Searches for Rare and Radiative Charm Decays – experimental review –

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on behalf of the LHCb Collaboration

Outline

Introduction & some History ...

Introduction

The search for *rare* and *forbidden* processes are fundamental for testing the Standard Model (SM) and looking for signals of New Physics (NP)

- Charm sector can provide constraints complementary/different than the K and B sectors
- Recall it was the the absence of flavor-changing neutral currents (FCNC) in K_L^0 decays that lead to the prediction of charm (GIM mechanism)
- Many NP models predict enhancements of rare processes and/or allow forbidden processes to occur

An historical overview....

20 years ago, back in 1994...

(... when doubly Cabibbo suppressed decays were still considered "rare"
– now $\mathcal{O}(10^6)$ $D^+ \to K^+\pi^+\pi^-$ are observed at LHCb!)

D^+ — Doubly Cabibbo suppressed (*DC*) modes, $\Delta C = 1$ weak neutral current (*C1*) modes, or Lepton Family number (*LF*) or Lepton number (*L*) violating modes

$K^+\pi^+\pi^-$	*DC*		< 5	$\times 10^{-3}$	CL=90%
$K^+K^+K^-$	*DC*		(5.2 ± 2.0)	$\times 10^{-3}$	
ϕK^+	*DC*		$(3.9\ ^{+2.2}_{-1.9})$	$\times 10^{-4}$	
$\pi^+e^+e^-$	*C1*		< 2.5	$\times 10^{-3}$	CL=90%
$\pi^+\mu^+\mu^-$	*C1*		< 2.9	$\times 10^{-3}$	CL=90%
$K^+e^+e^-$		[*ll*]	< 4.8	$\times 10^{-3}$	CL=90%
$K^+\mu^+\mu^-$		[*ll*]	< 9.2	$\times 10^{-3}$	CL=90%
$\pi^+e^\pm\mu^\mp$	*LF*	[*q*]	< 3.8	$\times 10^{-3}$	CL=90%
$\pi^+e^+\mu^-$	*LF*		< 3.3	$\times 10^{-3}$	CL=90%
$\pi^+e^-\mu^+$	*LF*		< 3.3	$\times 10^{-3}$	CL=90%
$K^+e^+\mu^-$	*LF*		< 3.4	$\times 10^{-3}$	CL=90%
$K^+e^-\mu^+$	*LF*		< 3.4	$\times 10^{-3}$	CL=90%
$\pi^-e^+e^+$	*L*		< 4.8	$\times 10^{-3}$	CL=90%
$\pi^-\mu^+\mu^+$	*L*		< 6.8	$\times 10^{-3}$	CL=90%
$\pi^-e^+\mu^+$	*L*		< 3.7	$\times 10^{-3}$	CL=90%
$K^-e^+e^+$	*L*		< 9.1	$\times 10^{-3}$	CL=90%
$K^-\mu^+\mu^+$	*L*		< 4.3	$\times 10^{-3}$	CL=90%
$K^-e^+\mu^+$	*L*		< 4.0	$\times 10^{-3}$	CL=90%

PDG, Phys.Rev.D50, 1173 (1994)

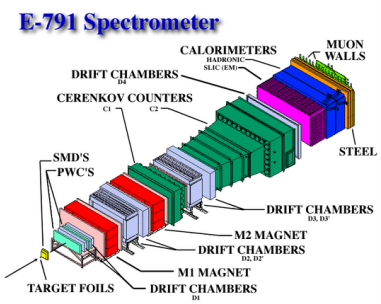
D^0 — Doubly Cabibbo suppressed (*DC*) modes, $\Delta C = 2$ forbidden via mixing (*C2M*) modes, $\Delta C = 1$ weak neutral current (*C1*) modes, or Lepton Family number (*LF*) violating modes

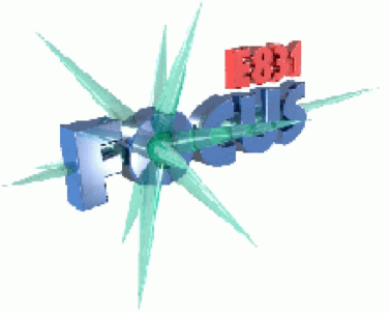
$K^+\pi^-$	*DC*		(3.1 ± 1.4)	$\times 10^{-4}$	
$K^+\pi^-$ (via $\overline{D}^0$)	*C2M*		< 1.5	$\times 10^{-4}$	CL=90%
$K^+\pi^+\pi^-\pi^-$	*DC*		< 1.5	$\times 10^{-3}$	CL=90%
μ^- anything (via $\overline{D}^0$)	*C2M*		< 6	$\times 10^{-4}$	CL=90%
e^+e^-	*C1*		< 1.3	$\times 10^{-4}$	CL=90%
$\mu^+\mu^-$	*C1*		< 1.1	$\times 10^{-5}$	CL=90%
$\overline{K}^0e^+e^-$			< 1.7	$\times 10^{-3}$	CL=90%
$\rho^0e^+e^-$	*C1*		< 4.5	$\times 10^{-4}$	CL=90%
$\rho^0\mu^+\mu^-$	*C1*		< 8.1	$\times 10^{-4}$	CL=90%
$\mu^\pm e^\mp$	*LF*	[*q*]	< 1.0	$\times 10^{-4}$	CL=90%

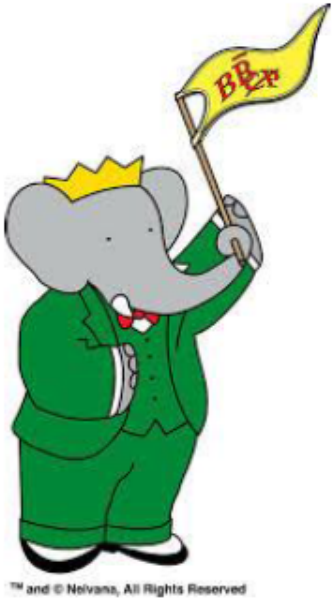
- A few FCNC, LFV, LNV searches performed
- limits at $\mathcal{O}(10^{-3})$ for D^+at most... and $\mathcal{O}(10^{-4})$ for D^0
- main experiments back then: E691, E791, Argus, Mark III, E653

An historical overview....

Since then: other experiments got into the scene...
In the last ∼15 years, main contributors in rare charm decays were/are







How rare are rare?

FCNC

- Short distance (SD) contributions to effective $c \to u$ are tiny: $\mathcal{B}'s \lesssim 10^{-9}$ or lower
- Long distance (LD) can rise $\mathcal{B}'s$ by several orders of magnitude
- 3- and 4-body get contributions from $h(h')V(\ell\ell)$ (VMD)
- Still predictions well below current experimental sensitivities for regions far from resonances

LFV, LNV, BNV

- strictly forbidden in the SM $\mathcal{B}'s \sim 0$
- many extensions of the SM predict such processes

Radiative

- not quite rare ...$\mathcal{B}'s \sim 10^{-6} - 10^{-3}$
- $D \to V\gamma,\ V = K^{*0}, \rho, \omega, \ldots$
- $D^0 \to \gamma\gamma$ [indeed FCNC] is a case apart: $\mathcal{B} \lesssim 10^{-11}$

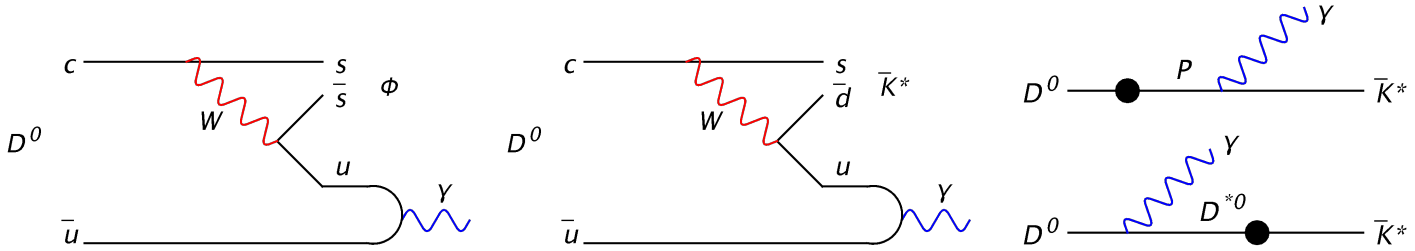
... predictions from SM ...

calculations make use of Operator Product Expansion $\mathcal{H}_{\text{eff}} = \sum_i C_i \cdot O_i$

Radiative decays

$D^0 \to V\gamma$

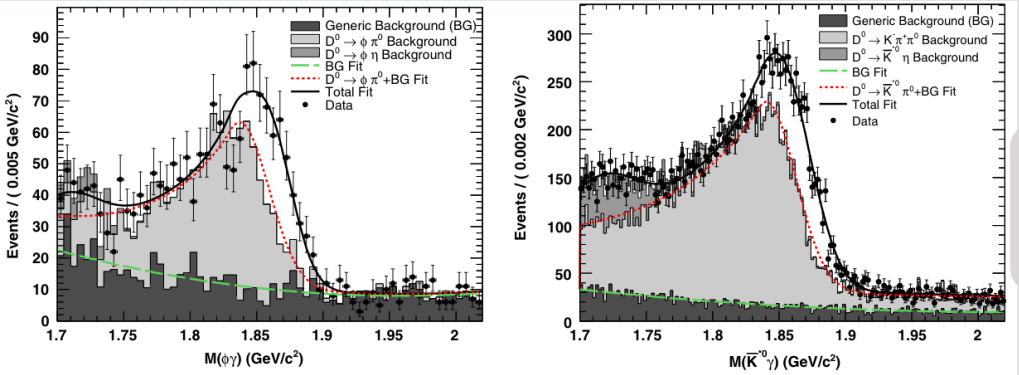
- decays like $D^0 \to V\gamma$ ($V = \rho, \phi, K^*, \omega$) cannot be said to be "rare" within the SM



- ... but NP could generate CP violation via chromomagnetic O_8 - asymmetries $\mathcal{O}(\%)$ [1], [2]

@ BaBar

PRD78, 071101 (2008)



$$\mathcal{B}(D^0 \to \phi\gamma) = (2.73 \pm 0.30 \pm 0.26) \times 10^{-5}$$

$$\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma) = (3.22 \pm 0.20 \pm 0.27) \times 10^{-4}$$

[1] J. Lyon and R. Zwicky, ArXiv 1210.6546; [2] G. Isidori, J.F. Kamenik, PRL 109 (2012) 171801

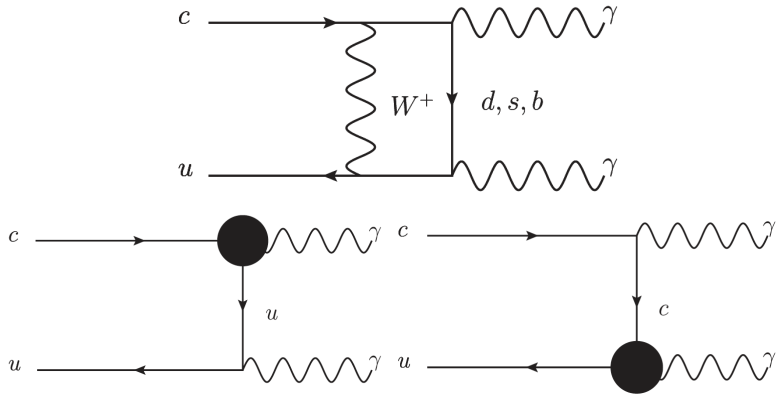
$D^0 \to \gamma\gamma$

- in the SM, dominated by LD, $\mathcal{B} \sim 10^{-8}$

  [3] G. Burdman *et al.* PRD 66 (2002) 014009

- could be enhanced to 10^{-6} by MSSM ($c \to u\gamma$ via gluino exchange)

  [4] S. Prelosev and D. Wyler, PLB 500 (2001) 304

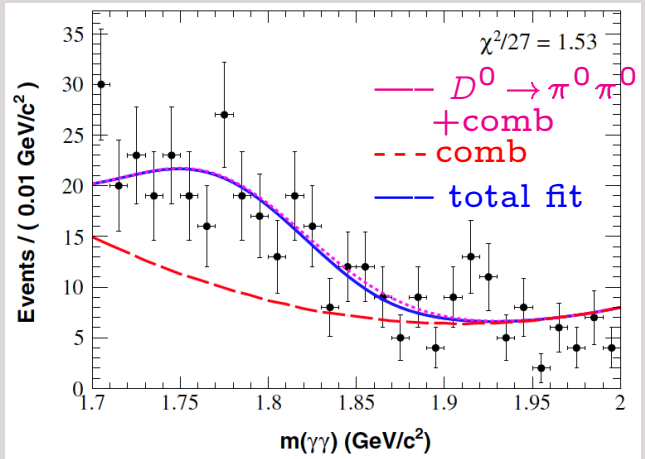


@ BaBar

PRD85, 091107R (2012)

- $D^0 \to K_S^0 \pi^+$ as normalization channel
- main peaking background $D^0 \to \pi^0\pi^0$

$$\mathcal{B}(D^0 \to \gamma\gamma) < 2.4 \times 10^{-6}$$
(90% CL)

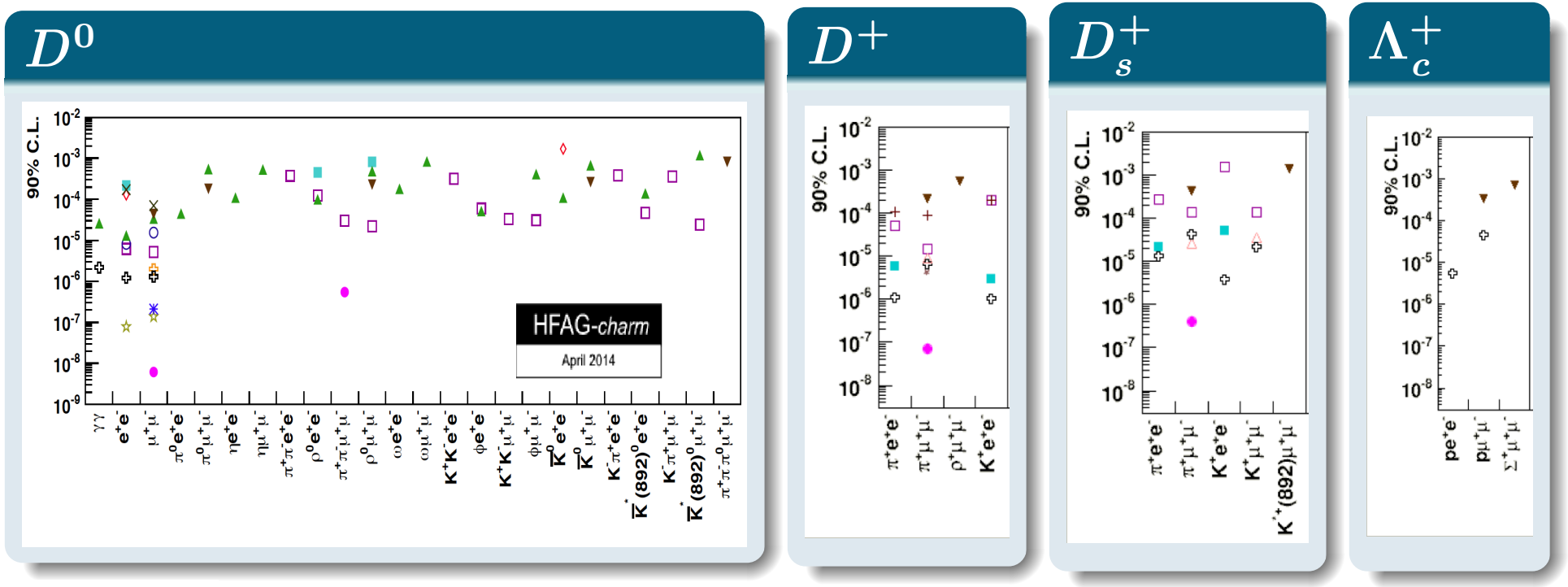


@ BES III NEW [arXiv:1505.03087 (2015)]

$$\mathcal{B}(D^0 \to \gamma\gamma) < 3.8 \times 10^{-6}$$

FCNC

Searches for Flavor-Changing Neutral Currents



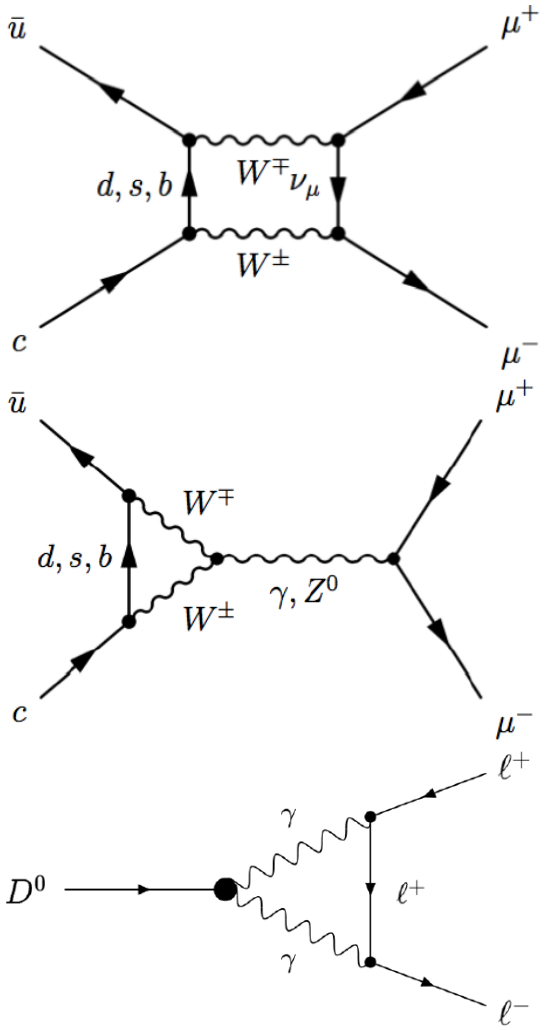
- very few limits below 10^{-6}
- many channels studied more than a decade ago !!

HFAG, ArXiv:1412.7515

http://www.slac.stanford.edu/xorg/hfag

2-body: $D^0 \to \mu^+\mu^-$

- Short distance (SD) strongly GIM suppressed $\mathcal{B} \sim 10^{-18}$ [3]
- In the SM, dominated by long-distance (LD) $\mathcal{B} \sim 10^{-11}$ [3]
- recent limits come from CDF [PRD 82 (2010) 091105R], Belle [PRD 81 (2010) 091102R] , and LHCb PLB 725 (2013) 15 [best limit]

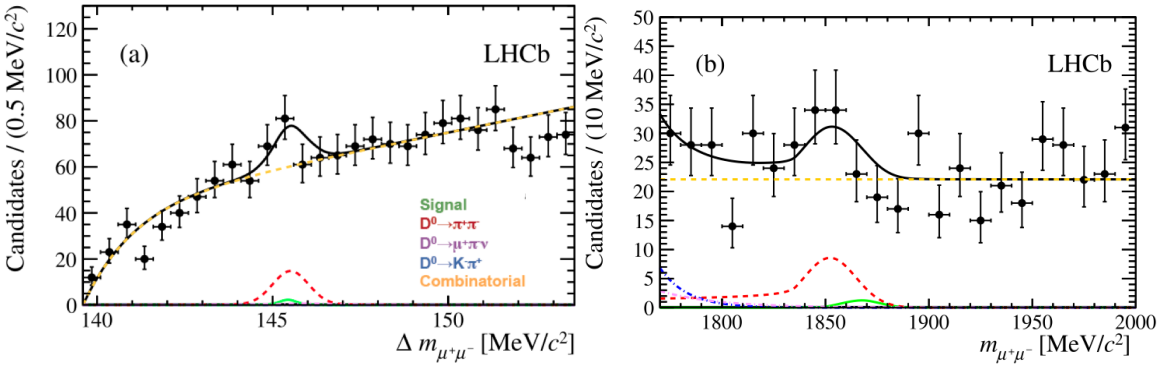


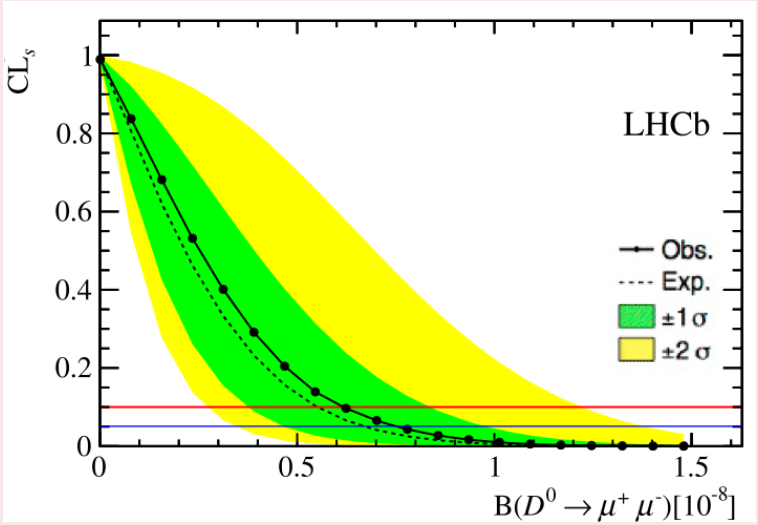
[3] G. Burdman *et al.* PRD 66 (2002) 014009

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

PLB 725 (2013) 15

- 0.9 fb^{-1}, 2011 data
- Uses D^* chain: $D^{*+} \to D^0(\mu\mu)\pi_s^+$
- main peaking backgrounds $D^0 \to hh$ $(h = K, \pi)$





$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2(7.6) \times 10^{-9}$$

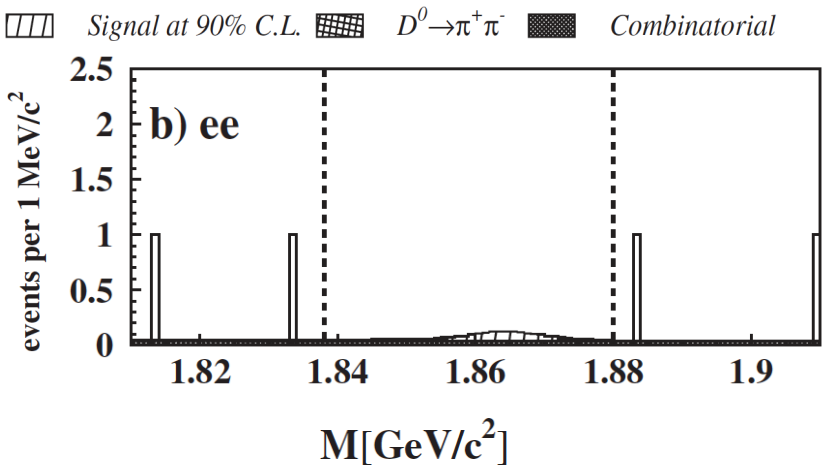
@ 90%(95%) CL

- currently best limit
- but still 100× SM and 10× NP predictions
- also the best limit for FCNC in charm (still above best limit for B)

2-body: $D^0 \to \ell^+\ell^-$ @ Belle

PRD81, 091102R (2010)

- $D^0 \to e^+e^-$ suffers stronger helicity suppression
- Belle searched for $\mu^+\mu^-$ and e^+e^-
- best limit for $D^0 \to e^+e^-$

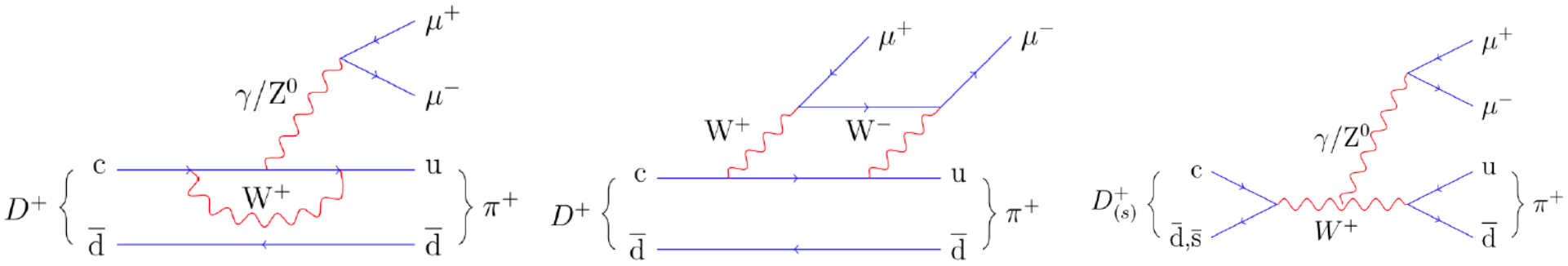


$$\mathcal{B}(D^0 \to e^+e^-) = 7.9 \times 10^{-8}$$

@ 90%CL

3-body: $D^+ \to \pi^+\mu^+\mu^-$

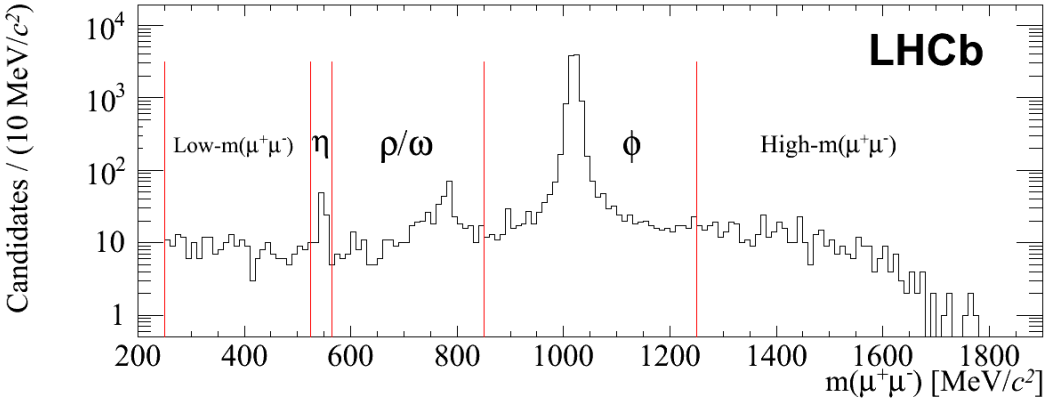
- Also suffer from strong GIM suppression for SD contributions ($\mathcal{B} \lesssim 10^{-9}$)
- LD process via resonances $V \to \mu^+\mu^-$ ($\mathcal{B} \sim 10^{-5} - 10^{-9}$)
- recent limits come from D0 [PRL 100 (2008) 101801] and BaBar [PRD 84(2011) 072006]
- best limit from LHCb [PLB 724 (2013) 203]

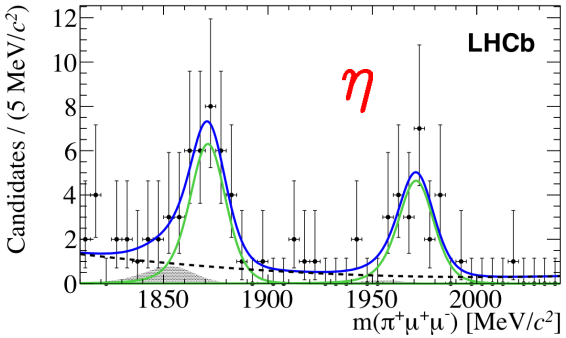


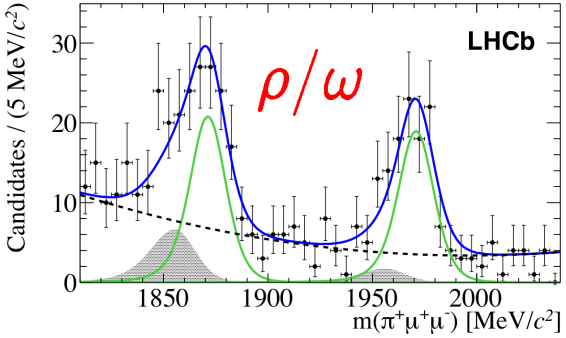
$D^+_{(s)} \to \pi^+\mu^+\mu^-$ @ LHCb

PLB 724 (2013) 203

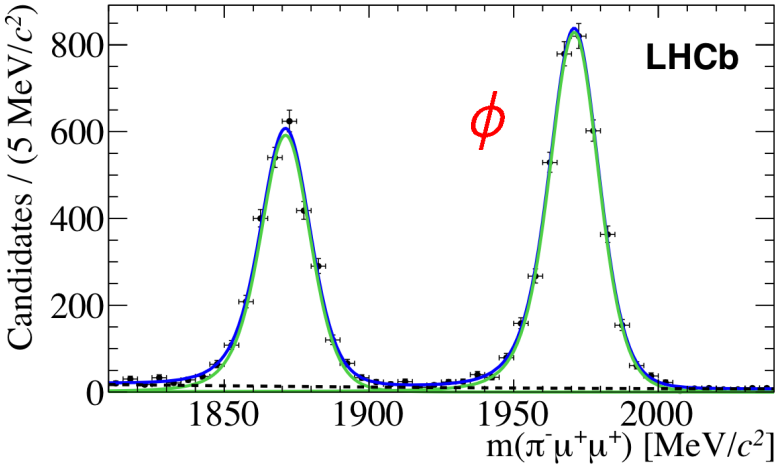
- 1 fb^{-1} of data (2011)
- search for signal away from resonance regions
- simultaneous fit to $m(\pi^+\mu^+\mu^-)$ in the 5 $m(\mu^+\mu^-)$ regions







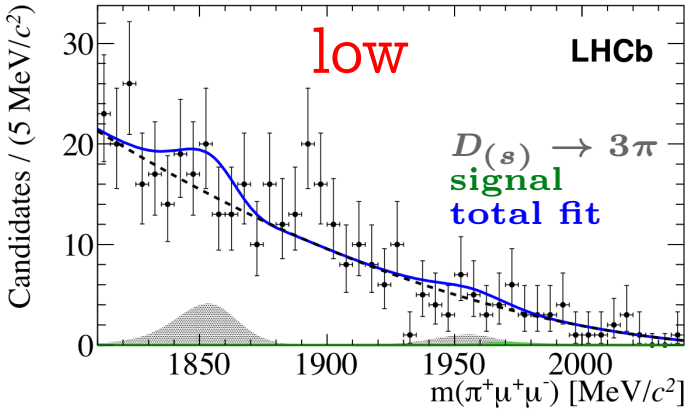
ϕ region serves as normalization

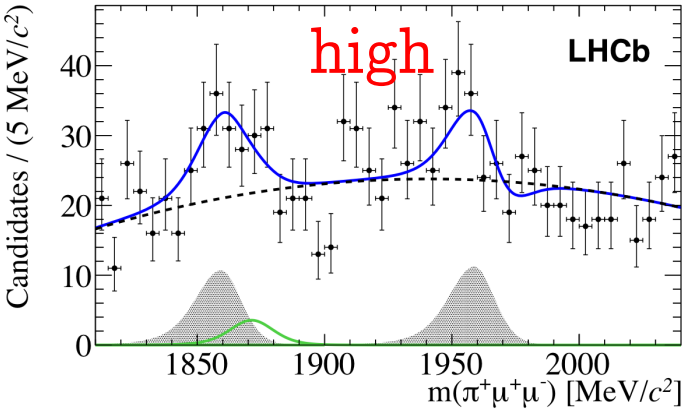


$D_{(s)} \to 3\pi$
signal
total fit

$D^+_{(s)} \to \pi^+\mu^+\mu^-$ LHCb

PLB 724 (2013) 203





- No observed signals.
- Upper limits are calculated from low and high $m(\mu\mu)$ extrapolated to the full spectrum:

$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3 \times 10^{-8}$$

$$\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) < 4.1 \times 10^{-7}$$

@ 90% CL

- Still $\sim 100\times$ SM predictions for D^+

3-body $X_c^+ \to h^+\ell^+\ell^-$ @ BaBar

PRD84, 072006 (2011)

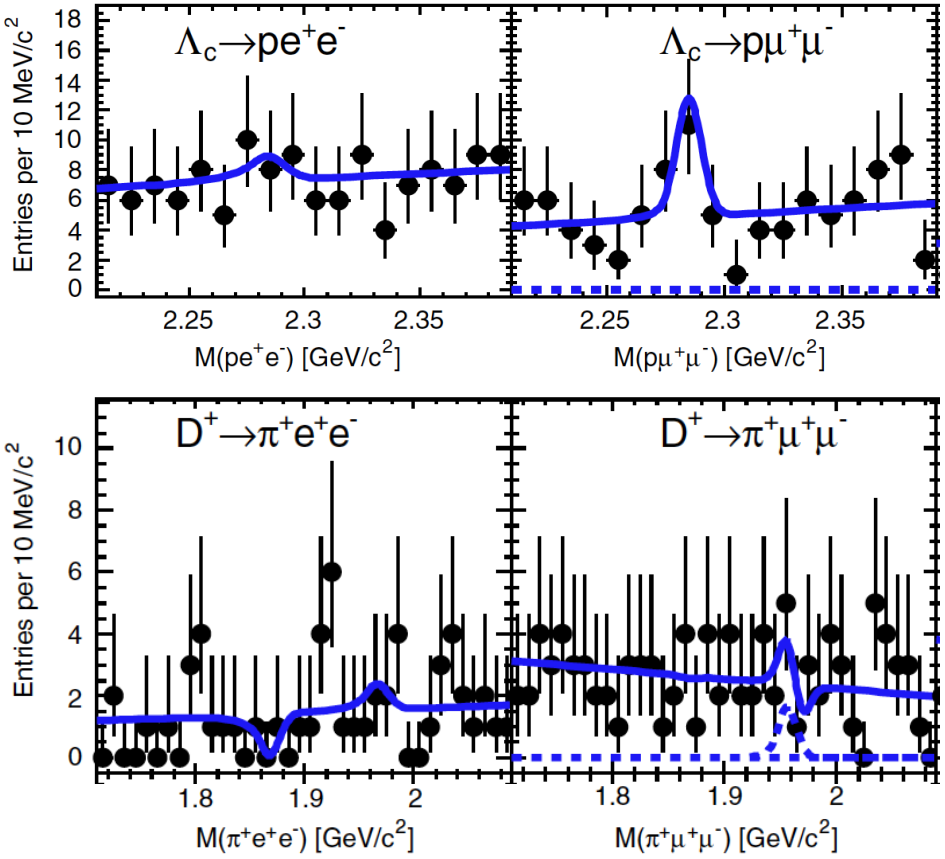
BaBar gave a very nice (and vast) contribution to the field

⇒ 10 FCNC channels

⇒ and many LFV & LNV (shown later on)

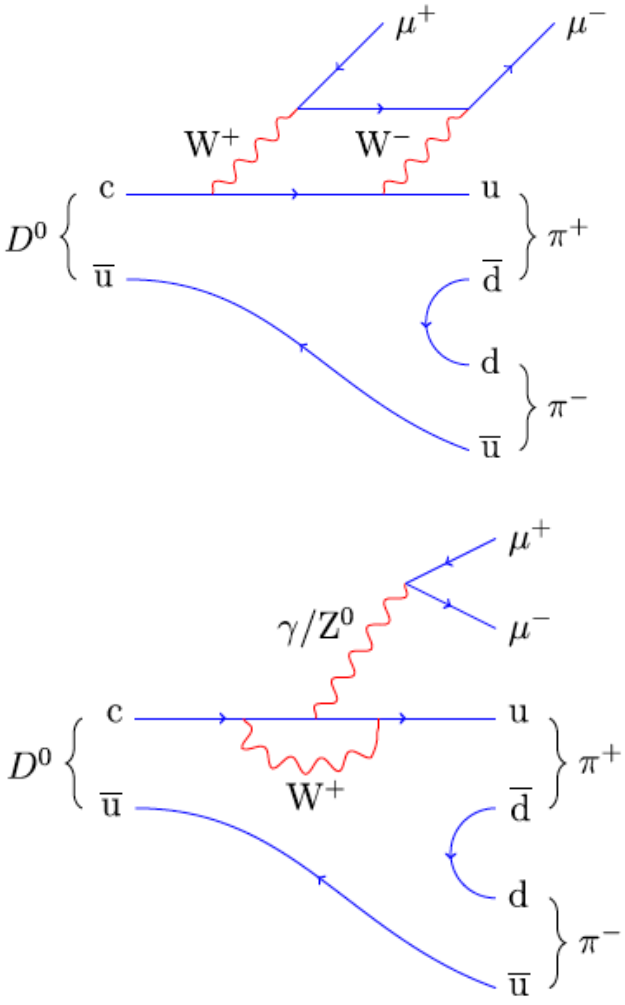
channel	90% CL limit
$D^+ \to \pi^+ e^+ e^-$	1.1×10^{-6}
$D^+ \to K^+ e^+ e^-$	1.0×10^{-6}
$D^+ \to K^+ \mu^+ \mu^-$	4.3×10^{-6}
$D_s^+ \to \pi^+ e^+ e^-$	1.3×10^{-5}
$D_s^+ \to K^+ e^+ e^-$	3.7×10^{-6}
$D_s^+ \to K^+ \mu^+ \mu^-$	2.1×10^{-5}
$\Lambda_c^+ \to p e^+ e^-$	5.5×10^{-6}
$\Lambda_c^+ \to p \mu^+ \mu^-$	4.4×10^{-5}

(only current best limits shown)



4-body: $D^0 \to h^- h^+ \ell^+ \ell^-$

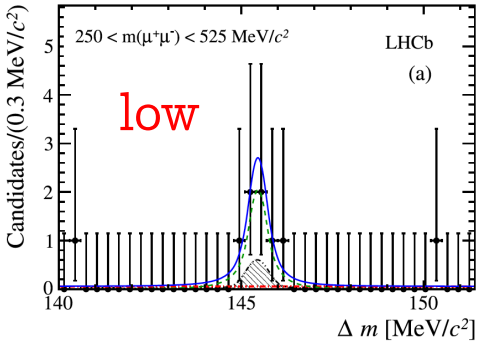
- as in 3-body, $\mathcal{B}$'s are dominated by resonances $V \to \ell\ell$
- essentially the same diagrams
- potential for the study of angular asymmetries; but high statistics are necessary
- the majority of the upper limits are in the range $10^{-5} - 10^{-3}$ (including resonant $V'\ell\ell$, like $K^* \to K^-\pi^+$, $\rho\pi^+\pi^-$, etc)
- ... and are $\gtrsim$ 15 years old
- exception: $D^0 \to \pi^-\pi^+\mu^+\mu^-$ @ LHCb

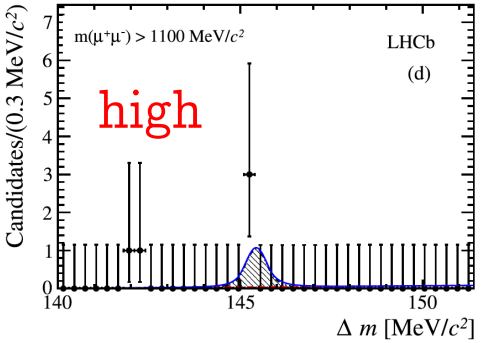


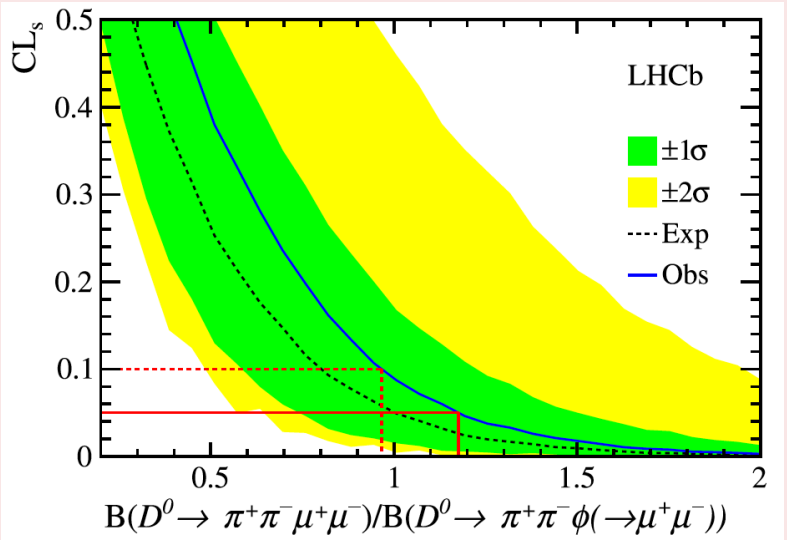
$D^0 \to \pi^+\pi^-\mu^+\mu^-$ @ LHCb

PLB 728 (2014) 234

- 1fb^{-1}, 2011 data
- uses decay chain $D^{*+} \to D^0\pi_s^+$
- study similar to $D^+ \to \pi^-\mu^+\mu^-$: divide in $m(\mu\mu)$ regions





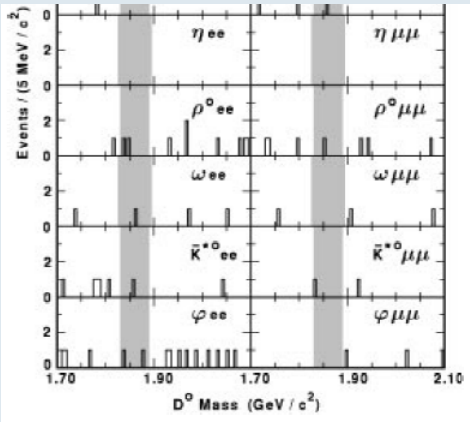


$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) < 5.5(6.7) \times 10^{-7}$$

@ 90%(95%) CL

3-body $D^0 \to h^0 \ell^+ \ell^-$ and 4-body $D^0 \to h^- h^+ \ell^+ \ell^-$

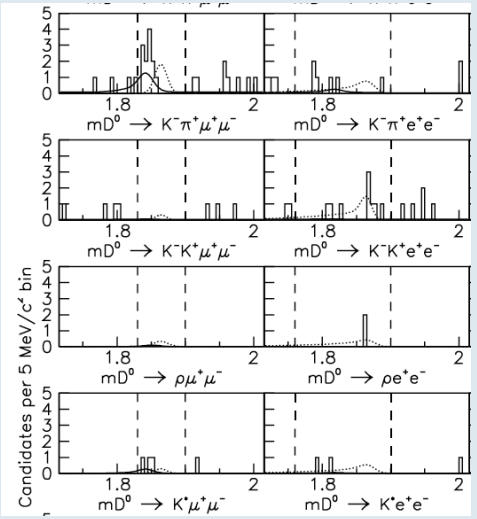
@ Cleo-II **PRL76, 3065 (1996)**



shaded: signal region

channel	90% CL limit
$\pi^0 e^+ e^-$	4.5×10^{-5}
$\bar{K}^0 e^+ e^-$	1.1×10^{-4}
$\eta e^+ e^-$	1.1×10^{-4}
$\eta \mu^+ \mu^-$	5.3×10^{-4}
$\omega e^+ e^-$	1.8×10^{-4}
$\omega \mu^+ \mu^-$	8.3×10^{-4}
$\phi e^+ e^-$	5.2×10^{-5}
$\rho e^+ e^-$	1.0×10^{-4}

@ E791 **PRL86, 3969 (2001)**



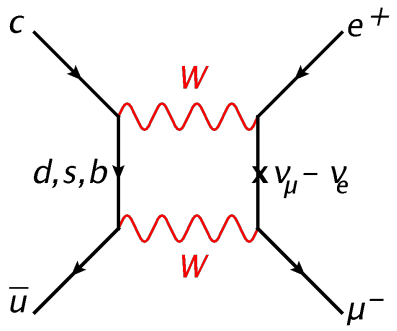
- - - backg.
—— signal at 90%CL limit

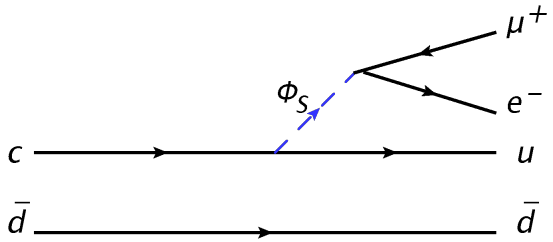
channel	90% CL limit
$\pi^+ \pi^- e^+ e^-$	3.7×10^{-4}
$K^+ \pi^- e^+ e^-$	3.9×10^{-4}
$\bar{K}^{*0} e^+ e^-$	4.7×10^{-5}
$K^+ \pi^- \mu^+ \mu^-$	3.6×10^{-4}
$\bar{K}^{*0} \mu^+ \mu^-$	2.4×10^{-5}
$\phi \mu^+ \mu^-$	3.1×10^{-5}
$\rho \mu^+ \mu^-$	2.2×10^{-5}

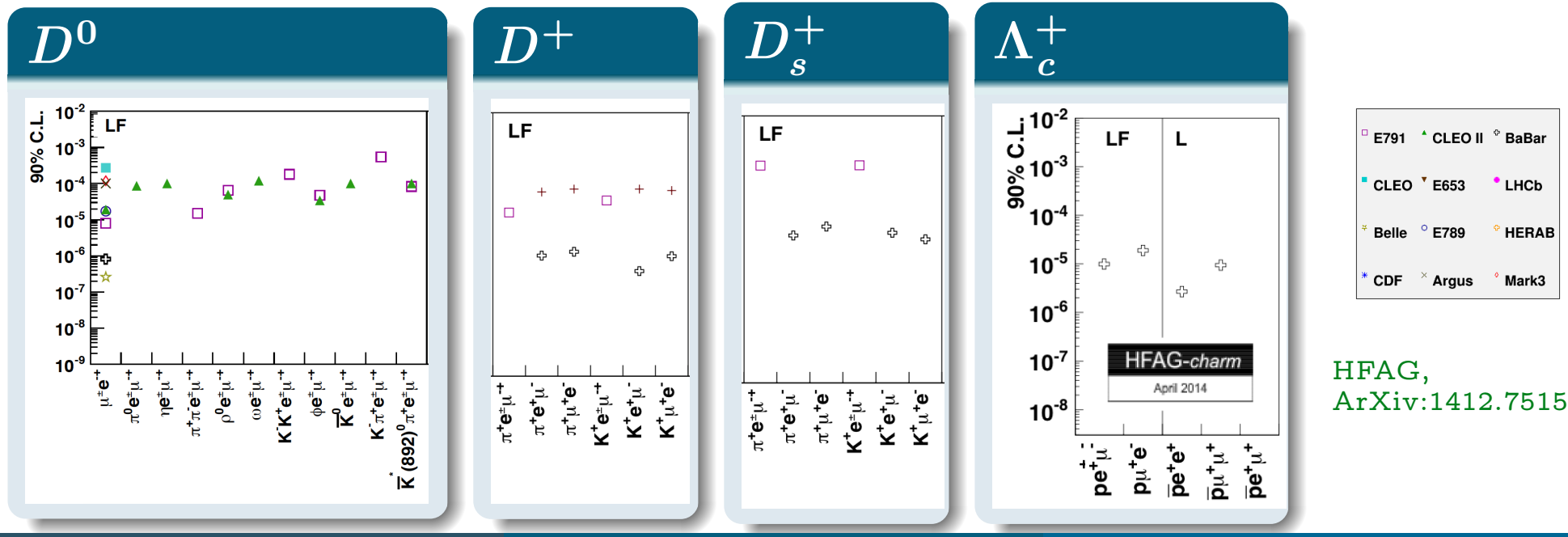
LFV, LNV, BNV

Lepton Flavor Violation (LFV)

- "possible" since $m_\nu \neq 0$
- ... but "essentially" forbidden: $\mu \leftrightarrow e$ should be absurdly suppressed
- could be enhanced by some NP models (Higgs extensions, leptoquarks,...)







HFAG, ArXiv:1412.7515

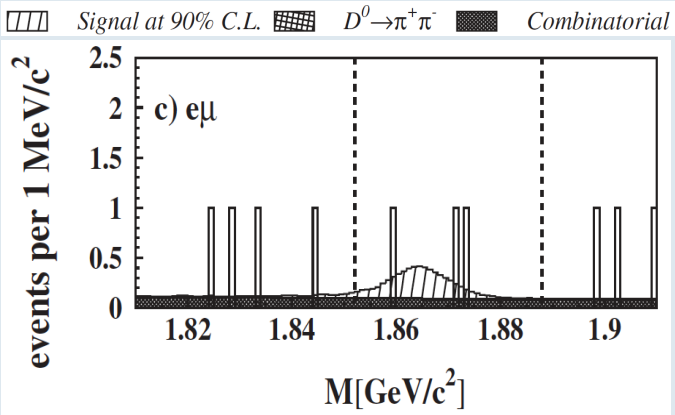
2- and 3-body: $D^0 \to (h^0) e^\pm \mu^\mp$

$D^0 \to e^\pm \mu^\mp$ @ Belle

PRD81, 091102R (2010)

$$\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 2.6 \times 10^{-7}$$

@ 90%CL

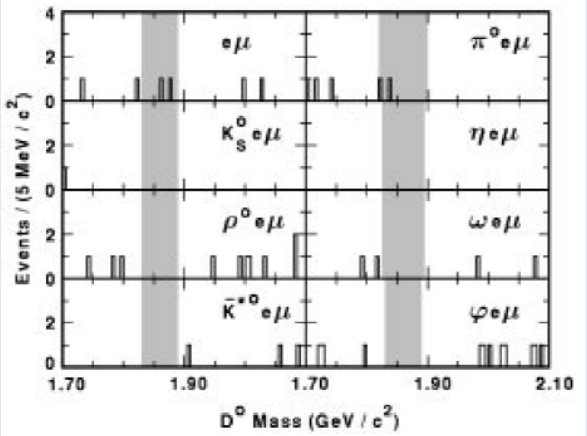


$D^0 \to h^0 e^\pm \mu^\mp$ @ Cleo-II

PRL76, 3065 (1996)

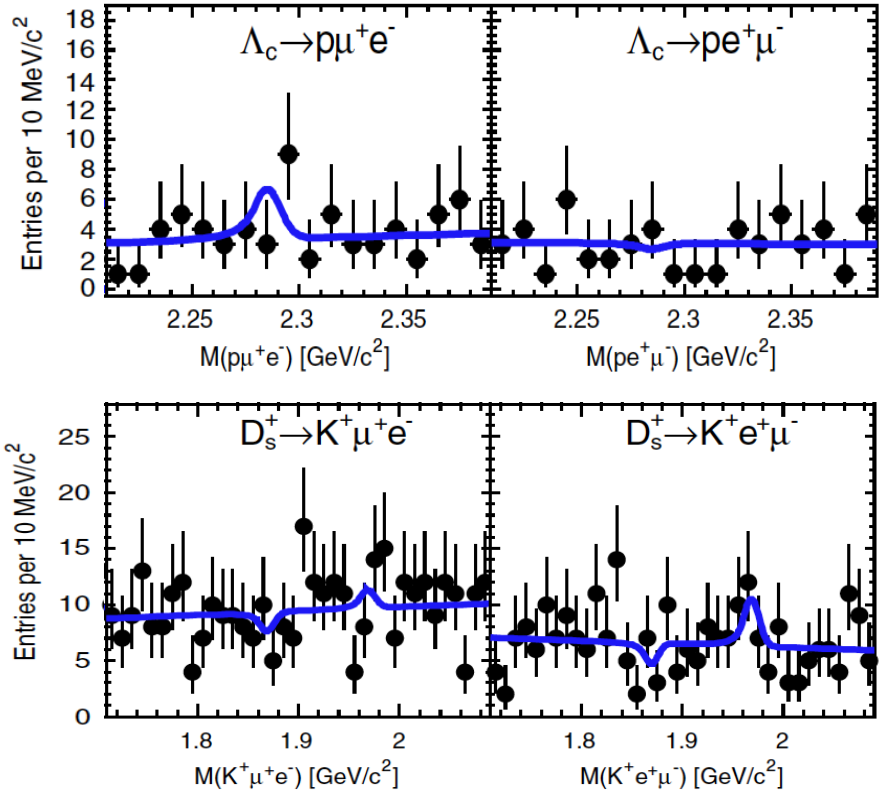
- "most recent" results date from 1996...

channel	90% CL limit
$D^0 \to \pi^0 e^\pm \mu^\mp$	8.6×10^{-5}
$D^0 \to \bar{K}^0 e^\pm \mu^\mp$	1.0×10^{-4}
$D^0 \to \eta e^\pm \mu^\mp$	1.0×10^{-4}



3-body: $X_c^+ \to h^+\mu^\pm e^\mp$ @ BaBar

PRD84, 072006 (2011)



channel	90% CL limit
$D^+ \to \pi^+ e^+ \mu^-$	2.9×10^{-6}
$D^+ \to \pi^+ \mu^+ e^-$	3.6×10^{-6}
$D^+ \to K^+ e^+ \mu^-$	1.2×10^{-6}
$D^+ \to K^+ \mu^+ e^-$	2.8×10^{-6}
$D_s^+ \to \pi^+ e^+ \mu^-$	1.2×10^{-5}
$D_s^+ \to \pi^+ \mu^+ e^-$	2.0×10^{-5}
$D_s^+ \to K^+ e^+ \mu^-$	1.4×10^{-5}
$D_s^+ \to K^+ \mu^+ e^-$	9.7×10^{-5}
$\Lambda_c^+ \to p e^+ \mu^-$	9.9×10^{-6}
$\Lambda_c^+ \to p \mu^+ e^-$	1.9×10^{-5}

- Limits at the same level of $\ell^+\ell^-$ partners: $10^{-5} - 10^{-6}$

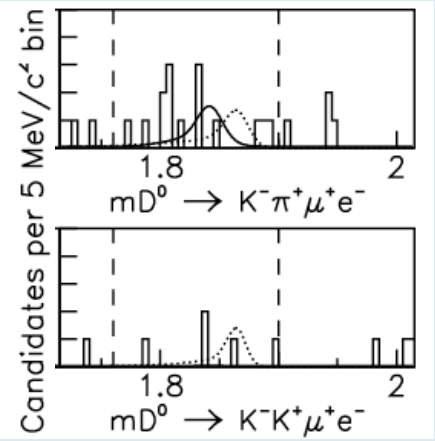
4-body: $D^0 \to h^+ h^- e^\pm \mu^\mp$

- again ... only quite old results

@ E791

PRL86, 3969 (2001)

channel	90% CL limit
$\pi^+\pi^- e^\pm\mu^\mp$	1.5×10^{-5}
$K^+\pi^- e^\pm\mu^\mp$	5.5×10^{-4}
$\bar{K}^{*0} e^\pm\mu^\mp$	8.3×10^{-5}
$K^+K^- e^\pm\mu^\mp$	1.8×10^{-4}



- - - backg.

—— signal at 90%CL limit

@ Cleo-II

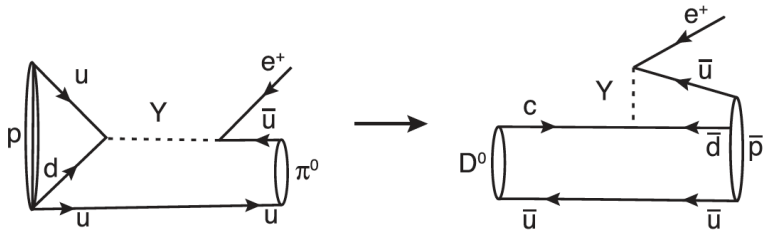
PRL76, 3065 (1996)

channel	90% CL limit
$D^0 \to \rho^0 e^\pm\mu^\mp$	4.9×10^{-5}
$D^0 \to \phi e^\pm\mu^\mp$	3.4×10^{-5}
$D^0 \to \omega e^\pm\mu^\mp$	1.2×10^{-4}

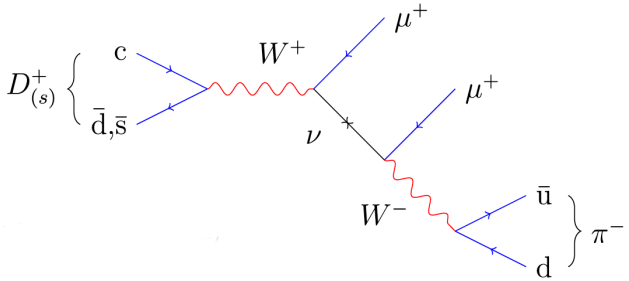
LNV & BNV

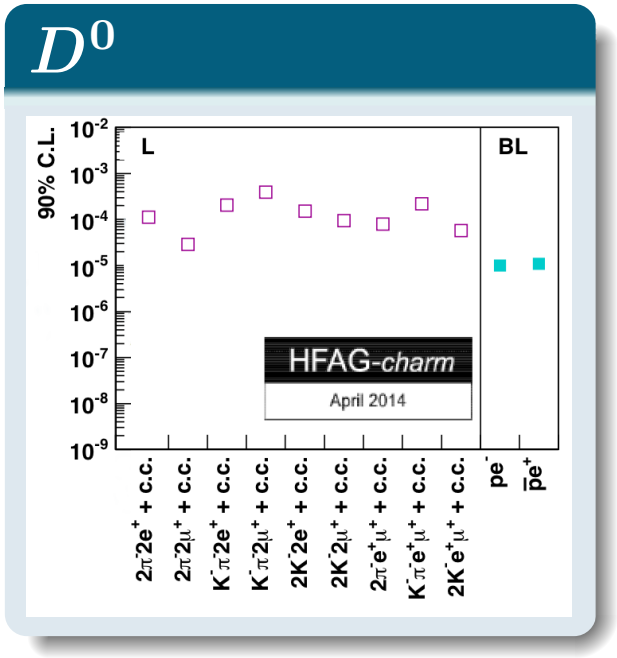
- various NP models predicts LNV and BNV

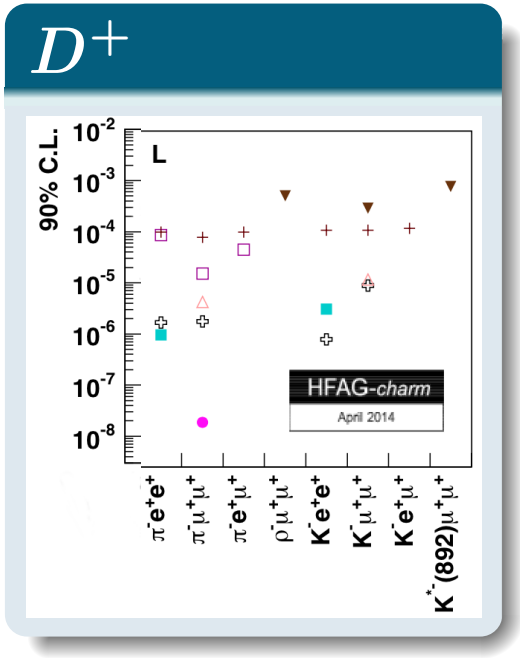
SU(5) leptoquarks

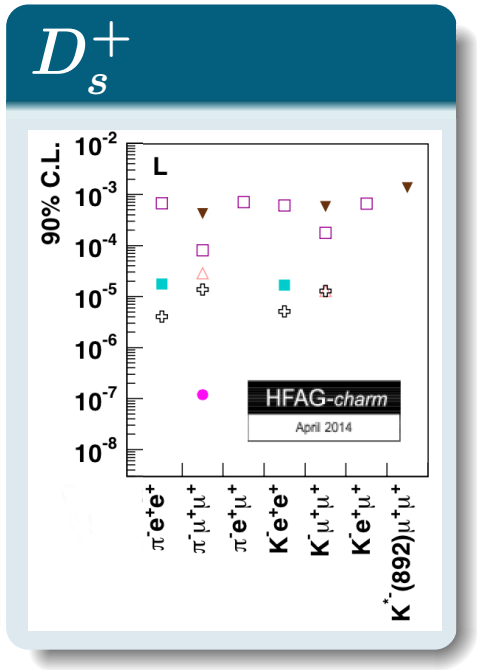


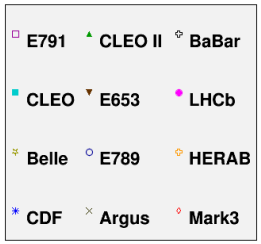
Majorana neutrinos









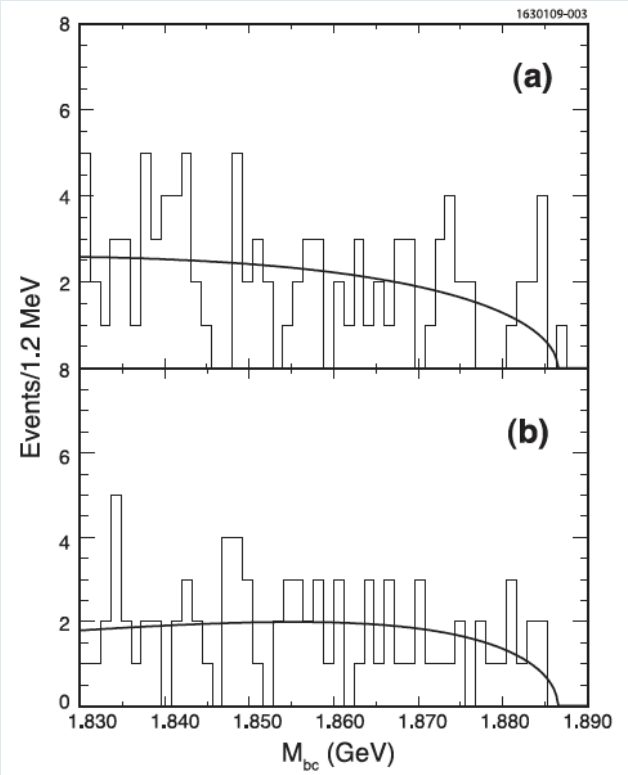


HFAG, ArXiv:1412.7515

2-body: $D^0 \to \bar{p}e^+$, $D^0 \to pe^-$

@ Cleo

PRD79, 097101 (2009)



- 281 pb^{-1} of data in e^+e^- collisions at $\psi(3770)$ resonance
- decays violate both L and B, while preserving $B - L$

$$\mathcal{B}(D^0[\bar{D}^0] \to \bar{p}e^+) < 1.1 \times 10^{-5}$$

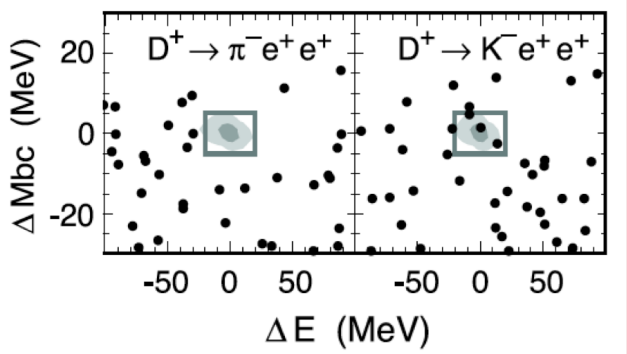
$$\mathcal{B}(D^0[\bar{D}^0] \to pe^-) < 1.0 \times 10^{-5}$$

3-body: $X_c^+ \to h^- \ell^+ \ell^+$

@ BaBar PRD84, 072006 (2011)

channel	90% CL limit
$D^+ \to K^- e^+ e^+$	0.9×10^{-6}
$D^+ \to K^- \mu^+ \mu^+$	1.0×10^{-5}
$D_s^+ \to \pi^- e^+ e^+$	4.1×10^{-6}
$D_s^+ \to K^- e^+ e^+$	3.7×10^{-6}
$D_s^+ \to K^- \mu^+ \mu^+$	1.3×10^{-5}
$\Lambda_c^- \to \bar{p} e^+ e^+$	2.7×10^{-6}
$\Lambda_c^- \to \bar{p} \mu^+ \mu^+$	9.4×10^{-5}

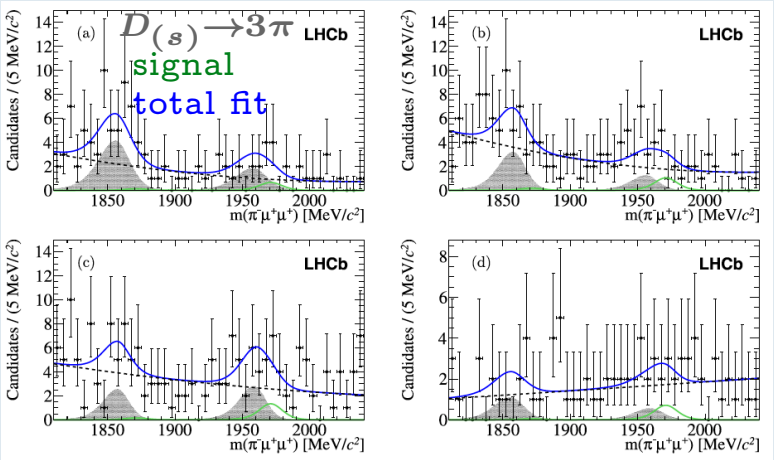
@ Cleo PRD82, 092007 (2010)



$\mathcal{B}(D^+ \to \pi^- e^+ e^+) < 1.0 \times 10^{-6}$
(90% CL)

@ LHCb

PLB 724 (2013) 203



$$\mathcal{B}(D^+ \to \pi^- \mu^+ \mu^+) < 7.3 \times 10^{-8}$$
$$\mathcal{B}(D_s^+ \to \pi^- \mu^+ \mu^+) < 4.1 \times 10^{-7}$$

Prospects

What to expect in the future?

- For FCNC, experimental limits are still well above SM predictions
- $D^0 \to \mu^+\mu^-$ and $D^+ \to \pi^+\mu^+\mu^-$ are the leading actors for the upcoming searches

  $D^0 \to \mu^+\mu^-$ gives the strongest constraints

  $D^+ \to \pi^+\mu^+\mu^-$ approaching most optimistic NP scenarios
- A number of channels have limits still too modest

  $\Rightarrow$ a search should be performed in many fronts

  combining constraints?
- Besides $\mathcal{B}$'s (U.L.) the search for asymmetries are interesting - although statistics is really an issue here
- let's see some expectations...

$\mathcal{B}$'s or Upper Limits

@ LHCb

Claudia Vacca, parallel talk

- For run II (2015–2018) expect mild improvements wrt run I
- LHCb upgrade:
  $\sigma(c\bar{c})_{14\,\mathrm{TeV}} \sim 2\sigma(c\bar{c})_{7\,\mathrm{TeV}}$, trigger $\sim 2\times$ better, ~ 50 fb^{-1}
- $10\times$ charm per year

Modes	Run I	Run II	Upgrade
$D^0 \to \mu^+\mu^-$	few 10^{-9}	fewer 10^{-9}	few 10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	few 10^{-8}	fewer 10^{-8}	few 10^{-9}
$D^+_s \to K^+\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	few 10^{-8}
$D^0 \to h^+h'^{(-)}\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	few 10^{-8}

- Rare charm program in LHCb includes/foresee:

  $D^0 \to \ell^+\ell'^-$, $\Lambda_c \to p\ell^+\ell^-$, $D \to h(h')\ell\ell'$, $D^0 \to \phi\gamma$
  with $\ell = \mu, e$ (FCNC, LFV and LNV modes)

$\mathcal{B}$'s or Upper Limits

@ Belle-II

- Should collect 50 ab^{-1} from e^+e^-
  low background, excellent γ and π^0 reconstruction
- Simple projections from BaBar $X_c \to h\ell\ell$ analysis [PRD 84 (2011) 072006]
  $\sim 100\times$ statistics
  $\Rightarrow$ should achieve U.L. of $\sim 10^{-7}$ for D^+ and 10^{-6} for D_s^+, Λ_c^+ on semileptonic FCNC, LNV and LFV
- also extrapolating from BaBar, could reach $\mathcal{B}(D^0 \to \gamma\gamma) \lesssim 10^{-7}$
- Can do a great job in $h\ell\ell$ with $h = \pi^0, \eta, \omega$

@ Super τ-charm Factory

- Assuming to collect $\sim 10^{10}$ D pairs $\Rightarrow$ $10^4\times$ Cleo-c
- can achieve U.L of few 10^{-8} for 3-body D^+ and 10^{-7} for 4-body D^0
- could reach $\mathcal{B}(D^0 \to \gamma\gamma) \lesssim 10^{-7}$

Asymmetries...

The ΔA_{CP} saga lead to some predictions of sizeable asymmetries in $c \to u\ell^+\ell^-$

- CP asymmetry: A_{CP} $D^+ \to \pi^+\mu^+\mu^-$ in the tails of ϕ resonance [5]
- FB asymmetry [6],[7]
- T-odd asymmetries in $D \to hh'\ell\ell$ [8]

$\Rightarrow$ asymmetries could reach a few % in the cases above

@ LHCb

	BF×10⁶	Run II → σ_{asym}	Upgrade → σ_{Asym}
$D^+ \to \pi^+\mu\mu$	6.	~30000 evts → 0.6 %	~300000 → 0.2 %
$D^0 \to K^-\pi^+\mu\mu$	6.2	~10000 evts → 1 %	~100000 → 0.3 %
$D^0 \to \pi^+\pi^-\mu\mu$	1.3	~1500 → 3 %	~15000 → 1 %
$D^0 \to K^+K^-\mu\mu$	0.11	~150 → 11 %	~1500 → 4 %
$D^0 \to K^+\pi^-\mu\mu$	0.017	~30 → 40 %	~300 → 12%

Claudia Vacca, parallel talk

- challenging due to the required statistics...
- $\mathcal{O}(1\%)$ asymmetries may be achievable for $D^+ \to \pi^+\mu^+\mu^-$ only with the upgrade

[5] S. Fajfer *et al*, PRD 87(2013) 054026 ; [6] A. Paul *et al* PRD90 (2014) 014035;
[7] S. Fajfer *et al.* PRD76 (2007) 074010; [8] L. Capiello *et al.* JHEP 1304 (2013) 135

Conclusions

- Charm is a unique environment for the study of SM rare & forbidden decays
  clean windows for NP searches
- Results from the last ~ 5 years (CDF, Cleo, BaBar, Belle, LHCb) brought limits down to 10^{-6} and below
  $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ (90%CL)
- ... and although at the level of or approaching the most optimistic NP scenarios, there's still a wide window wrt to SM predictions
- Nevertheless, a vast number of channels have U.L. too modest ($10^{-4} - 10^{-5}$), from more than a decade ago
  (3-body with neutrals, most 4-body ...)

- For the near future we can expect new studies and updates for run I and run II (about to start!) @ LHCb
- but the focus should go to the next frontier:
  LHCb upgrade, Belle-II, super τ-charm factory