Rare Charm Decays

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IHEP, Beijing, 22nd October 2011

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Overview

- Introduction
- Neutral final states
- (semi-)leptonic final states
- Final states with missing energy
- Summary

Introduction

- What is rare?
  - CLEO-c at $\psi(3770)$: $0.8fb^{-1}$ ($\sim 3.2\times10^6$ D pairs)
  - BES III at $\psi(3770)$: $\sim 10fb^{-1}$ ($\sim 40\times10^6$ D pairs)
  - SuperB at $\psi(3770)$: $500fb^{-1}$ ($\sim 2\times10^9$ D pairs)
    - Two large jumps in data samples could change the perspective on rare decays with time ...
    - Superb will approach a single event sensitivity at $\sim 10^{-9}$

  - BaBar/Belle at the $\Upsilon(4S)$: $\sim$0.5-1ab^{-1} of data [0.6-1.2 $\times10^9$ events]
  - SuperB/Belle II at the $\Upsilon(4S)$: 50-75ab^{-1} of data [60-90 $\times10^9$ events]
    - Rely on D* tagged mesons, not always the best (but with 50 times more data than at threshold)

  - LHCb:
    - Vast numbers in a hadronic environment: good for charged track final states if channel can be triggered on efficiently.
    - Not so good with neutral final states (ν's, γ's, π^0's etc.)

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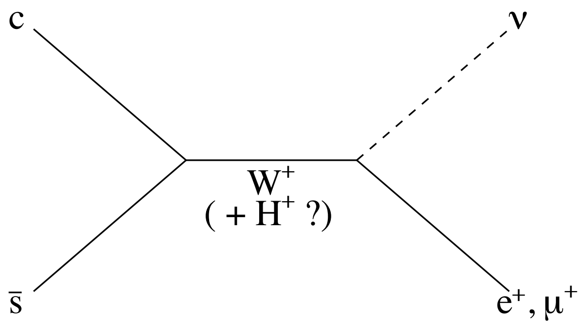
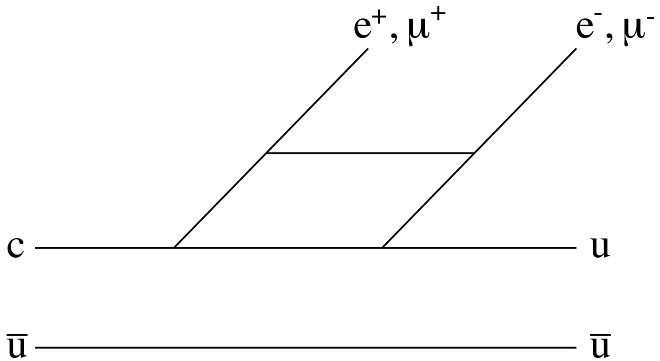
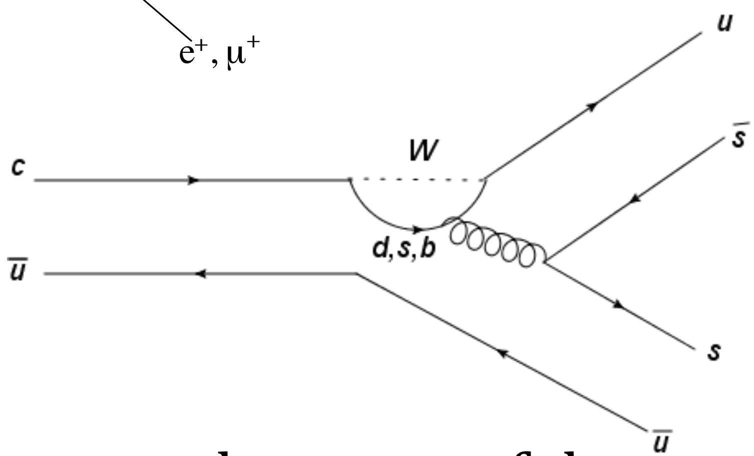
Perspective changes from threshold to D* tagged events at the Υ(4S) to pp collisions.

What do we want to measure

- NP sensitive processes
  - (or modes controlling theoretical uncertainties for these).



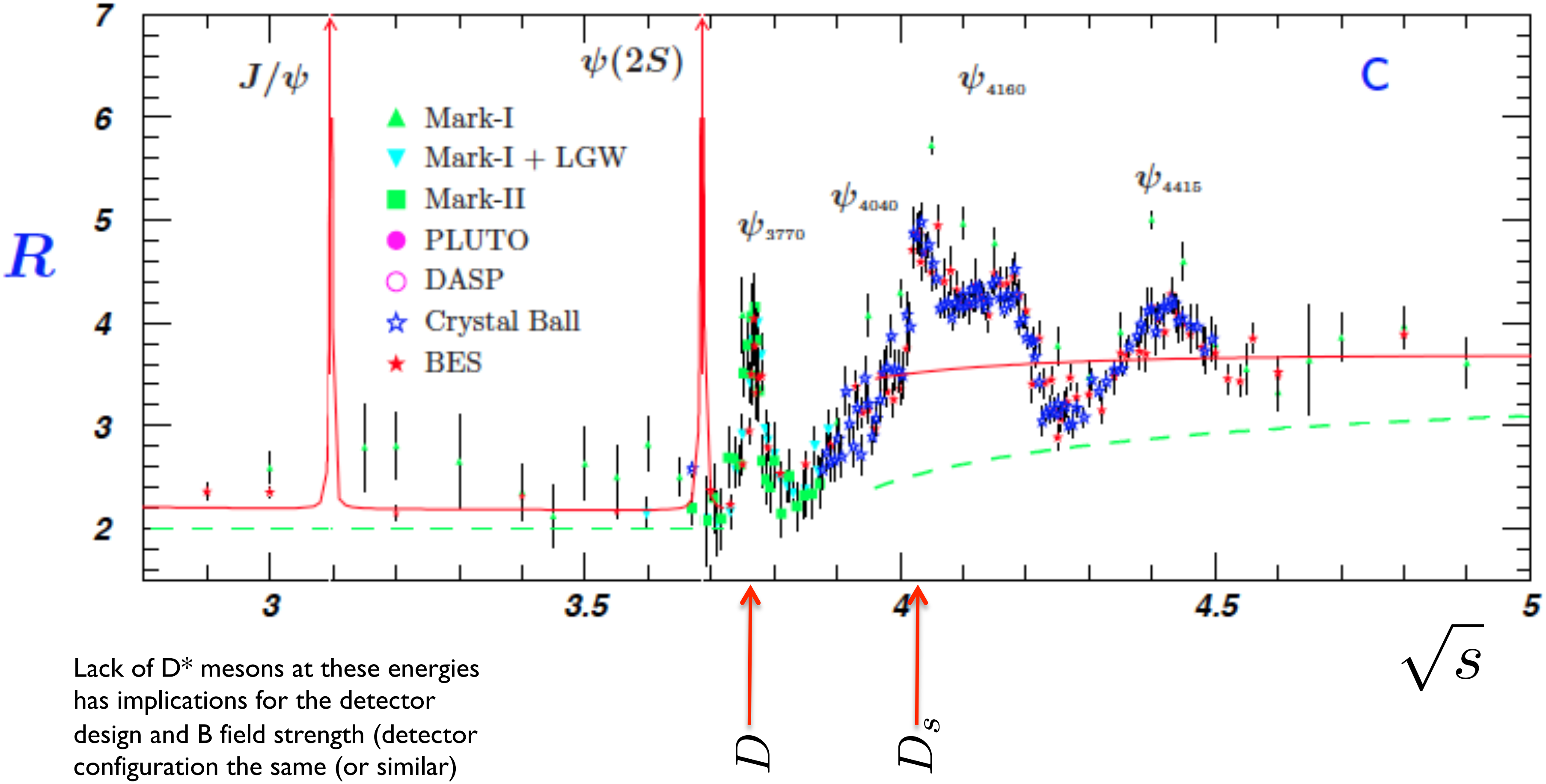




- But long distance (LD) interactions can obscure usefulness of the short distance (SD) ones, so not always straightforward to understand NP reach.

Introduction

- Focus on thresholds that SuperB is thinking about



Lack of D* mesons at these energies has implications for the detector design and B field strength (detector configuration the same (or similar) to 4S running).

Neutral final states

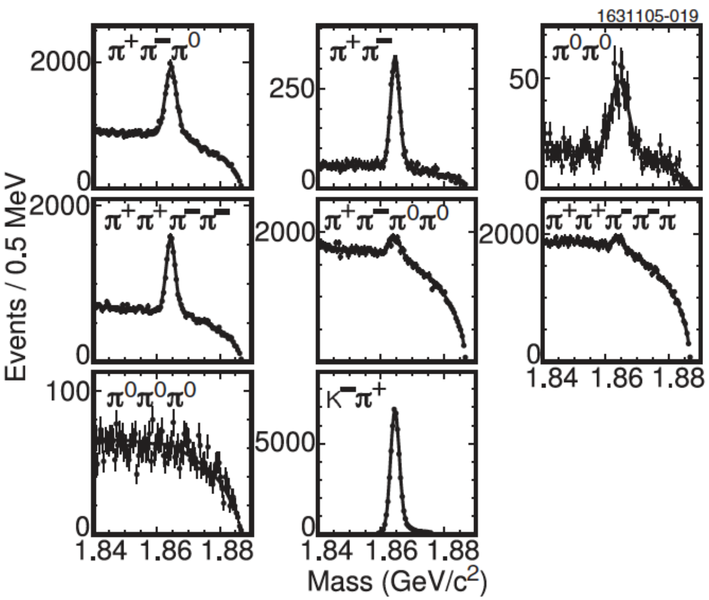
$$D \longrightarrow \pi^0 \pi^0$$

$$D \longrightarrow \gamma\gamma$$

$D \to \pi^0\pi^0$

- Not particularly rare... but
  - Input to the Isospin analysis required to constrain penguin pollution for the TDCPV measurement of $\pi^+\pi^-$ (see Brian Meadows' talk).
  - Also background to other rare decays (would be nice to determine this a bit more precisely).

$$\mathcal{B}(D^0 \to \pi^0\pi^0) = (8.0 \pm 0.8) \times 10^{-4} \qquad \text{(CLEO)}$$



- CLEO recorded 500 events in a sample of 0.281fb^{-1}.
- ε ~30%.
- but dominated by systematic uncertainties (comparable syst. & stat. errors).
- Some improvement possible, but will be dominated by the ultimate systematic errors achievable.

$D \to \gamma\gamma$

- Dominated by long distance effects as

$$\mathcal{B}(D^0 \to \gamma\gamma)_{SD} = 3.0 \times 10^{-11}$$
$$\mathcal{B}(D^0 \to \gamma\gamma)_{LD} = (1.0 \pm 0.5) \times 10^{-8}$$

Burdman/Fajfer

  - VMD model based calculations suggest a slightly larger BF.
  - Rate can be enhanced by New Physics.
- Rate is related to the rare di-lepton decay via:

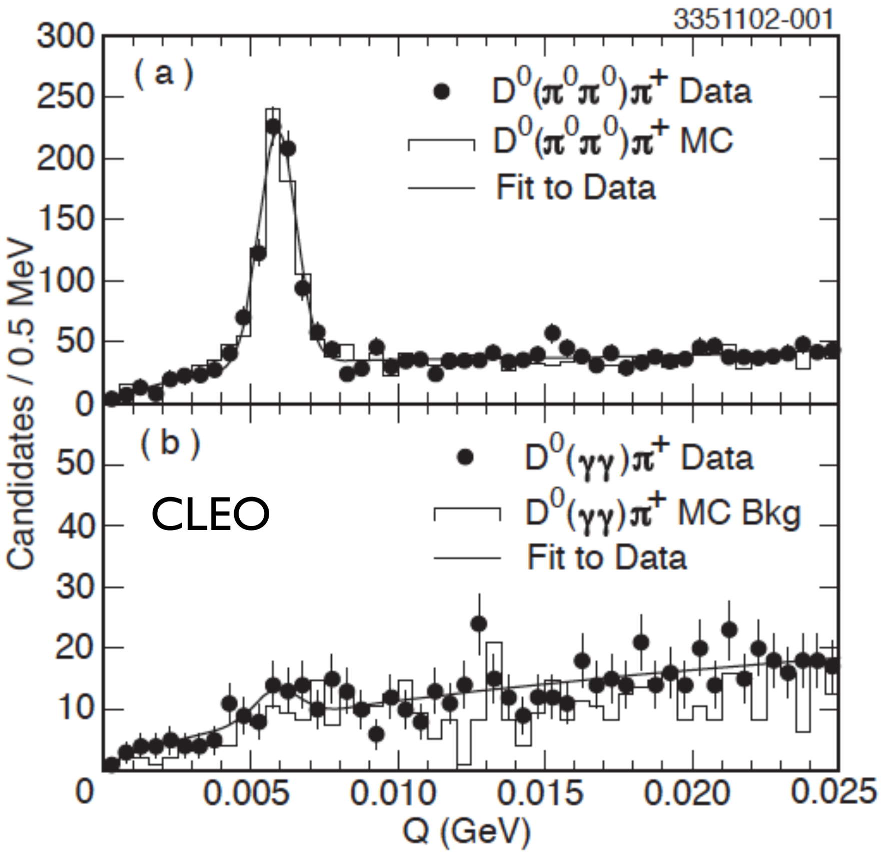
$$\mathcal{B}(D^0 \to \mu^+\mu^-)_{LD} = 3.0 \times 10^{-5} \times \mathcal{B}(D^0 \to \gamma\gamma)$$

- BES III would reach a limit of 0.5×10^{-7} with 20fb^{-1} of data.

- SuperB should be able to reach a sensitivity of $\sim10^{-7}$ (current limit from CLEO $<2.7 \times 10^{-5}$).
  - Should be good enough to place a strong constraint on the di-muon mode LD contribution.
  - Potential backgrounds include $\pi^0\pi^0$, $\pi^0\eta$, $\eta\eta$, charged semi-leptonic decays.

$D \to \gamma\gamma$

- CLEO data PRL **90** 201801 (2003) using 13.8 fb^{-1} of data.



- Measured $\gamma\gamma/\pi^0\pi^0$

- Current value reported in PDG $<2.7\times10^{-5}$.

- Measurement used D* tagged events from the 4S data sample to isolate signal region.

- Systematic uncertainties dominated by π and γ reconstruction efficiencies.

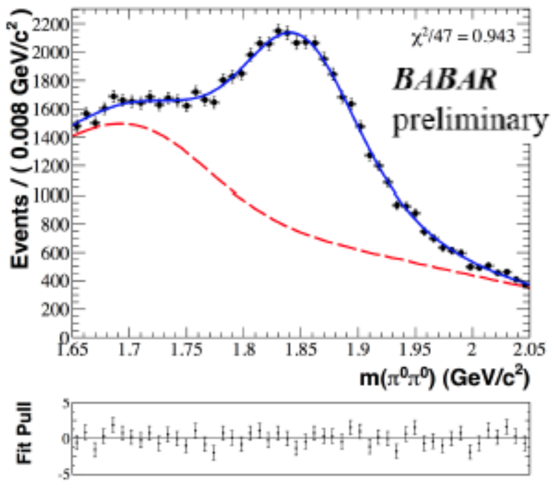
$D \to \gamma\gamma$

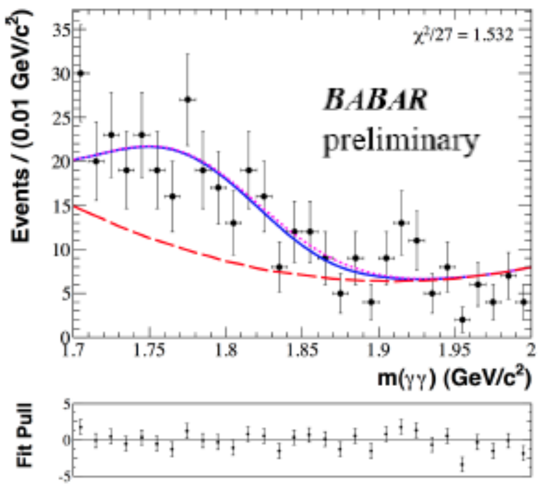
Search for the Decay D^0 to $\gamma\gamma$ (previously presented at FPCP 2011)

Search for forbidden FCNC decay
Dominant background from D^0 to $\pi^0\pi^0$
Branching fraction measurements for $\gamma\gamma$ and $\pi^0\pi^0$ modes normalized to D^0 to $K_s\pi^0$
D^0 decays from D^* used to suppress backgrounds along with pion veto (95% rejection 66% signal efficiency)

$$B(D^0 \to \pi^0\pi^0) = \frac{\frac{1}{\epsilon_{\pi^0\pi^0}} N(D^0 \to \pi^0\pi^0)}{\frac{1}{\epsilon_{K_S^0\pi^0}} N(D^0 \to K_S^0\pi^0)} \times B(D^0 \to K_S^0\pi^0)$$

$$B(D^0 \to \gamma\gamma) = \frac{\frac{1}{\epsilon_{\gamma\gamma}} N(D^0 \to \gamma\gamma)}{\frac{1}{\epsilon_{K_S^0\pi^0}} N(D^0 \to K_S^0\pi^0)} \times B(D^0 \to K_S^0\pi^0)$$





Final Results (about a factor 10 improvement over previous results)

$$B(D^0 \to \pi^0\pi^0) = (8.4 \pm 0.1 \pm 0.4 \pm 0.3) \times 10^{-4}$$

$$B(D^0 \to \gamma\gamma) < 2.4 \times 10^{-6}$$

Rare Leptonic decays

$$D \longrightarrow \ell^+ \ell^-$$

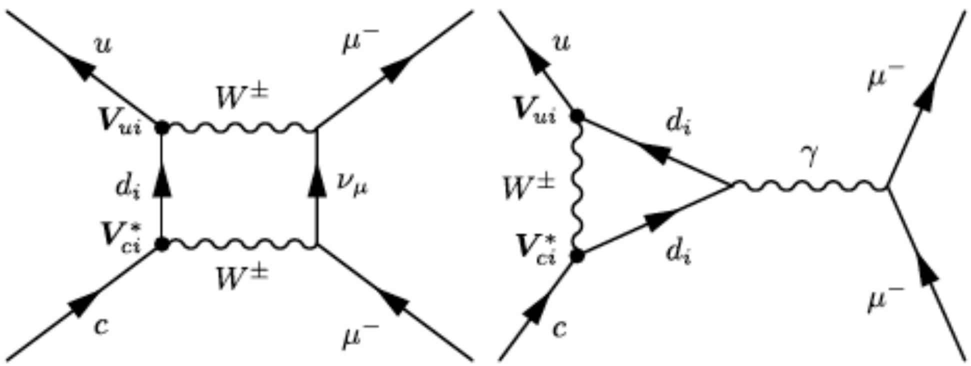
$$D \longrightarrow u \ell^+ \ell^-$$

$D \to \ell^+ \ell^-$

- Expect a low rate in the SM.
  - SD contribution $\sim 10^{-18}$ (Burdman et al.)
  - LD contribution related to D→γγ

$$\mathcal{B}(D^0 \to \mu^+\mu^-)_{LD} \quad = \quad 3.0 \times 10^{-5} \times \mathcal{B}(D^0 \to \gamma\gamma)$$

- SD contributions allow for possible NP enhancements:



arXiv:1003.2345

  - But we need to understand LD rate in order to interpret any signals found.

$D \to \ell^+\ell^-$

- Recent results from Belle:

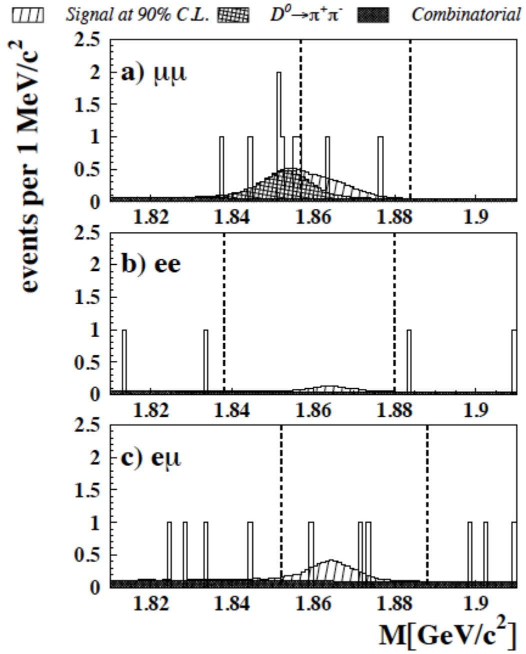


TABLE II. Summary of the number of expected background events (N_{bkg}), number of observed events (N) in the signal region, the reconstruction efficiencies ($\epsilon_{\ell\ell}$ and $\epsilon_{\pi\pi}$) of the $D^0 \to \ell^+\ell^-$ and $D^0 \to \pi^+\pi^-$ decays, the factors f and the branching fraction upper limits at the 90% confidence level.

	$D^0 \to \mu^+\mu^-$	$D^0 \to e^+e^-$	$D^0 \to e^\pm\mu^\mp$
N_{bkg}	3.1 ± 0.1	1.7 ± 0.2	2.6 ± 0.2
N	2	0	3
$\epsilon_{\ell\ell}[\%]$	7.02 ± 0.34	5.27 ± 0.32	6.24 ± 0.27
$\epsilon_{\pi\pi}[\%]$	12.42 ± 0.10	10.74 ± 0.09	11.22 ± 0.09
$f[10^{-8}]$	$4.84(1 \pm 5.3\%)$	$6.47(1 \pm 6.4\%)$	$5.48(1 \pm 4.8\%)$
UL $[10^{-7}]$	1.4	0.79	2.6

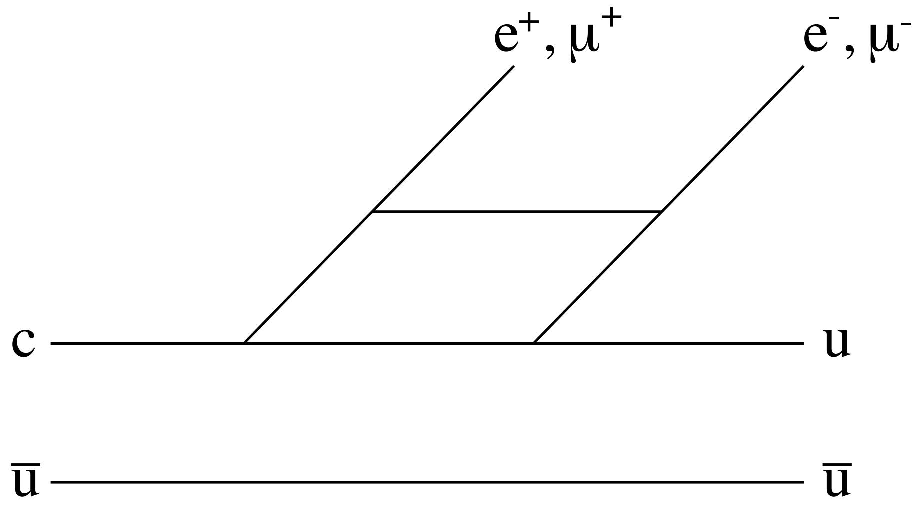
arXiv:1003.2345

- BES III expects to reach 2-17×10^{-8} with 20fb^{-1}.
- SFFs should reach limits of ~10^{-8}.
- LHCb expected to encounter a wall from systematic errors at ~ 2.4 × 10^{-8}...

$D \to u\ell^+\ell^-$

- Inclusive branching fraction ~0.8×10^{-8} [charged rate ~×2]

$$\frac{d\Gamma_{c\to u\ell^+\ell^-}}{d\hat{s}} = \tau_D \frac{G_F^2\alpha^2 m_c^6}{768\pi^5}(1-\hat{s})^2\left[\left(\left|C_9^{(\prime)\ \mathrm{eff}}(m_c)\right|^2 + |C_{10}|^2\right)(1+2\hat{s}) + 12\, C_7^{\mathrm{eff}}(m_c)\ \mathrm{Re}\left[C_9^{(\prime)\ \mathrm{eff}}(m_c)\right] + 4\left(1+\frac{2}{\hat{s}}\right)\left|C_7^{\mathrm{eff}}(m_c)\right|^2\right]$$



+ LD contributions.

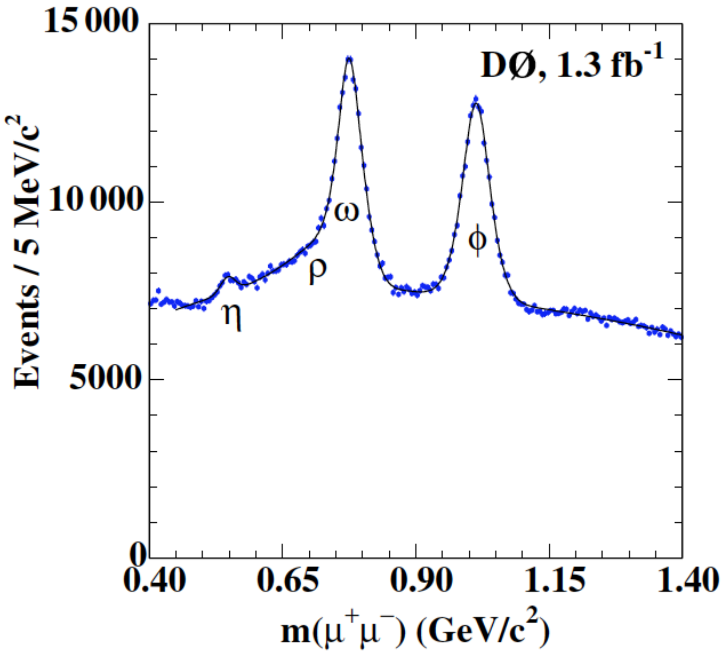
Differential rate is dominated by contributions from Φ and ω resonances.

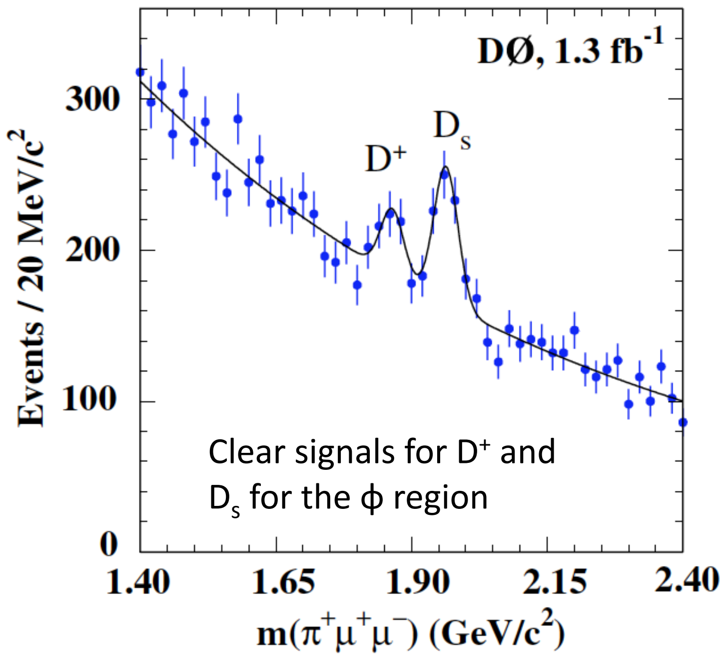
LD saturates SD effects, but NP enhancements can be clearly determined (away from resonant structure).

Burdman & Shipsey hep-ph/0310076

$D \to u\ell^+\ell^-$: The D0 result

- D0 searched for $c \to u\mu^+\mu^-$ transitions: PRL **100** 101801 (2008)
  - Clearly visible signal around resonances, however there is a lot of background...

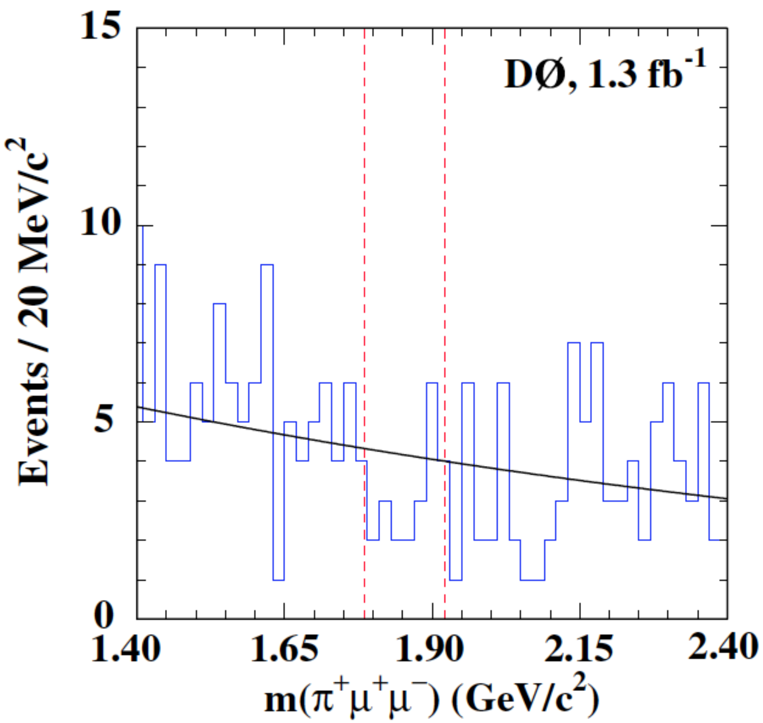




CLEO, FOCUS and BaBar have results on FCNC searches as well

$D \to u\ell^+\ell^-$: The D0 result

- D0 searched for $c \to u\mu^+\mu^-$ transitions: PRL **100** 101801 (2008)
  - Vetoing the resonance however shows no evidence for signal...



D0 place an upper limit on this channel of (excluding the ϕ):

$$< 3.9 \times 10^{-6} \ (90\%, C.L.)$$

Given that enhancement depends on q^2 of the di-lepton pair, we want to analyse both ee and μμ channels.

SuperB should be able to probe sensitivities down to ~1×10^{-8}.

Search results from BaBar

Search for Rare and Forbidden Semileptonic Charm Decays

$$X_c^+ \to h^\pm l^\mp l^\pm (X_c^+ = D^+, D_s^+, \Lambda_c^+)$$

BABAR preliminary

Search for FCNC processes, LFV decays, LNV violating decays

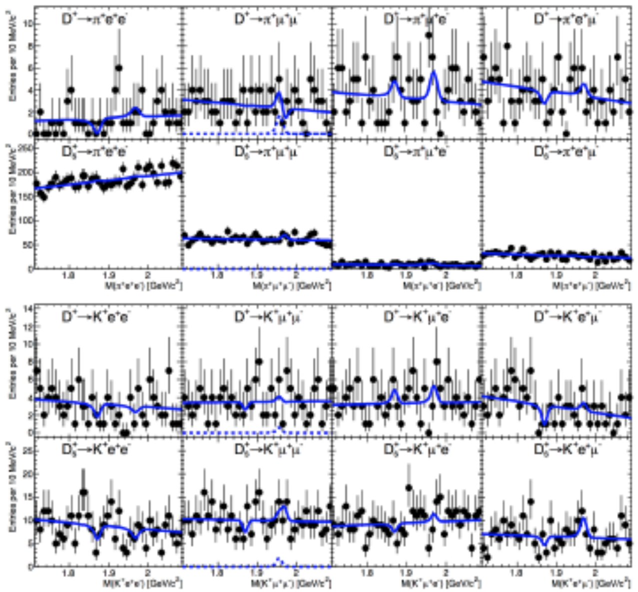
Hadrons are either kaons or pions (protons)

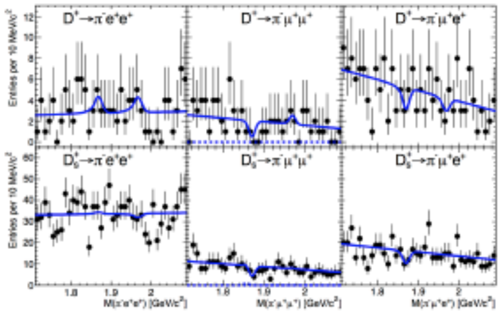
Leptons are either muons or electrons

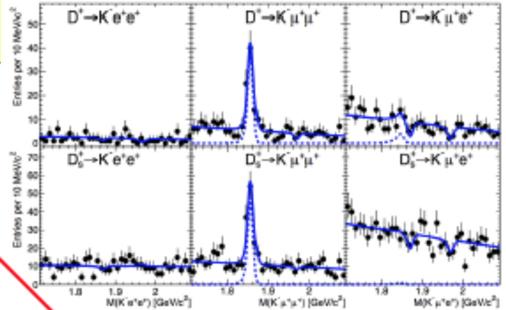
Total of 35 decay modes analyzed

Branching fractions normalized to D^+ and D_s^+ to $\varphi\pi^+$ or Λ_c to $pK\pi$

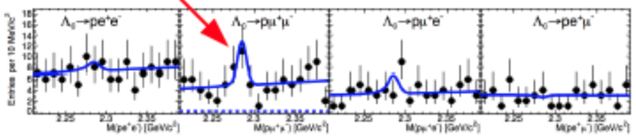
No observation of new signal, improvement over previous results

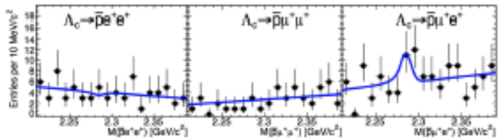






Most significant signal 2.6σ (stat. only)





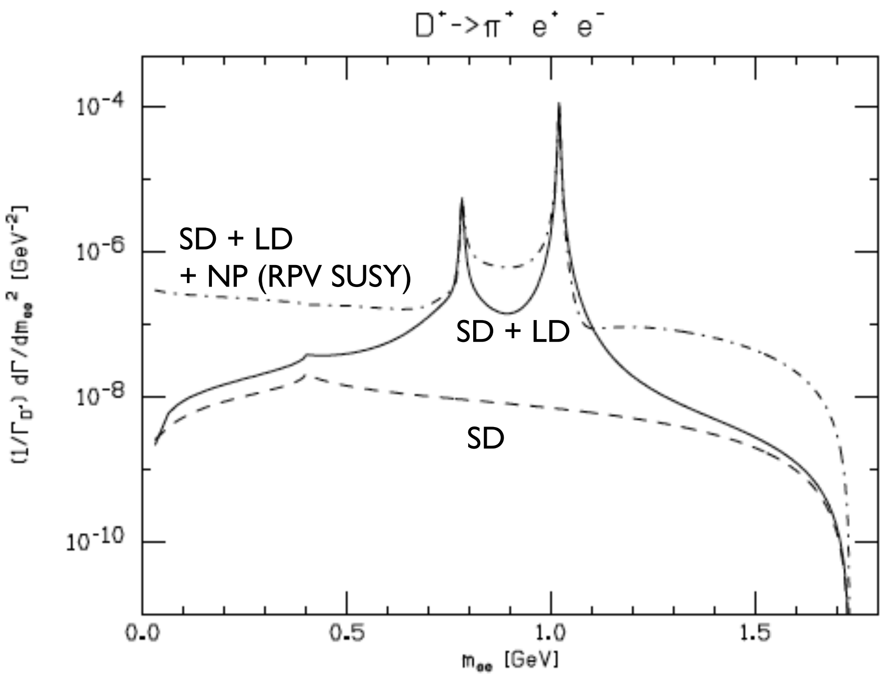
Limits on branching fractions between 1×10^{-6} and 44×10^{-6}

June 23, 2011 R. M. White, ICPP-II 2011, Istanbul, Turkey 14

$D \to u\ell^+\ell^-$

- Exclusive BRs:

Channel	Sensitivity	BR (th.)	UL (expt.)
$D^0 \to \pi^0\ell^+\ell^-$	2×10^{-8}	0.8×10^{-6}	4.5×10^{-5} (CLEO)
$D^+ \to \pi^+\ell^+\ell^-$	1×10^{-8}	2×10^{-6}	$< 3.9 \times 10^{-6}$ (D0)
$D^0 \to \pi^0 e^\pm\mu^\mp$	2×10^{-8}	–	
$D^+ \to h^-\ell^+\ell^+$ $(h = \pi, K)$	1×10^{-8}	–	$< 3.6 \times 10^{-6}$ (CLEO)
$D^+ \to h^- e^\pm\mu^\mp$ $(h = \pi, K)$	1×10^{-8}	–	$< 3.4 \times 10^{-6}$ (CLEO)



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Burdman & Shipsey hep-ph/0310076

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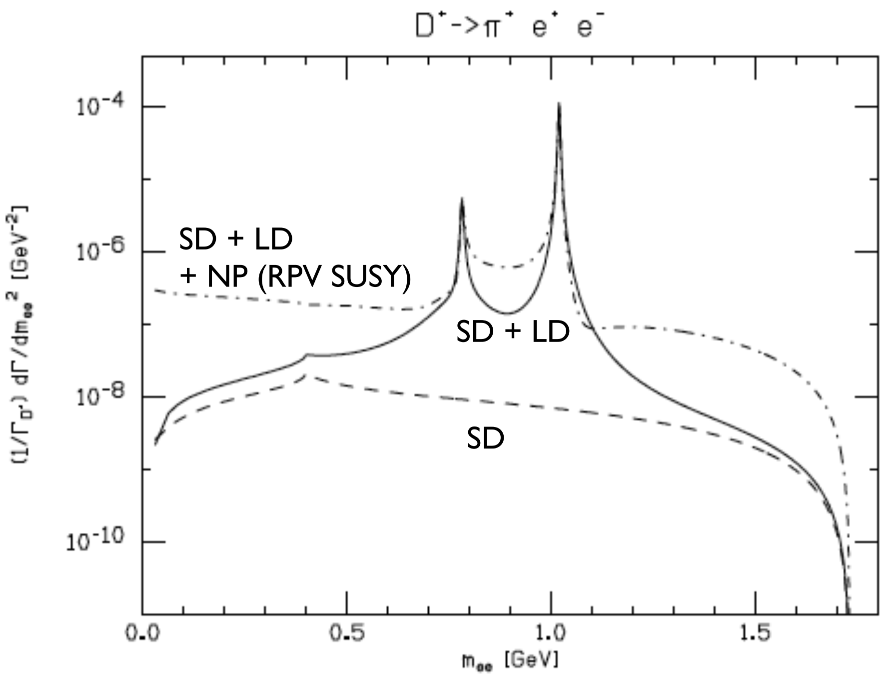

Broadly speaking there are 3 regions of interest:

- Low q^2 (below resonances)
- High q^2 (above resonances)
- in between resonances (challenging?)

Easier to see NP effects away from resonant structure.

SuperB can start probing this.

Burdman & Shipsey hep-ph/0310076

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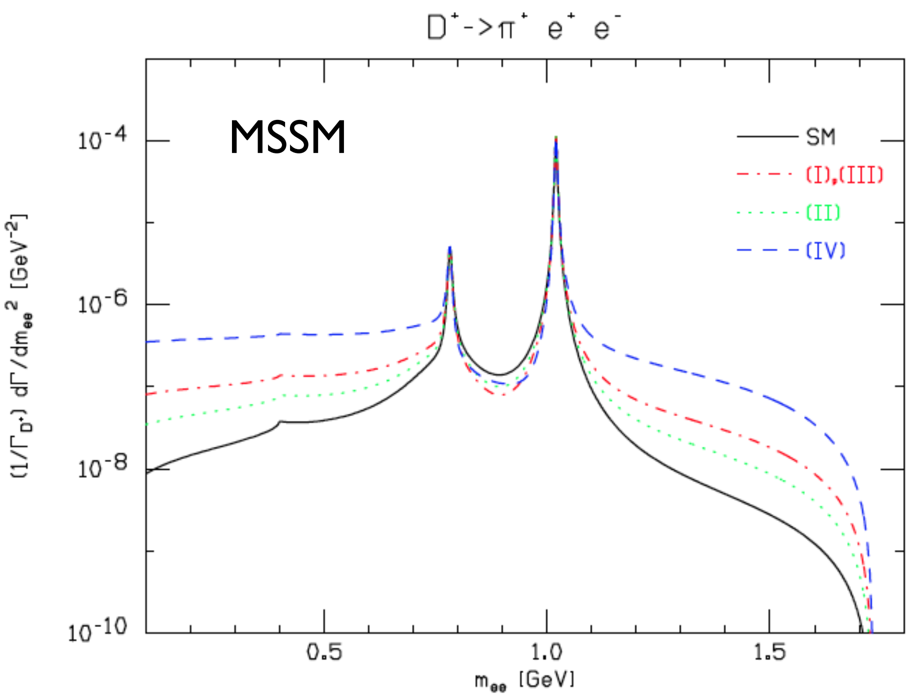

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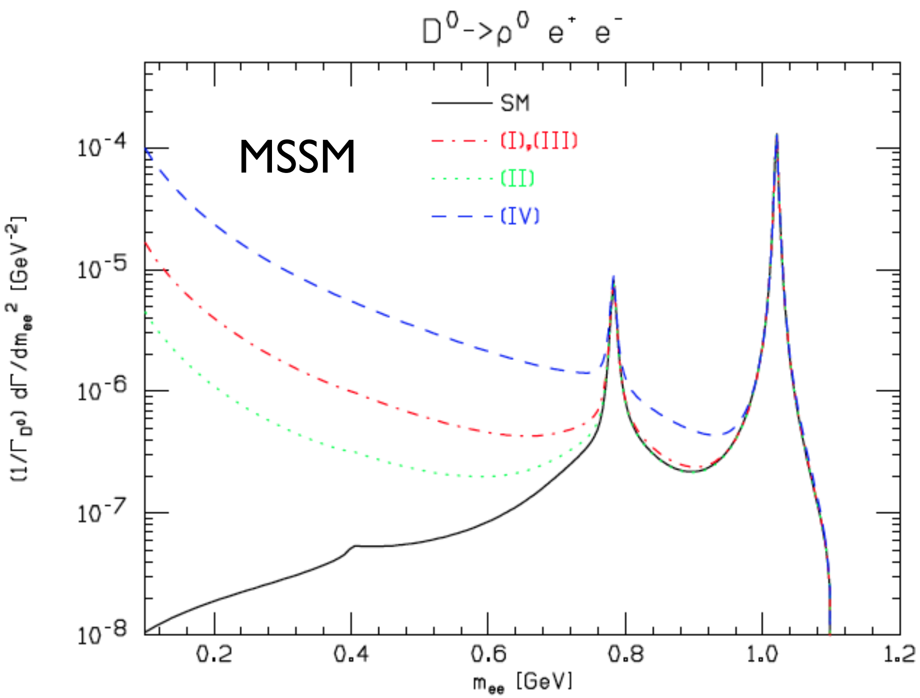


N.B. $\rho\ell\ell$ has a larger enhancement at low di-lepton mass.

Experimentally more challenging, but could provide a clearer signal for NP.

Low q^2 region is of most interest, so e^+e^- is potentially much more interesting than $\mu^+\mu^-$.

Burdman & Shipsey hep-ph/0310076

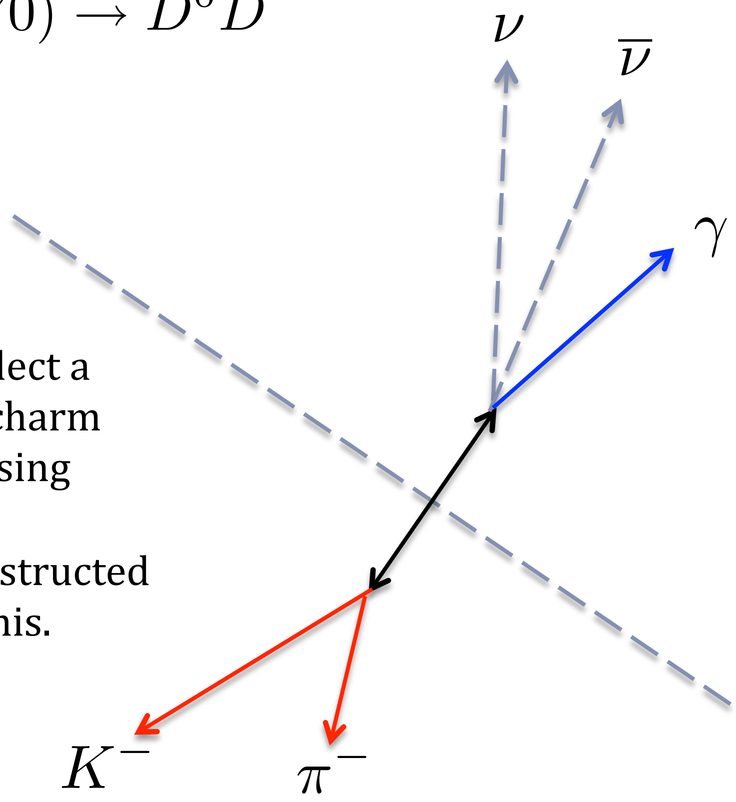
Final states with missing energy

$$D \to \nu\overline{\nu}(+\gamma)$$

$$D \to X_u\nu\overline{\nu}$$

D recoil method

- Here we need to resort to D recoil methodology to reconstruct the event.
  - e.g. $\psi(3770) \rightarrow D^0\overline{D}^0$



• Missing energy used to discriminate signal from background.
• Any other particles in the event can be used to add discrimination.

• Use tag D to select a pure sample of charm decays with missing energy.
• Use fully reconstructed final states for this.

Cartoon of the CM frame

$D \to \nu\overline{\nu}(+\gamma)$

- Helicity suppressed in the Standard Model
  - BF ~ 1.1×10^{-30}
  - The final state with a photon is much more copious: 10^{-14}
  - Beyond the SM one could find significant enhancements
    - e.g. scalar particles such as DM candidates: PRD **82**:034005, 2010.
  - Require either an isolated photon in the detector ($\nu\overline{\nu}\gamma$), or nothing ....
    - Experimentally challenging: backgrounds include where both particles go down the beam pipe... e.g. $D \to K\pi$
    - $\nu\overline{\nu}\gamma$ has the added advantage of the photon (and smaller allowed phase space for NP).
    - Also worth searching for the corresponding D_s decays ... see next topic.

+ Analogues for $B_{d,s}$ and K decays

$D \to X_u \nu \overline{\nu}$

- Similar to the invisible decay searches...
  - Can perform inclusive or exclusive measurements, both sets of measurements will provide more information to constrain NP.
    - Analogy with $B \to X \nu \overline{\nu}$
    - Similar interest for $D_s \to X_s \nu \overline{\nu}$
  - LD contributions should be small, and SM rate is tiny

$$\mathcal{B}(B^+ \to X_u \nu \overline{\nu}) \simeq 1.2 \times 10^{-15}$$
$$\mathcal{B}(B^0 \to X_u \nu \overline{\nu}) \simeq 5 \times 10^{-16}$$

Bigi & Paul arXiv:1110.2862

$D \to X_u \nu\overline{\nu}$

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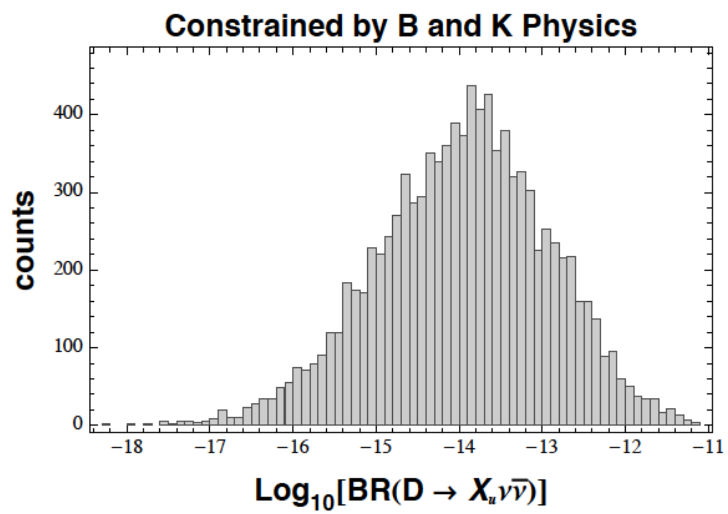
$$\begin{aligned}\mathcal{B}(B^+ \to X_u\nu\overline{\nu}) &\simeq 1.2 \times 10^{-15} \\ \mathcal{B}(B^0 \to X_u\nu\overline{\nu}) &\simeq 5 \times 10^{-16}\end{aligned}$$

• Large enhancements possible in NP models
  - Up to ×1000 in LHT models

• Plausibly could reach ~10^{-8} with SuperB at threshold, need to study potential for D* tagged samples.

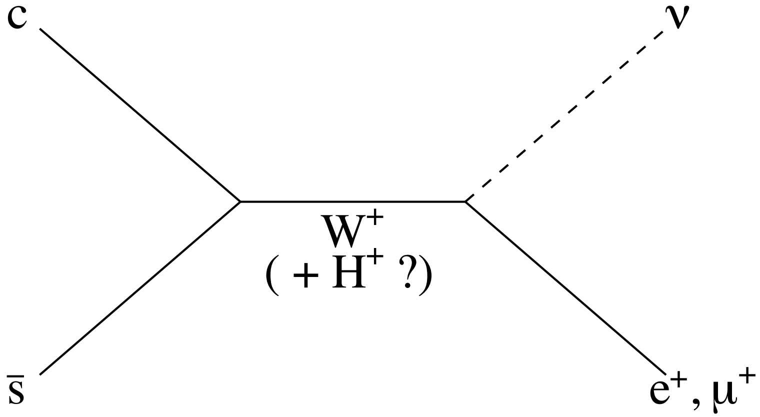
• π^0 mode is worth searching for as an indication for CPV.



Bigi & Paul arXiv:1110.2862

$D^+_{(s)} \to \ell^+ \nu_\ell$

- Complementary to $B^+ \to \ell^+ \nu_\ell$



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

$$\Gamma(D_s^+ \to \ell^+\nu) = \frac{G_F^2}{8\pi} f_{D_s^+}^2 m_\ell^2 M_{D_s^+} \left(1 - \frac{m_\ell^2}{M_{D_s^+}^2}\right)^2 |V_{cs}|^2$$

- Can also test lepton universality with ratios of rates.

- Lots of excitement a few years ago because of a discrepancy with f_{Ds} from lattice ... unfortunately this was not a sign of NP.
- CLEO find:

$$\begin{aligned} \mathcal{B}(D_s^+ \to e^+\nu) &= < 1.2 \times 10^{-4} (90\% \, C.L.) \\ \mathcal{B}(D_s^+ \to \mu^+\nu) &= (0.565 \pm 0.045 \pm 0.017)\% \\ \mathcal{B}(D_s^+ \to \tau^+\nu) &= (6.42 \pm 0.81 \pm 0.18)\% \end{aligned}$$

- which are compatible with SM expectations.

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Summary

- Indication of luminosities required to reach 0.5% statistical precision on different modes vs. precision at $500fb^{-1}$:

Channel	Integrated luminosity (fb^{-1})	Integrated luminosity (fb^{-1})	precision with $500fb^{-1}$ (% stat.)
$D^0 \to K^- e^+ \nu_e$	1.3	33	0.03
$D^0 \to K^{*-} e^+ \nu_e$	17	425	0.09
$D^0 \to \pi^- e^+ \nu_e$	20	500	0.10
$D^0 \to \rho^- e^+ \nu_e$	45	1125	0.15
$D^+ \to K_S^0 e^+ \nu_e$	9	225	0.07
$D^+ \to \bar{K}^{*0} e^+ \nu_e$	9	225	0.07
$D^+ \to \pi^0 e^+ \nu_e$	75	1900	0.19
$D^+ \to \rho^0 e^+ \nu_e$	110	2750	0.23
$D_s^+ \to \phi e^+ \nu_e$	85	2200	0.21
$D_s^+ \to K_S^0 e^+ \nu_e$	1300	33000	0.81
$D_s^+ \to K^{*0} e^+ \nu_e$	1300	33000	0.81

Summary

Channel	Sensitivity
$D^0 \to e^+e^-$, $D^0 \to \mu^+\mu^-$	1×10^{-8}
$D^0 \to \pi^0 e^+e^-$, $D^0 \to \pi^0\mu^+\mu^-$	2×10^{-8}
$D^0 \to \eta e^+e^-$, $D^0 \to \eta\mu^+\mu^-$	3×10^{-8}
$D^0 \to K^0_S e^+e^-$, $D^0 \to K^0_S\mu^+\mu^-$	3×10^{-8}
$D^+ \to \pi^+ e^+e^-$, $D^+ \to \pi^+\mu^+\mu^-$	1×10^{-8}
$D^0 \to e^\pm\mu^\mp$	1×10^{-8}
$D^+ \to \pi^+ e^\pm\mu^\mp$	1×10^{-8}
$D^0 \to \pi^0 e^\pm\mu^\mp$	2×10^{-8}
$D^0 \to \eta e^\pm\mu^\mp$	3×10^{-8}
$D^0 \to K^0_S e^\pm\mu^\mp$	3×10^{-8}
$D^+ \to \pi^- e^+e^+$, $D^+ \to K^- e^+e^+$	1×10^{-8}
$D^+ \to \pi^- \mu^+\mu^+$, $D^+ \to K^- \mu^+\mu^+$	1×10^{-8}
$D^+ \to \pi^- e^\pm\mu^\mp$, $D^+ \to K^- e^\pm\mu^\mp$	1×10^{-8}

- Great potential to search for NP and understand the rare branching fractions in charm.
- Threshold running will give SuperB another angle, and make it competitive compared to the previous generation.
  - Was not always the case with 4S for BaBar and Belle.

Summary

- A number of interesting rare decays to study
  - In many cases can complements searches that can be performed at φ and ϒ(4S) resonances.
  - Provides a clean environment to study low multiplicity states:
    - Help understand the detector hermiticity for more complicated environments such as ϒ(4S) and ϒ(5S).
  - Correlations between decays need to be understood
    - i.e. what can we learn about NP from this set of modes.
    - & where do long distance contributions wash out NP effects?
  - Many interesting decays have been ignored, and quite a few discussed here need to be studied in detail on SuperB
    - If people want to work on this area, extra effort would be welcome.
    - .... lets start the discussion.