Rare charm decays

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On behalf of the LHCb Collaboration.

NIKHEF

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Outline

- Introduction on rare decays
- Results on flavour changing neutral currents
  - $X_c \to h\ell^+\ell^-$
  - $D^0 \to \ell^+\ell^-$
  - $D^0 \to \gamma\gamma$
- Results on forbidden decays
- Conclusions

Introduction

- Rare decays are a crucial place to look for new physics
- Higher energy scales than direct production are *virtually* accessible
- In the *down* sector (K and B) they have been extensively studied and are playing a major role in constraining beyond the Standard Model scenarios
- In the *charm* sector theoretical uncertainties are larger and less effort was devoted to these processes in the past
- However how the experimental limits are approaching the SM predictions a renewed interest is growing
- This talk will review some experimental results on rare decays: apologies for the ones I am not able to cover!

  For future prospects: see M. Gersabeck talk on Thursday.

Rare decays in charm

Flavour changing neutral currents

- Flavour changing neutral currents are very rare in SM being suppressed by absence of tree level diagrams and by GIM mechanism
- FCNC in Charm are even more suppressed due to absence of high mass down-type quark
- Many new physics scenarios can therefore contribute enhancing these processes with new particles running in the loops or even at tree level
- Some models predict enhancements in the *up* sector only

Forbidden decays

- Lepton flavour, lepton number of baryon number violating decays are essentially forbidden in the Standard Model
- No theoretical uncertainties
- However in some new physics models they can be allowed at sizeable levels
- If not seen can put strong constraints on NP parameters

Flavour changing neutral currents: $c \to u\ell^+\ell^-$

Standard Model:

- Short distance contributions heavily suppressed by GIM mechanism

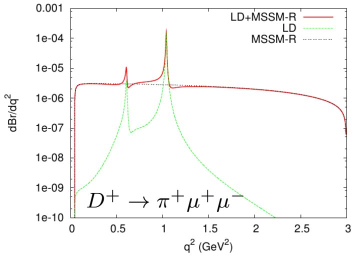
$$\mathcal{B}_{D^+ \to X_u^+ e^+ e^-} \simeq 2 \cdot 10^{-8} \qquad \mathcal{B}_{D^0 \to X_u^0 e^+ e^-} \simeq 8 \cdot 10^{-9}$$

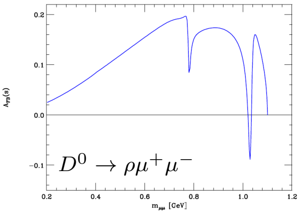
- SM rate dominated by long distance contribution due to $D \to XV \to X\ell^+\ell^-$ where $V = \phi, \rho, \omega$
- Long distance contribution are of non-perturbative nature giving large theoretical errors
- Branching fractions at 10^{-6}, but non-resonant part is at the level of 10^{-7}
- Outside of the resonances (both low and high q^2) there is still big room to discover new physics contributions

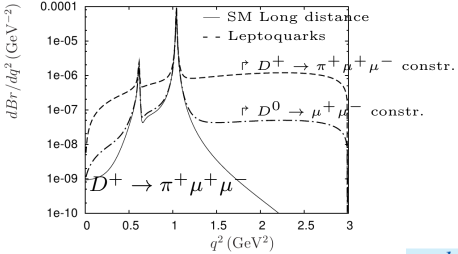
[Phys.Rev. D66 (2002) 014009]

Flavour changing neutral currents: $c \to u\ell^+\ell^-$ new physics

- Different new physics scenarios allow for enhancement of FCNC processes
- MSSM$\not{R}_p$ gives large contributions
  [Phys.Rev. D66 (2002) 014009]
- Leptoquarks can also contribute
  [Phys.Rev. D79 (2009) 017502]
- For $D^0 \to \rho^0\mu^+\mu^-$ also forward backward asymmetry

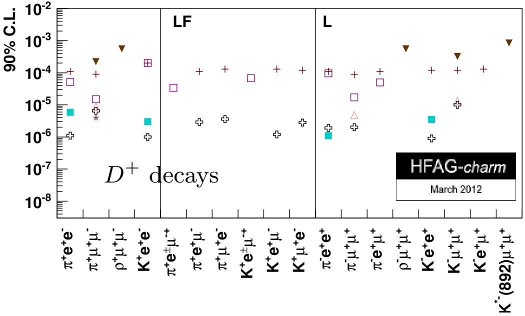


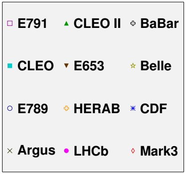


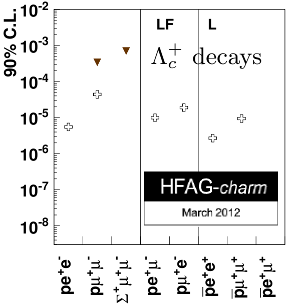


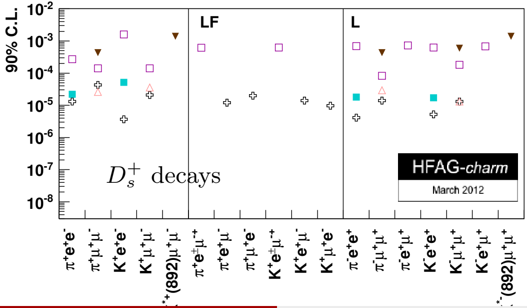
Note: plots with not up to date experimental limits.

Overview of charged rare decays









[HFAG]

$X_c^{\pm} \to h^{\pm}\ell^{+}\ell^{-}$ at BaBar

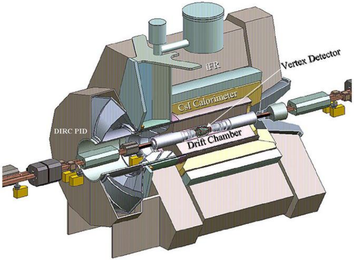
Large number of channels studied recently at BaBar

[Phys.Rev. D84 (2011) 072006]

Data: 347 fb^{-1} at the $\Upsilon(4S)$ plus 37 fb^{-1} below it

Selection:

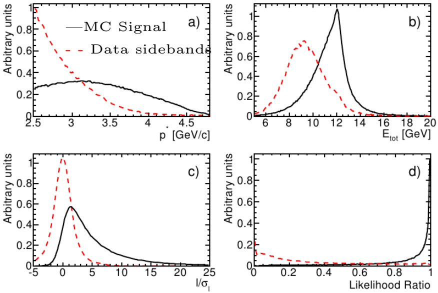
- Two charged tracks identified as leptons plus one as hadron
- ϕ resonance region excluded in invariant mass
- QED background suppressed requiring high multiplicity
- Combinatorial suppressed by requirement on momentum, χ^2 of the secondary vertex fit and $DOCA < 250\mu m$ for the two leptons



For more on RD at BaBar see O. Long dedicated talk.

$X_c^\pm \to h^\pm \ell^+ \ell^-$ at BaBar

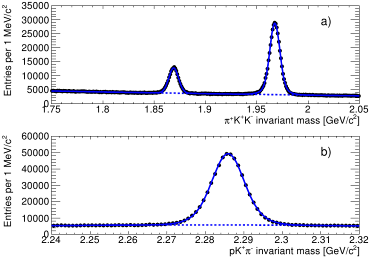
- A Likelihood ratio is used to further discriminate signal from combinatorial background.
- Variables: p^* of charmed candidate, total energy in the event, flight length significance
- PDFs are empirical combinations of functions providing good description of data
- Signal from MC simulations, background from data invariant mass sidebands
- Both likelihood and its cut value optimized for the single channels



$X_c^\pm \to h^\pm \ell^+ \ell^-$ at BaBar

Normalization:

- $D^+_{(s)}$ channels are normalized to $D^+_{(s)} \to \phi(KK)\pi$ decays
- Λ_c^+ normalized to $\Lambda_c^+ \to pK^-\pi^+$
- Very same selection with the exception of the likelihood and particle ID
- Fits to the invariant mass to extract the signal yields



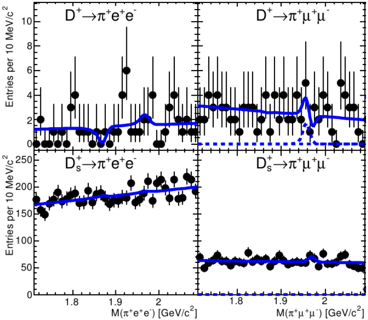
Signal extraction:

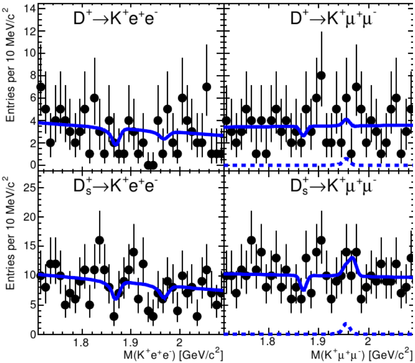
- Unbinned extended maximum likelihood fit to invariant mass
- Crystal Ball function for the signal to take into account radiative tail
- First order polynomial for combinatorial background
- Mis-identified hadronic charm decays included in the fit even if significantly (15 Mev/c^2) displaced in mass

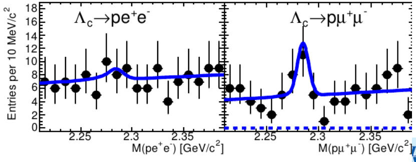
[Phys.Rev. D84 (2011) 072006]

$X_c^{\pm} \to h^{\pm}\ell^{+}\ell^{-}$ at BaBar

[Phys.Rev. D84 (2011) 072006]







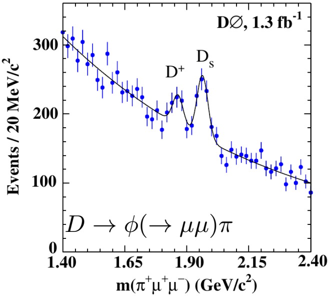
Decay	UL on $\mathcal{B}$ in 10^{-6} at 90% CL
$D^{+} \to \pi^{+}e^{+}e^{-}$	1.1
$D^{+} \to \pi^{+}\mu^{+}\mu^{-}$	6.5
$D_s^{+} \to \pi^{+}e^{+}e^{-}$	13
$D_s^{+} \to \pi^{+}\mu^{+}\mu^{-}$	43
$D^{+} \to K^{+}e^{+}e^{-}$	1.0
$D^{+} \to K^{+}\mu^{+}\mu^{-}$	4.3
$D_s^{+} \to K^{+}e^{+}e^{-}$	21
$D_s^{+} \to K^{+}\mu^{+}\mu^{-}$	14
$\Lambda_c^{+} \to pe^{+}e^{-}$	5.5
$\Lambda_c^{+} \to p\mu^{+}\mu^{-}$	44

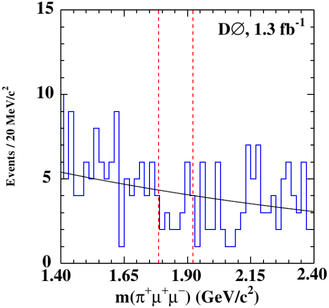
$D^+ \to \pi^+\mu^+\mu^-$ at DØ

- 1.3 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
- Pairs of muons with $p_T > 2$ GeV/c and $\sum p > 3$ GeV/c
- Pion impact parameter significance, D transverse flight length significance, collinearity angle, vertex fit χ^2 and angular separation are used for a preselection and for a tighter one
- Normalized to $D^+ \to \pi^+\phi(\to \mu^+\mu^-)$
- Both D^+ and $D_s^+ \to \pi^+\phi(\to \mu^+\mu^-)$ seen at the expected level
- No signal outside the ϕ resonance $(0.96 < m(\mu\mu) < 1.06\text{GeV/c}^2)$

$\mathcal{B}_{D^+\to\pi^+\mu^+\mu^-} < 3.9 \cdot 10^{-6}$ at 90%CL

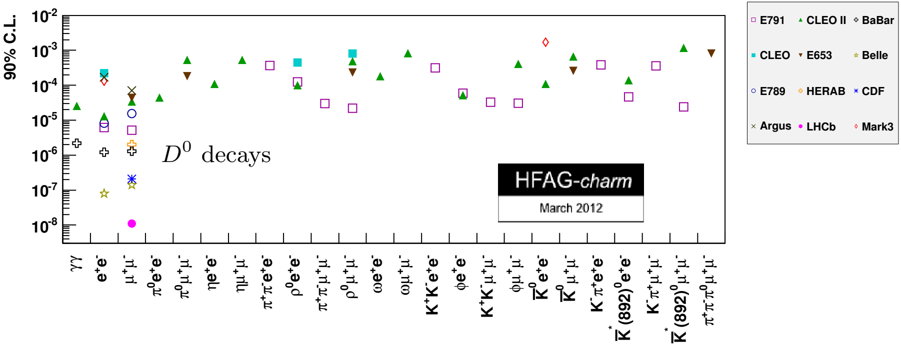
[Phys.Rev.Lett. 100 (2008) 101801]





Overview of $X_c^0 \to X^0 l^+ l^-$ decays

Results on corresponding decays for D^0 decays are at least 10 years old
Best upper limits are from E791 [Phys.Rev.Lett. 86 (2001) 3969-3972] and CLEO II [Phys.Rev.Lett. 76 (1996) 3065-3069] collaborations for most of the channels



[HFAG]

$X_c^0 \to X^0 l^+ l^-$ decays at E791

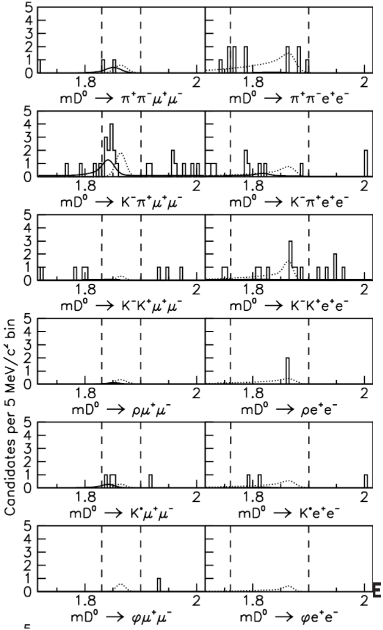
E791 Analysis

- $2 \cdot 10^{10}$ events of 500 GeV/c π^- beam to target
- Well separated secondary vertex
- Blind analysis optimized on MC
- Normalized on correspondent hadronic modes (*e.g.* $D^0 \to K^{0*}\pi\pi$ for $K^{0*}\ell\ell$)
- Mis-ID background removed by kinematic vetoes

No signal seen, all limits at the level of 10^{-5}

e.g. $\mathcal{B}_{D^0 \to \rho^0 \mu^+ \mu^-} < 2.2 \cdot 10^{-5}$ at 90%CL

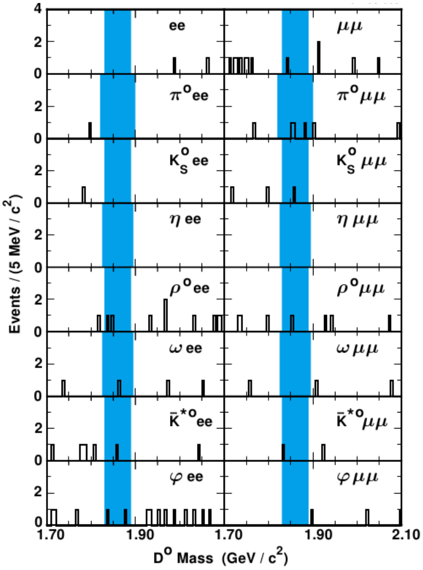
[Phys.Rev.Lett. 86 (2001) 3969-3972]



$X_c^0 \to X^0 l^+ l^-$ decays at CLEO II

- Data: 3.85 fb^{-1} of e^+e^- collisions at and just below the $\Upsilon(4S)$
- $D^0 \to X\ell\ell$ where $X = \eta \to \gamma\gamma$, $\pi^0 \to \gamma\gamma$, $K_S^0 \to \pi^+\pi^-$, $\rho \to \pi^+\pi^-$, $\omega \to \pi^+\pi^-\pi^0$, $K^{*0} \to K^-\pi^+$, $\phi \to K^+K^-$
- D^* tagged analysis
- PID with dE/dx, calorimeter, TOF and muon chambers for charged tracks
- No signal seen, limits are in the $10^{-5} - 10^{-4}$ range
  e.g. $\mathcal{B}_{D^0\to\pi^0 e^+e^-} < 4.5 \cdot 10^{-5}$ at 90% CL

[Phys.Rev.Lett. 76 (1996) 3065-3069]

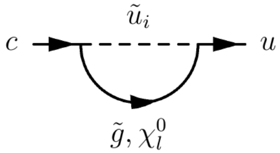


$D^0 \to \gamma\gamma$

- SM short distance contribution at 3×10^{-11}
- Long distance contribution mainly due to Vector Meson Dominance, predicted to be [Phys.Rev. D66 (2002) 014009]

$$\mathcal{B}^{VMD}_{D^0\to\gamma\gamma} \simeq 3.5^{4.0}_{-2.6} \cdot 10^{-8}$$

- However $c \to u\gamma$ process can be enhanced up to $6 \cdot 10^{-6}$ (200 times the SM) level in MSSM [Phys.Lett. B500 (2001) 304-312]



$D^0 \to \gamma\gamma$ at BaBar

[BaBar submitted to Physical Review D]

- 470.5 fb^{-1} of e^+e^- collisions
- MC events to optimize the selection criteria
- $D^{*+} \to D^0\pi^+$ tagged analysis
- Normalization to $D^0 \to K^0_S\pi^0$ decay
- Same analysis applied to reconstruct $D^0 \to \pi^0\pi^0$

Selection

- Pairs of photons with $1.7 < m_{\gamma\gamma} < 2.1\mathrm{GeV/c}^2$
- $0.74 < E_\gamma < 4$ GeV and $0.05 < p_\pi < 0.45$ GeV/c
- Kinematic fit of the D^0 candidate and constrain to the primary vertex
- QED background rejected requiring $N^\pm > 4$ and $N^0 > 4$
- Large background from $D^0 \to \pi^0\pi^0$ rejected with π^0 veto

Note: don't miss H. Muramatsu talk about $D^0 \to \gamma\gamma$ at BESIII, on Wednesday!

$D^0 \to \gamma\gamma$ at BaBar

Fit procedure:

- Unbinned maximum likelihood fit to invariant mass
- $D^0 \to \gamma\gamma$ signal: crystal ball and bifurcated gaussian
- Combinatorial background: 2^{nd} order Chebychev polynomial
- $D^0 \to \pi^0\pi^0$ background Crystal Ball function

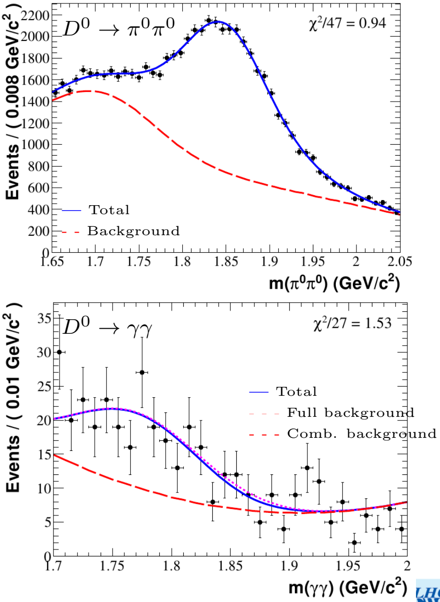
Results:[BaBar submitted to Physical Revew D]
Measured a $D^0 \to \pi^0\pi^0$ branching fraction:

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

For $D^0 \to \gamma\gamma$ found negative signal yield $N = -6 \pm 15$ events leading to an upper limit:

$$\mathcal{B}_{D^0\to\gamma\gamma} < 2.2 \cdot 10^{-6} \quad \text{at90\%CL}$$

which is constraints NP to at most 70 times the SM.

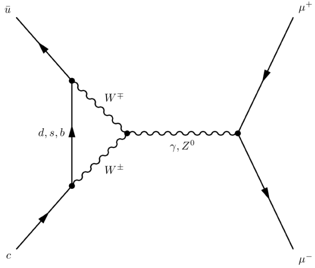


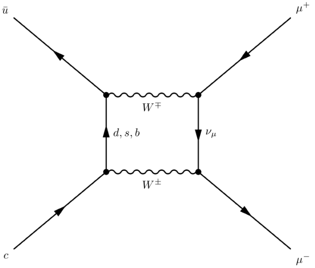
$D^0 \to \mu^+\mu^-$ decay: Standard Model

- Highly suppressed in the Standard Model. Short distance contribution $(D^0 \to \mu^+\mu^-) \simeq 10^{-18}$
- Dominated by long distance contribution in particular from $D^0 \to \gamma\gamma$: $\mathcal{B}(D^0 \to \mu^+\mu^-) \simeq 2.7 \times 10^{-5} \mathcal{B}(D^0 \to \gamma\gamma)$

  [Phys.Rev. D66 (2002) 014009]

  which gives an estimate: $\mathcal{B}(D^0 \to \mu^+\mu^-) \gtrsim 10^{-13}$
- Using BaBar upper limit: [BaBar 2011]: $\mathcal{B}(D^0 \to \gamma\gamma) < 2.2 \times 10^{-6}$ at 90% C.L. one could estimate an upper limit on this contribution of $\mathcal{B}(D^0 \to \mu^+\mu^-) \lesssim 6 \times 10^{-11}$
- $D^0 \to e^+e^-$ even more suppressed





$D^0 \to \mu^+\mu^-$ decay: new physics

- Different NP scenarios give rise to possible contributions
- $\mathcal{B}$ related to $D^0 - \bar{D}^0$ mixing rate
- MSSM gives negligible contribution
- One of the largest contributions is from $\not{R}_p$ SUSY

  $\mathcal{B}^{\not{R}_p}_{D^0 \to \mu^+\mu^-} \simeq 4.8 \times 10^{-7} x_{\rm D} \left(\frac{300 \text{ GeV}}{m_{\tilde{d}_k}} \right)^2 \leq 4.8 \times 10^{-9} \left(\frac{300 \text{ GeV}}{m_{\tilde{d}_k}} \right)^2$

  [Phys.Rev. D79 (2009) 114030]
- Contributions from Lepto-Quark were calculated to be even larger at the level $\mathcal{B} \simeq 5 \cdot 10^{-7}$ and are being already strongly constrained by current experimental limits.

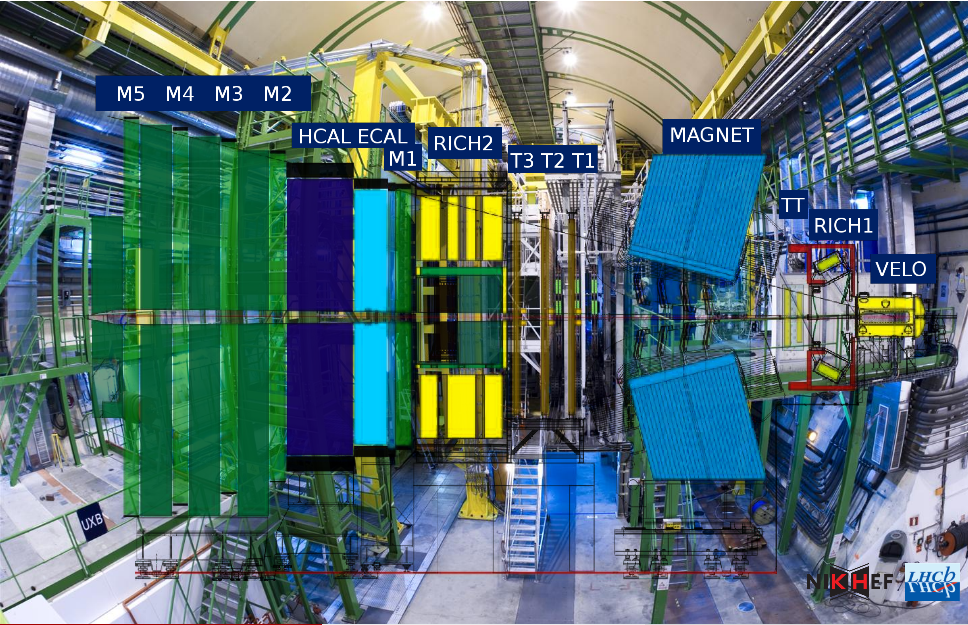
  [Phys.Lett. B672 (2009) 172-176]

Model	$\mathcal{B}_{D^0 \to \mu^+\mu^-}$
Experiment	$\leq 1.3 \times 10^{-6}$
Standard Model (SD)	$\sim 10^{-18}$
Standard Model (LD)	$\sim$ several $\times 10^{-13}$
$Q = +2/3$ Vectorlike Singlet	4.3×10^{-11}
$Q = -1/3$ Vectorlike Singlet	1×10^{-11} $(m_S/500 \text{ GeV})^2$
$Q = -1/3$ Fourth Family	1×10^{-11} $(m_S/500 \text{ GeV})^2$
Z' Standard Model (LD)	$2.4 \times 10^{-12}/(M_{Z'}(\text{TeV}))^2$
Family Symmetry	0.7×10^{-18} (Case A)
RPV-SUSY	4.8×10^{-9} $(300 \text{ GeV}/m_{\tilde{d}_k})^2$

Constrained with $x_D \sim 1\%$

See also A. Petrov talk!

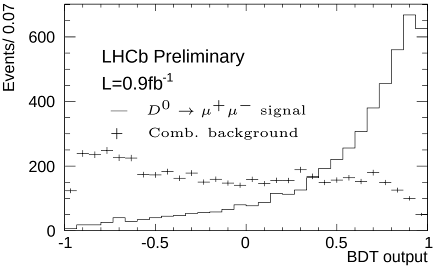
LHCb detector



$D^0 \to \mu^+\mu^-$ at LHCb

- 0.9 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV were used
- An additional sample of 79 pb^{-1} for background studies
- Monte Carlo generated samples with full detector simulation

- Tagged analysis: *i.e.* search for $D^{*+} \to D^0(\to \mu^+\mu^-)\pi^+$ decays
- Normalization to $D^{*+} \to D^0(\to \pi^+\pi^-)\pi^+$
- BDT to reject combinatorial background
- Single $\pi \to \mu$ mis-ID probability taken from $D^0 \to K^-\pi^+$
  Double mis-ID $p(D^0 \to \pi^+\pi^- \to \mu\mu) = (27.3 \pm 3.4 \pm 2.0) \cdot 10^{-6}$



$D^0 \to \mu^+\mu^-$ at LHCb

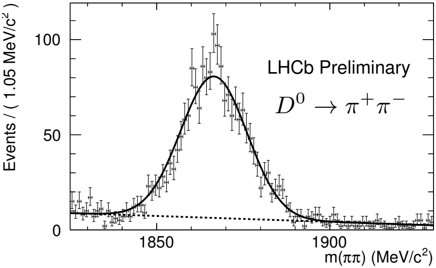
Normalization: $D^{*+} \to D^0(\to \pi^+\pi^-)\pi^+$ yield extracted with an unbinned extended two-dimensional fit in mass and Δm

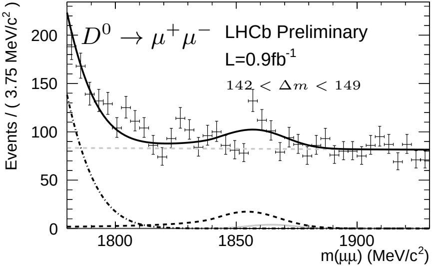
Single event sensitivity :

$$\alpha = (1.96 \pm 0.23) \cdot 10^{-10}$$

- Two-dimensional fit in M($\mu\mu$) and Δm
- Signal: gaussian(M) × double gauss (Δm)
- $D^0 \to \pi^+\pi^-$ mis-ID: Crystal Ball(M) × double gauss (Δm)
- $D^0 \to K^-\pi^+$ tail mis-ID: gaussian(M) × gaussian (Δm)
- Combinatorial background: expo(M) × f(Δm)
  $f(\Delta m) = \left(\frac{\Delta m}{a}\right)^2 (1 - e^{\frac{\Delta m - \Delta m_0}{c}}) + b \cdot (\frac{\Delta m}{d} - 1)$

[LHCb-CONF-2012-005]



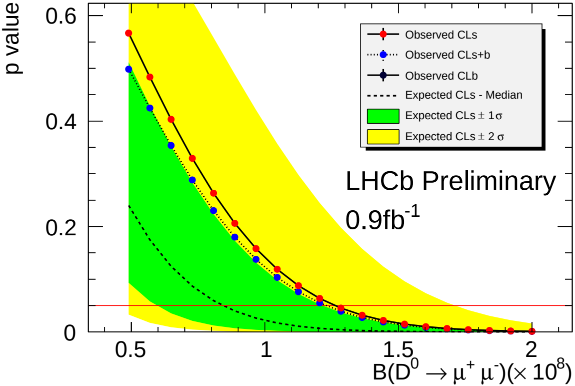


Upper limit on branching fraction

No significant excess is seen with respect to expected background therefore we set a preliminary upper limit on the branching fraction using the CLs method

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.3\ (1.1) \cdot 10^{-8} \quad \text{at 95 (90)\%CL}$$

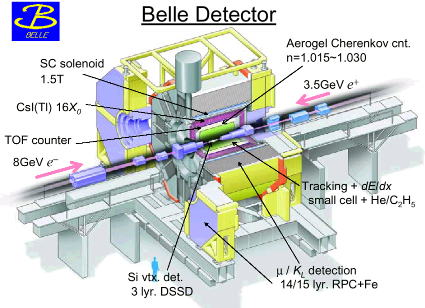
[LHCb-CONF-2012-005]



Stay tuned for new CMS results! See D. Pedrini talk.

$D^0 \to \ell^+\ell^-$ at Belle

- Data: 660 fb^{-1} in e^+e^- collisions at $\Upsilon(4S)$ and just below it
- Only $e^+e^- \to c\bar{c}$ (No B decays).
- $D^{*+} \to D^0\pi^+$ tagged analysis to improve purity
- First selection based on two charged tracks with standard PID
- Blind analysis optimized for single channels in E_{miss}, PID, and search window



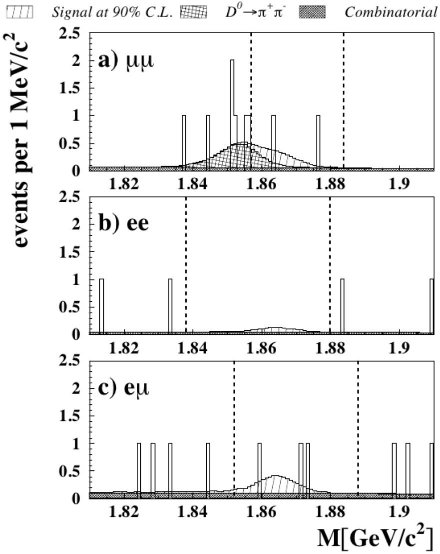
[Phys.Rev. D81 (2010) 091102]

$D^0 \to \ell^+\ell^-$ at Belle

- Normalization $D^0 \to \pi^+\pi^-$
- Peaking mis-ID background from $D^0 \to \pi^+\pi^-$ with single mis-ID estimated from $D^0 \to K^-\pi^+$
- Efficiencies from MC with corrections from data
- UL from extended Feldman-Cousins method
- Single event sensitivity $\sim 1 \cdot 10^{-7}$

Upper limits at 90% CL:

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.4 \cdot 10^{-7}$$
$$\mathcal{B}(D^0 \to e^+e^-) < 7.9 \cdot 10^{-8}$$
$$\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 2.6 \cdot 10^{-7}$$

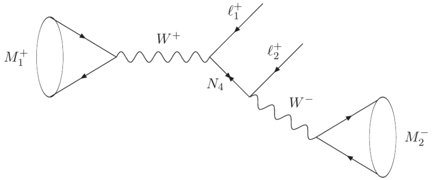


Best limits for ee and $e\mu$ final states.

[Phys.Rev. D81 (2010) 091102]

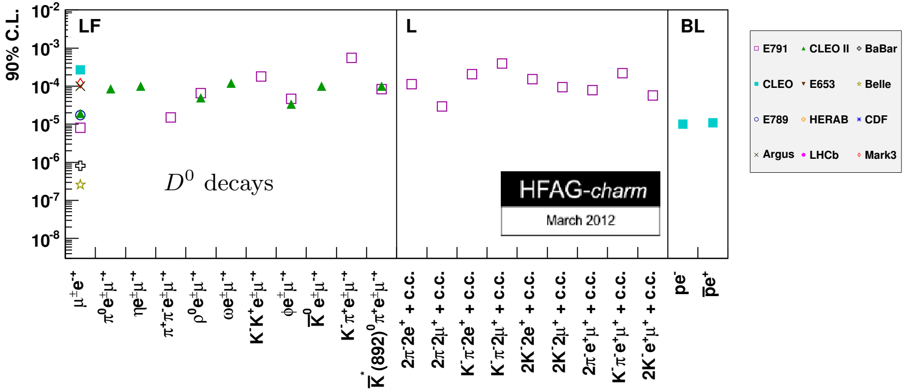
Lepton or baryon number violating decays

- Lepton flavour violating decays (e.g. $D^0 \to e^+\mu^-$, $D^+ \to \pi^+ e^+ \mu^-$ etc) are essentially forbidden in Standard Model
- Lepton number violating decays are forbidden in SM (e.g. $D^+ \to \pi^- \ell^+ \ell^+$).
- Baryon number violating decays (e.g. $D^0 \to p e^-$) are also forbidden
- However different NP models can allow such decays: $\not{R}_p$ SUSY, Leptoquarks, Majorana neutrinos
- Completely unambiguous probes of new physics



Overview of lepton or baryon number violating decays

Most of the limits are from the already mentioned E791, CLEOII (D^0) and BaBar ($D^+_{(s)}$ and Λ_c) papers

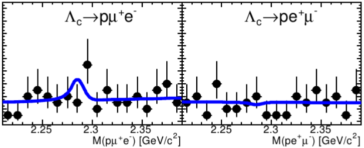


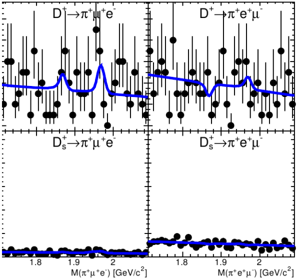
[HFAG]

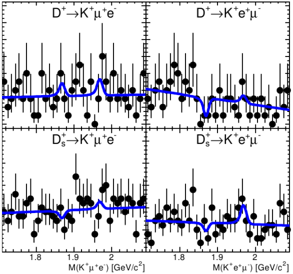
LFV at BaBar

- Same analysis shown for FCNC $D \to h\ell\ell$ decays
- No signal seen in any of the channels
- First and best limits for most of the channels
- Limits at the level of 10^{-6} (10^{-5}) for D^+ (D_s^+ and Λ_c)

[Phys.Rev. D84 (2011) 072006]

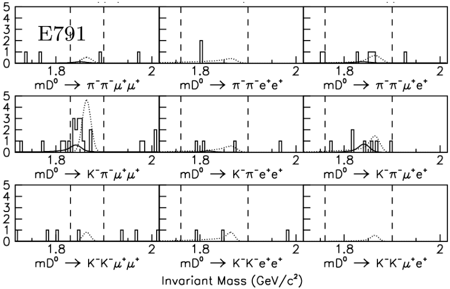




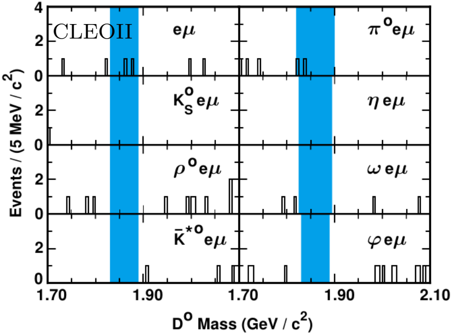


LFV at E791 and CLEOII

- Same analysis as for FCNC
- Background from $D^0 \to K\pi\pi\pi$



[Phys.Rev.Lett. 86 (2001) 3969-3972]



[Phys.Rev.Lett. 76 (1996) 3065-3069]

Conclusions

- Rare decays in charm are a fundamental tool to explore NP
- Long distance SM effects give large theoretical uncertainties
- Most of the experimental results are not yet hitting SM levels, but are constraining NP models
- LHC experiments have just started to explore rare charm decays and results are already interesting
- There is a large playground of 10 years old analyses which could be improved with current experiments
- While LHC upgrade and future *B* factories will continue the pursuit of NP in rare decays, a lot can be said by present experiments and experiments which have just ended data taking