 10^{-4}$
$\pi^- \mu^+ \mu^+$	LV	$< 2.9 \times 10^{-5}$
$\pi^- e^+ \mu^+$	LV	$< 7.3 \times 10^{-4}$
$K^- e^+ e^+$	LV	$< 6.3 \times 10^{-4}$
$K^- \mu^+ \mu^+$	LV	$< 1.3 \times 10^{-5}$
$K^- e^+ \mu^+$	LV	$< 6.8 \times 10^{-4}$
$K^{*-} \mu^+ \mu^+$	LV	$< 1.4 \times 10^{-3}$

From **Flavor Physics in the Quark Sector**: hep-ph 0907.5386

$$D_{(s)}^{+} \to h^{\pm} e^{\mp} e^{\pm}$$

CLEO-c

FCNC	LNV
$D^+ \to \pi^+ e^+ e^-$	$D^+ \to \pi^- e^+ e^+$
$K^+ e^+ e^-$	$K^- e^+ e^+$
$D_s^+ \to \pi^+ e^+ e^-$	$D_s^+ \to \pi^- e^+ e^+$
$K^+ e^+ e^-$	$K^- e^+ e^+$

D^+
Ecm = 3.774 GeV
L = 818 pb^{-1}
N_{DD} = 2.4 x 10^6

D_s^+
Ecm = 4.170 GeV
L = 602 pb^{-1}
N_{DsDs*} = 0.6 x 10^6

FCNC: Highly suppressed
SM rates $10^{-10} - 10^{-9}$
Long distance (Vector pole) rates $10^{-6} - 10^{-5}$

LNV: If seen may indicate Majorana nature of neutrino.

PRD
Accepted for publication

Analysis Details $D^+_{(s)} \rightarrow h^\pm e^\mp e^\pm$

- All track mode (excellent E,p resolution)
- Standard tracking cuts (vertex and fiducial)
  - K/π PID (RICH and dEdx)
- Electrons required to be more central and p>200Mev.
  - This ensures E/p discrimination reliable.
  - Radiation recover is used for electrons.

D^+D^- events

$$\Delta E = (E_{D^+} - E_{beam}) \qquad \Delta M_{bc} = \sqrt{E^2_{beam} - p^2_{D^+}} - m_{D^+}$$

± 20 MeV

± 5 MeV

$D_s^*D_s$ events

$$\Delta M_{recoil} = \sqrt{(E_0 - E_{D_s^+})^2 - (\vec{p}_0 - \vec{p}_{D_s^+})^2} \qquad \Delta M = M_{D^+} - m_{D^+}$$

± 55 MeV

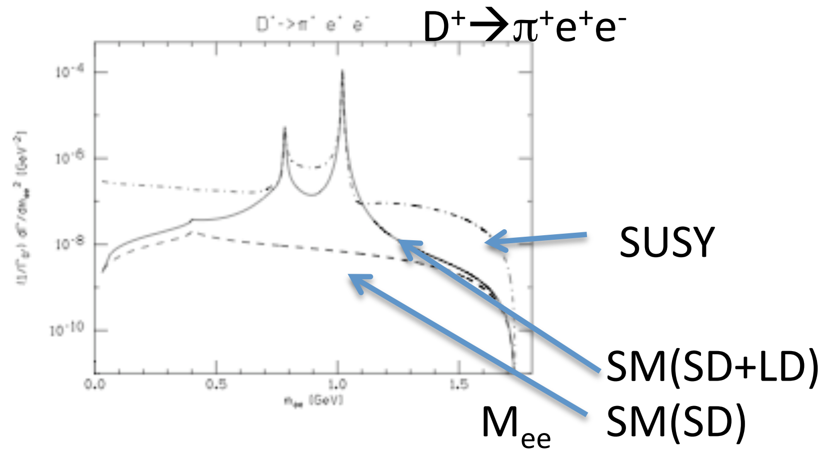
± 20 MeV

Larger spread from transition photon

Analysis Details

$$D^{+}_{(s)} \rightarrow h^{\pm} e^{\mp} e^{\pm}$$

- Hadrons faking electron rate very low.
  - Mass assignment for hadron is wrong.
  - Negligible background for two electron mode.
- Backgrounds arise from processes that produce two true electrons.
  - Double semileptonic decay.
    - Require energy on other side to be significant (>1.0 to 1.7 GeV)
  - Additional electrons may arise from conversions (continuum)
- $\phi(ee)\,\pi$ final state is expected to be of order 10^{-6}. The regions around the poles are used for separate analysis.
- All selection cuts were optimized for best upper limit with MC before analyzing data.
- Backgrounds are estimated from MC.



NP Models are tuned so as to obey constraints imposed by D mixing.

Efficiencies and Backgrounds

$$D^+_{(s)} \to h^\pm e^\mp e^\pm$$

Channel	ϵ (%)	N_{bg}
$D^+ \to \pi^+ e^+ e^-$	34.55 ± 0.21	5.73 ± 0.70
$D^+ \to \pi^- e^+ e^+$	44.37 ± 0.22	1.29 ± 0.26
$D^+ \to K^+ e^+ e^-$	23.58 ± 0.19	4.87 ± 0.58
$D^+ \to K^- e^+ e^+$	35.99 ± 0.21	1.24 ± 0.31
$D^+ \to \pi^+ \phi(\to e^+ e^-)$	47.13 ± 0.22	0.25 ± 0.17

Channel	ϵ (%)	N_{bg}
$D_s^+ \to \pi^+ e^+ e^-$	24.80 ± 0.19	6.66 ± 0.82
$D_s^+ \to \pi^- e^+ e^+$	34.07 ± 0.21	2.23 ± 0.36
$D_s^+ \to K^+ e^+ e^-$	17.67 ± 0.17	2.96 ± 0.45
$D_s^+ \to K^- e^+ e^+$	28.31 ± 0.20	4.08 ± 0.46
$D_s^+ \to \pi^+ \phi(\to e^+ e^-)$	34.59 ± 0.21	0.72 ± 0.19

Results

$$D^+_{(s)} \rightarrow h^\pm e^\mp e^\pm$$

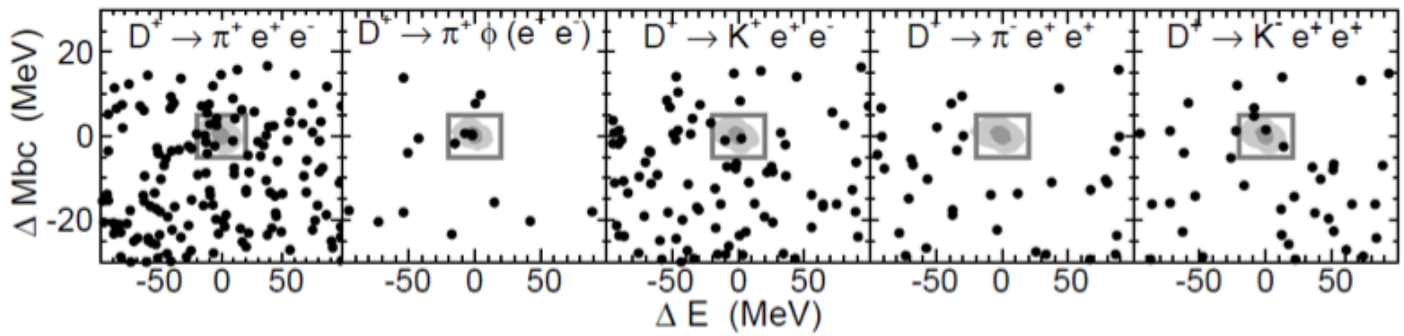


FIG. 1. Scatter plots of $\Delta M_{\rm bc}$ vs ΔE. The two contours for each mode enclose regions determined with signal MC simulation to contain 50% and 85% of signal events, respectively. The signal region, defined by $(\Delta E, \Delta M_{\rm bc}) = (\pm 20\,{\rm MeV}, \pm 5\,{\rm MeV})$, is shown as a box.

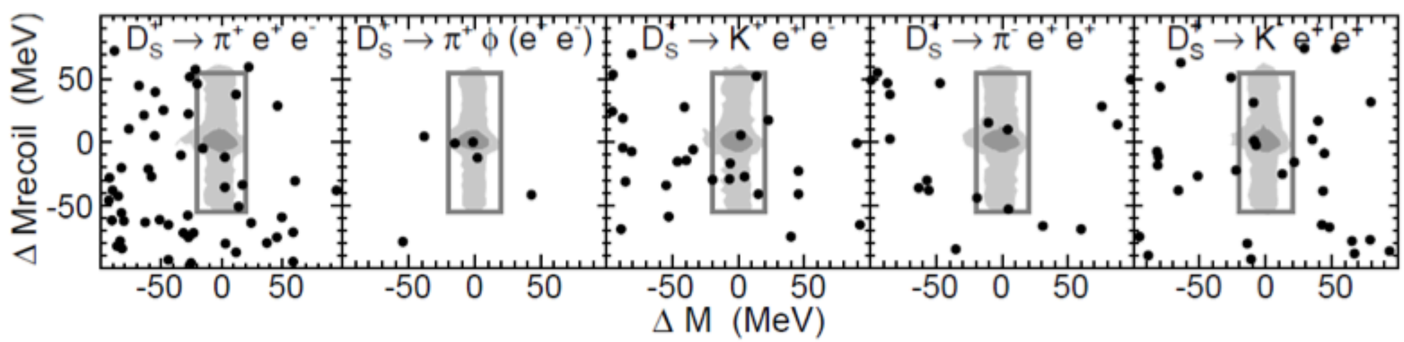


FIG. 2. Scatter plots of $\Delta M_{\rm recoil}$ vs ΔM. The two contours for each mode enclose regions determined with signal MC simulation to contain 40% and 85% of signal events, respectively. The signal region, defined by $(\Delta M, \Delta M_{\rm recoil}) = (\pm 20\,{\rm MeV}, \pm 55\,{\rm MeV})$, is shown as a box.

Results

$$D_{(s)}^{+} \rightarrow h^{\pm} e^{\mp} e^{\pm}$$

Channel	N	ϵ (%)	$N_{\rm exp}$	$N_{\rm obs}$	$\mathcal{C}(N_{\rm obs}\|N_{\rm exp})$	$\mathcal{B}$
$D^+ \to \pi^+ e^+ e^-$	4.76×10^6	33.9	5.7	9	9.3	$< 5.9 \times 10^{-6}$
$D^+ \to \pi^- e^+ e^+$	4.76×10^6	43.5	1.3	0	2.3	$< 1.1 \times 10^{-6}$
$D^+ \to K^+ e^+ e^-$	4.76×10^6	23.1	4.9	2	3.2	$< 3.0 \times 10^{-6}$
$D^+ \to K^- e^+ e^+$	4.76×10^6	35.3	1.2	3	5.8	$< 3.5 \times 10^{-6}$
$D^+ \to \pi^+ \phi(e^+ e^-)$	4.76×10^6	46.2	0.3	4		$(1.7^{+1.4}_{-0.9} \pm 0.1) \times 10^{-6}$
					7.9	$< 3.7 \times 10^{-6}$
$D_s^+ \to \pi^+ e^+ e^-$	1.10×10^6	24.3	6.7	6	5.6	$< 2.2 \times 10^{-5}$
$D_s^+ \to \pi^- e^+ e^+$	1.10×10^6	33.4	2.2	4	6.2	$< 1.8 \times 10^{-5}$
$D_s^+ \to K^+ e^+ e^-$	1.10×10^6	17.3	3.0	7	9.3	$< 5.2 \times 10^{-5}$
$D_s^+ \to K^- e^+ e^+$	1.10×10^6	27.7	4.1	4	5.0	$< 1.7 \times 10^{-5}$
$D_s^+ \to \pi^+ \phi(e^+ e^-)$	1.10×10^6	33.9	0.7	3		$(0.6^{+0.8}_{-0.4} \pm 0.1) \times 10^{-5}$
					6.2	$< 1.8 \times 10^{-5}$

These are the most stringent upper limits to date.
Still a gap of few orders of magnitude from SM.
The resonance searches are at a significance of 3.5 and 1.8 for D^+ and Ds respectively so upper limits are quoted along with the BR.

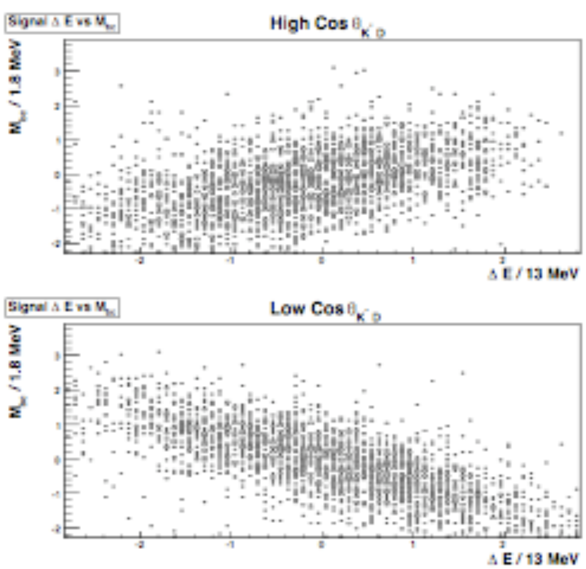
Radiative Decays ($D^0 \rightarrow X\gamma$)

- More difficult target than electron final states
  - Resolution relatively poor.
  - Fake photon rates high.
  - Vector-photon final states have large expected contributions from LD physics so "New Physics" opportunities are limited. Must look at relative rates of ρ and ω final states for example.
- B factories have done better with $V\gamma$ modes.
  - First observation of $D^0 \rightarrow \phi\, \gamma$ (Belle)
  - First observation of $D^0 \rightarrow K^*\gamma$ (BaBar)

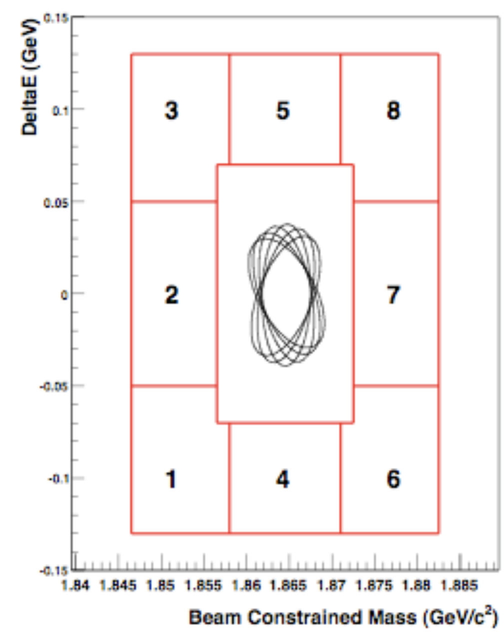
Radiative D Decay:

- Full reconstruction of $D^0 \rightarrow K^* \gamma$ (No D-Tag)
  - Standard photon requirements.
  - K^* is well measured while photon is not.
    - Introduces correlation in primary discrimination variables:

      ΔE & M_{bc}



Plots show M_{bc} versus ΔE for D anti-aligned with photon (top) and aligned with photon (bottom).

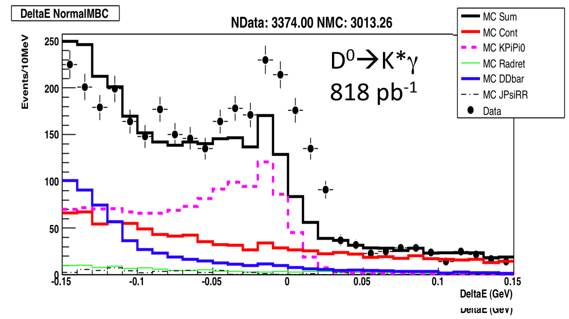


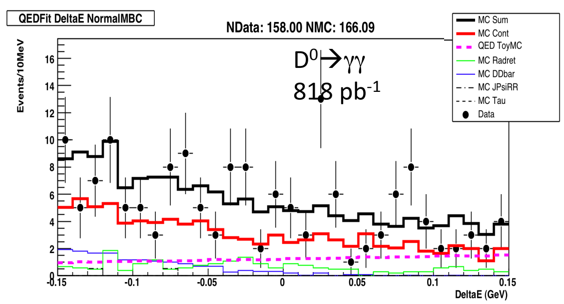
CLEO-c: D→X γ Analysis

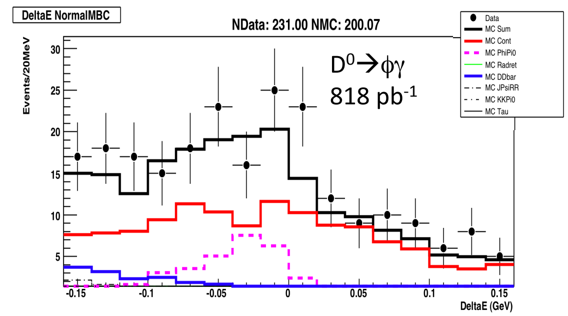
- Modes: $D^0 \to K^*\gamma$, $D^0 \to \phi\gamma$, $D^0 \to \rho\gamma$, $D^0 \to \omega\gamma$, $D^0 \to \gamma\gamma$
- Luminosity: 818 pb^{-1}
- Improved upper limits
- Confirm: K^*, ϕ observations

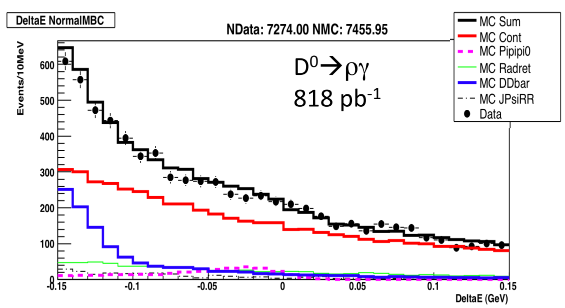
CLEO-c Preliminary

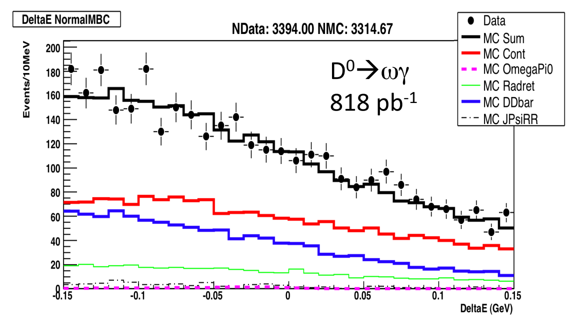
Channel	$\epsilon[\%]$	N_{Bknd}	$N_{observed}$	$\mathcal{B}$
$D \to \bar{K}^*\gamma$	12.29	355.79 ± 2.55	677	$[4.37 \pm 0.37 \pm 0.52] \times 10^{-4}$
$D \to \phi\gamma$	11.61	28.66 ± 1.08	44	$[2.21 \pm 0.95 \pm 0.29] \times 10^{-5}$
$D \to \gamma\gamma$	19.90	15.79 ± 0.81	17	$< 8.63 \times 10^{-6}$ (UL @90% CL)
$D \to \rho\gamma$	23.41	615.4 ± 4.9	625	$< 3.63 \times 10^{-5}$ (UL @90% CL)
$D \to \omega\gamma$	11.37	247.8 ± 4.5	235	$< 3.00 \times 10^{-5}$ (UL @90% CL)











Prospects for BESIII

- The BESIII detector has very similar capabilities when compared to the CLEO-c.
  - TOF system at BESIII as opposed to Cherenkov system at CLEO-c. Two body final states could be more difficult.
  - BESIII will be able to include muon modes.
- Currently BESIII has the world's largest sample at 3770 MeV (~910 pb^{-1}) but it is still comparable to the CLEO-c sample size.
- Will need an order of magnitude more data to improve limits (or make discoveries).
- With 10 fb^{-1} some new Vγ observations are possible, a significant observation of D→ $\tau\,\nu$ and . These data will close the gap between the current experimental limits and the SM rates for FCNC where new physics may lurk.
- We are hoping for ~5 fb^{-1} in the next series of runs.

Summary

- I have presented results from CLEO-c for FCNC and LNV decays $D_{(s)}^{+} \to h^{\pm}e^{\mp}e^{\pm}$
  - No observations made. Improved upper limits.
- On radiative D^0 decays
  - Confirmation of $K^*/\phi\ \gamma$.
  - Improved upper limits on $\rho/\omega\ \gamma$ as well $\gamma\gamma$.
- BESIII collecting and analyzing open charm data.
  - World's largest sample near threshold.
  - Will probe gap between current limits and SM.
  - Potential for observations ($\phi(l^+l^-)\pi$, $\rho/\omega\ \gamma$, $D^0 \to \tau\ \nu$)

BESIII (20 fb^{-1})

Mode	Reference Experiment	Best Upper limits(10^{-6})	*BES-III* ($\times 10^{-8}$)
$\gamma\gamma$	CLEO [442]	28	5.0
$\mu^+\mu^-$	D0 [444]	2.4	17.0
μ^+e^-	E791 [438]	8.1	4.3
e^+e^-	E791 [438]	6.2	2.4
$\pi^0\mu^+\mu^-$	E653 [445]	180	12.3
$\pi^0\mu^+e^+$	CLEO [443]	86	9.7
$\pi^0e^+e^-$	CLEO [443]	45	7.9
$K_S\mu^+\mu^-$	E653 [445]	260	10.6
$K_S\mu^+e^-$	CLEO [443]	100	9.6
$K_Se^+e^-$	CLEO [443]	110	7.5
$\eta\mu^+\mu^-$	CLEO [443]	530	15.0
$\eta\mu^+e^-$	CLEO [443]	100	12.0
ηe^+e^-	CLEO [443]	110	10.0

Table 27.3: Current and projected 90%-CL upper limits on rare D^0 decay modes at *BES-III* with a 20 fb^{-1} data sample taken at the $\psi(3770)$ peak.