Rare Charm decays at LHCb

Andrea Contu[1], Benoit Viaud[2]
On behalf of the LHCb collaboration.

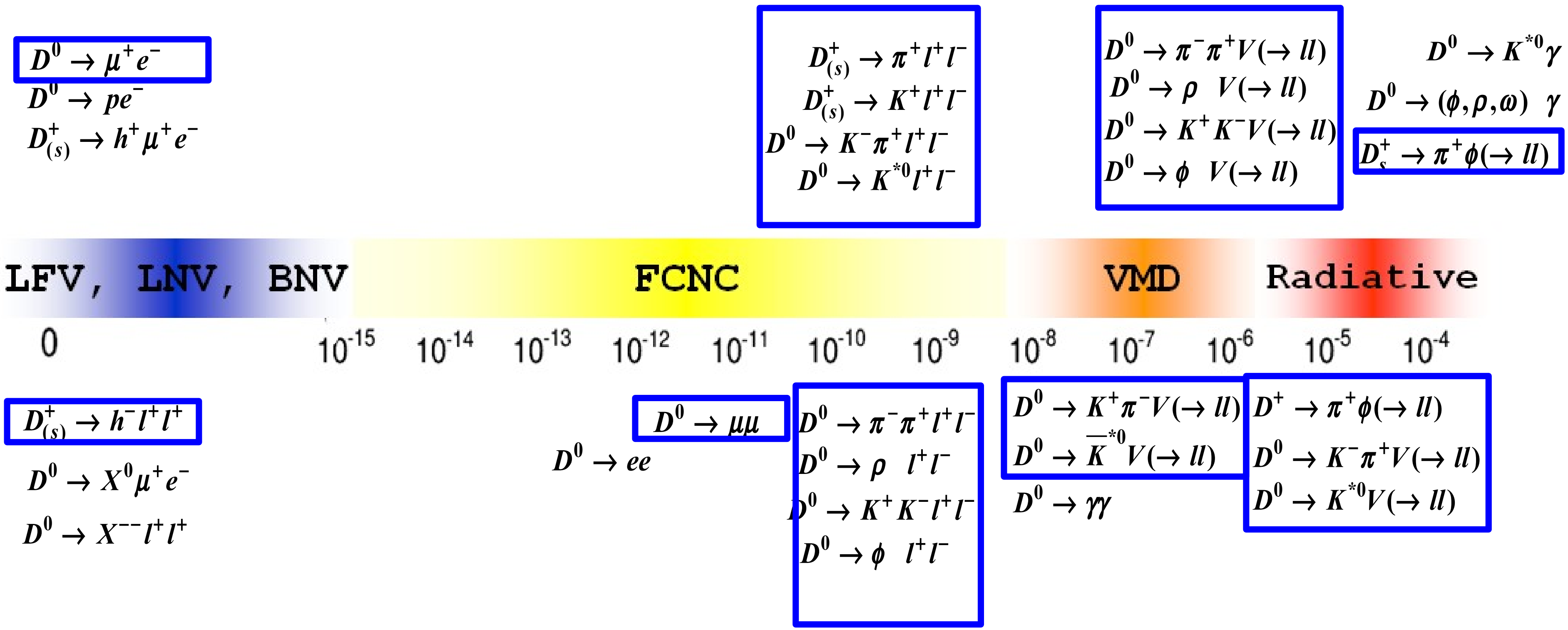
Workshop on the implications of LHC measurements.
CERN, October 16 2014

1. INFN/CERN
2. IN2P3/CNRS

Overview

- Introduction
- Theoretical predictions
- Published analyses
- On-going analyses
- Estimation of sensitivities with future datasets
- Questions to theorists

Rare Charm: several kinds of physics and many decays modes, ranging from forbidden to not so rare.



Studied at LHCb…

Run I = 1 fb^{-1} at $\sqrt{s}$=7 TeV (2011)+ 2 fb^{-1} at $\sqrt{s}$=8 TeV (2012)
Run II = ~5 fb^{-1} at $\sqrt{s}$=13 TeV
Upgrade = ~50 fb^{-1} at $\sqrt{s}$=14 TeV

...And by theorists

[1] G. Burdman *et al.*,PR D66, 014009 (2002).

[2] A. Paul *et al.*, Phys. Rev. D83 (2011) 114006, arXiv:1101.6053.

[3] L. Cappiello *et al*, JHEP 1304 (2013) 135, arXiv:1209.4235.

[4] S. Fajfer *et al*, Phys. Rev. D87 (2013) 054026, arXiv:1208.0759.

[5] A. Paul *et al*, arXiv:1212.4849.

[6] S. Fajfer *et al*, Conf. Proc. C060726 (2006) 811, arXiv:hep-ph/0610032 and Phys. Rev. D73 (2006) 054026, arXiv:hep-ph/0511048.

[7] S. Fajfer *et al*, Phys. Rev. D76 (2007) 074010, arXiv:0706.1133.

[8] G. F. Giudice *et al*, JHEP 1204 (2012) 060, arXiv:1201.6204.

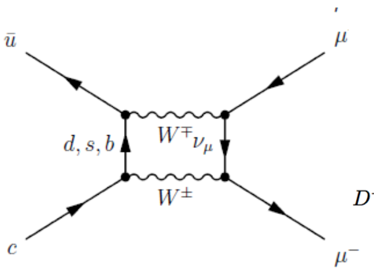
[9] S. Fajfer *et al*, Phys. Rev. D79 (2009) 017502, arXiv:0810.4858.

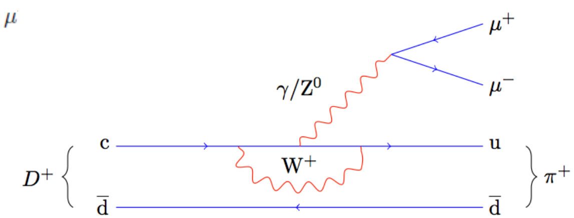
Main processes studied at LHCb

Flavor Changing Neutral Currents (FCNC)

- Short Distance (SD) very suppressed in the SM (very strong GIM suppr. in charm sector)
- Actually dominated by Long Distance (LD) contributions

***Ex:* $D^0 \rightarrow \mu^+\mu^-$** **$D \rightarrow h(h')\mu^+\mu^-$**

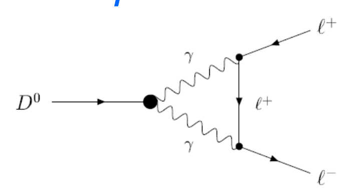




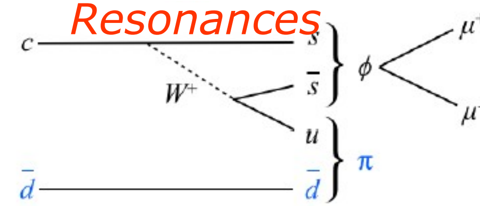
$B_{SM} \sim 10^{-18}$ [1] **$B_{incl}^{SD,\, SM} \sim 10^{-9}$ [2]**

***Ex:* $D^0 \rightarrow \mu^+\mu^-$** **$D \rightarrow h(h')\mu^+\mu^-$**

2-photon



Resonances

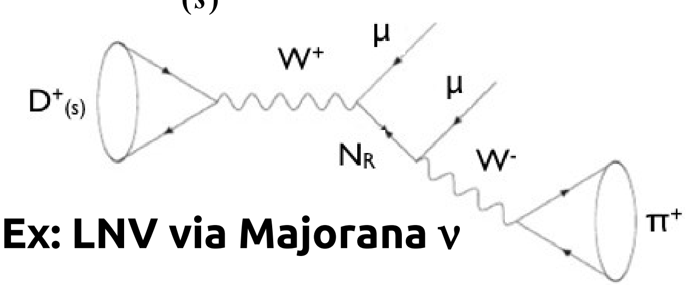


$B_{SM} < 6.\ 10^{-11}$ [1] **10^{-5} to 10^{-8} [PDG, 3]**

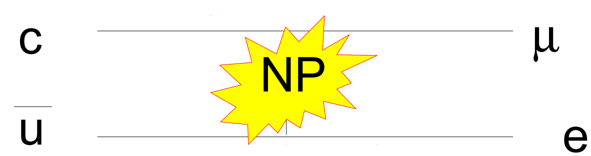
Lepton Flavor or Number Violation

- Forbidden in the SM.
- Probes Majorana neutrinos and many NP models

$$D^+_{(s)} \rightarrow h^- l^+ l^+$$



Ex: LNV via Majorana ν



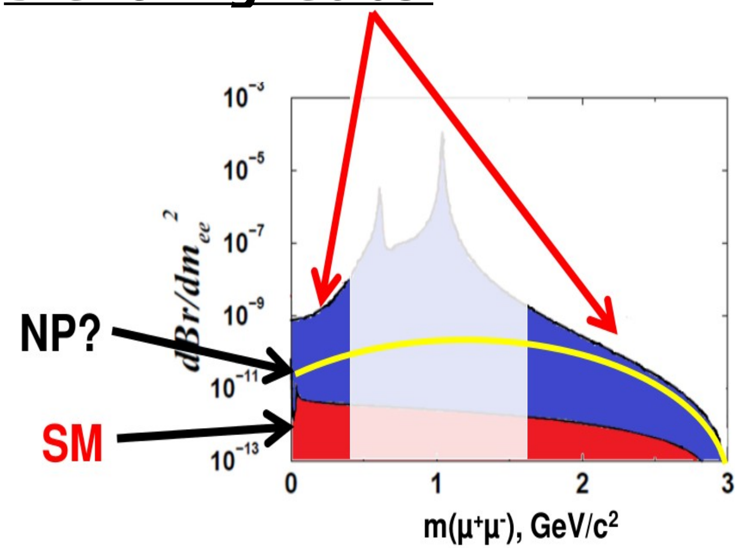
Ex: D → eμ

Observable for future studies in multi-body modes ?

<u>Up to ~2010</u>, theoretical literature focused on <u>Branching ratios</u>

- The A_{SD} can't be accessed in resonant regions!
  Low/high m(μμ): A_{SD} ! Or resonances tail ??
- Can answer via Amplitude Analysis, but hard:
  - Some modes won't have more than ~100 events there even with the Upgrade,
  - Need to know the shape of SD contribution (Form Factor from th), etc...

→ Another way to access A_{SD} would be welcome!

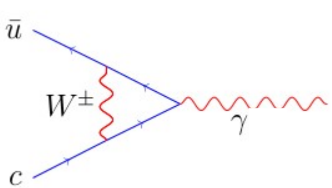


$$A = |A_{LD}|^2 + \underbrace{|A_{SD}|^2 + 2\mathrm{Re}(A_{LD}A_{SD}^*)}_{\text{Small !}}$$

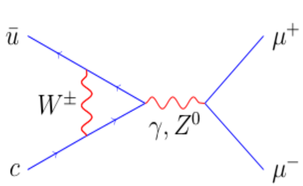
<u>2012 (Large ΔA_{CP})</u>:
SD in interferences ("$2\mathrm{Re}(A_{LD}A_{SD}^*)$") accessible via <u>Asymmetries</u> !
Generically: O(1%) effects expected. Sometimes :5% or more.
Most of these predictions should probably be revised down now (× ~1/3)

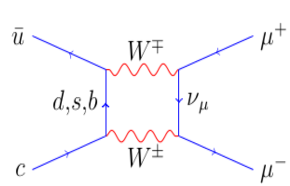
<u>NB</u>: Rare charm decays are described via $\mathcal{H}_{eff} = \sum C_i \cdot O_i$,
We look for NP effects on operators ruling c → u ll, and on associated C_i's.

$C_7 .O_7$



$C_9 .O_9$
$C_{10} .O_{10}$





Asymmetries

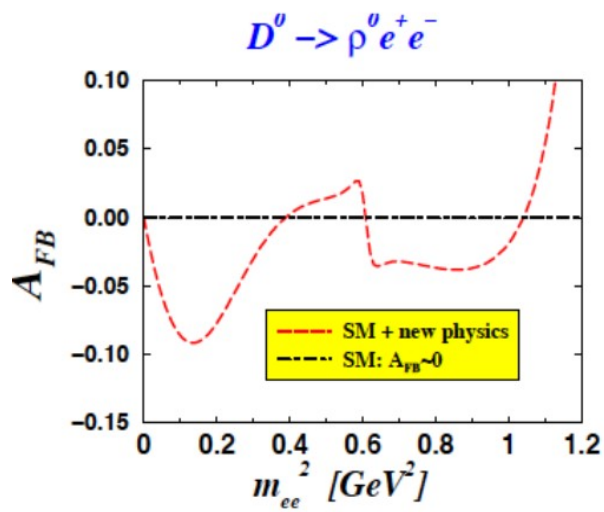
- **CP asymmetry**. Ref [4] uses the fact that ΔA_{CP} can be explained by an NP-induced enhancement of C_8 (chromomagnetic operator), which can be propagated to C_7 via QCD corrections.

  It predicts A_{CP} up to (5%) 0.2% in $D^+ \to \pi^+\mu\mu$ on the (tails of) ϕ resonance.

  The same mechanism was invoked first to predict $A_{CP} \sim 5\%$ in $D \to \phi\gamma$. But this is hard to measure at LHCb.

- **FB asymmetry**. Generated by semileptonic penguin operator O_{10} (chirality different from O_7 and O_9, the other operators contributing to $c \to u\, ll$).

  Essentially 0 in the SM since $C_{10} \sim 0$.
  Enhanced by Warped Extra Dims in [5]
  or by Extra vector-like up-quarks in [6].
  $\to A_{FB}$ up to ~5% in $D^+ \to X_u ll$, or $D^0 \to \rho ll$.



- **T-odd asymmetry** up to 7% in all $D \to h^+h^{(-)} \mu^+\mu^-$ modes [3]

Already studied, or on-going at LHCb.

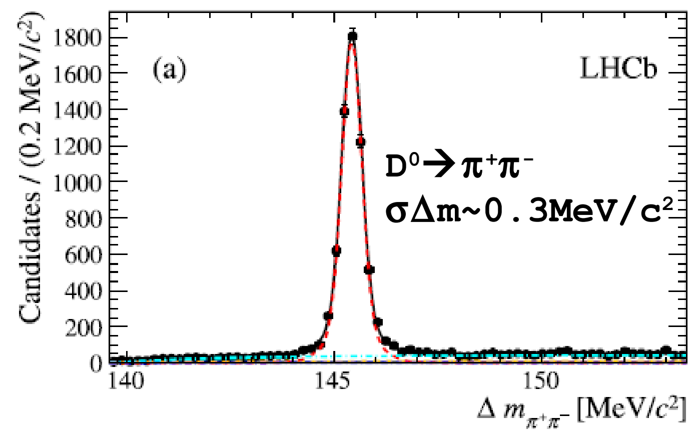
Published analyses.

3 limits on branching ratios with 2011 data (1 fb^{-1} @ Vs=7 TeV)

- $D^0 \to \mu^+\mu^-$
- $D^+_{(s)} \to \pi^+\mu^+\mu^-$ and $D^+_{(s)} \to \pi^-\mu^+\mu^+$
- $D^0 \to \pi^+\pi^-\mu^+\mu^-$

Main features of a search for rare charm decays at LHCb

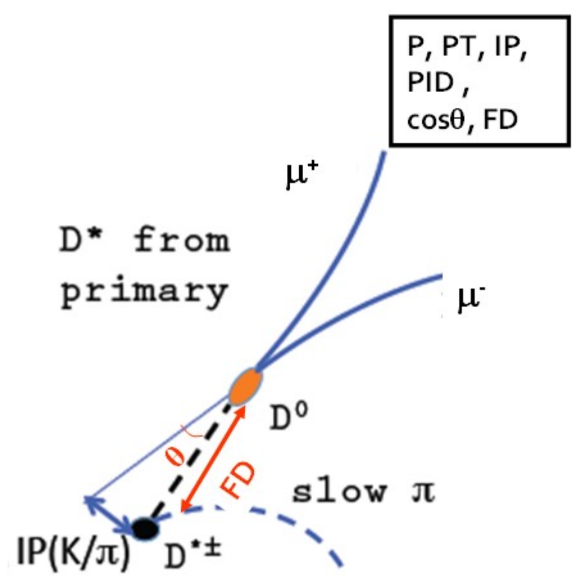
- Rely on very high charm X-section: ~5(2) 10^{12} $D^0(D^+)$ prod. in LHCb acceptance in 3 fb^{-1}.
- Benefits from the high performance LHCb trigger:
  - highly flexible and configurable. Allows to select a breadth of control modes.



- Neutral D^0's taken from $D^{*+} \to D^0\pi^+$ decays (D* tag) to reduce the combinatorial bkg (also tags flavor)
- Search normalized to a well-known mode, with similar features, to minimise σ_{syst}

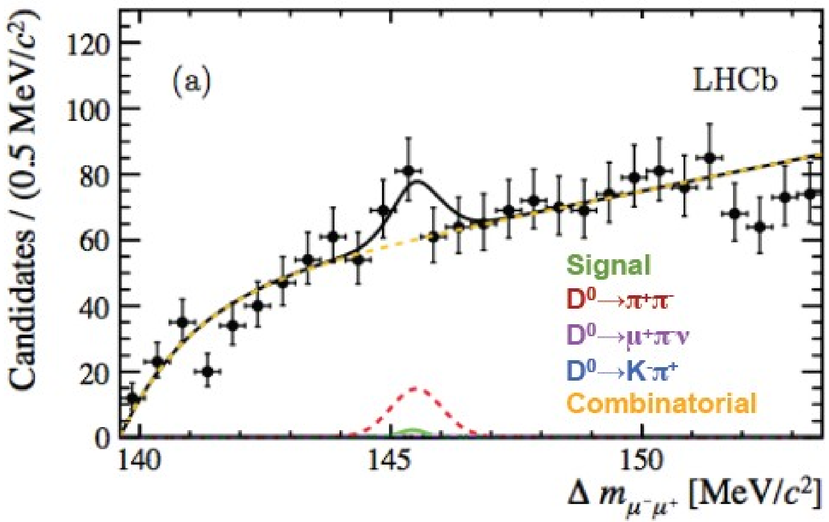
$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \frac{N_{D^{*+}\to D^0(\to\mu^+\mu^-)\pi^+}}{N_{D^{*+}\to D^0(\to\pi^+\pi^-)\pi^+}} \frac{\varepsilon_{\pi\pi}}{\varepsilon_{\mu\mu}} \cdot \mathcal{B}(D^0 \to \pi^+\pi^-)$$

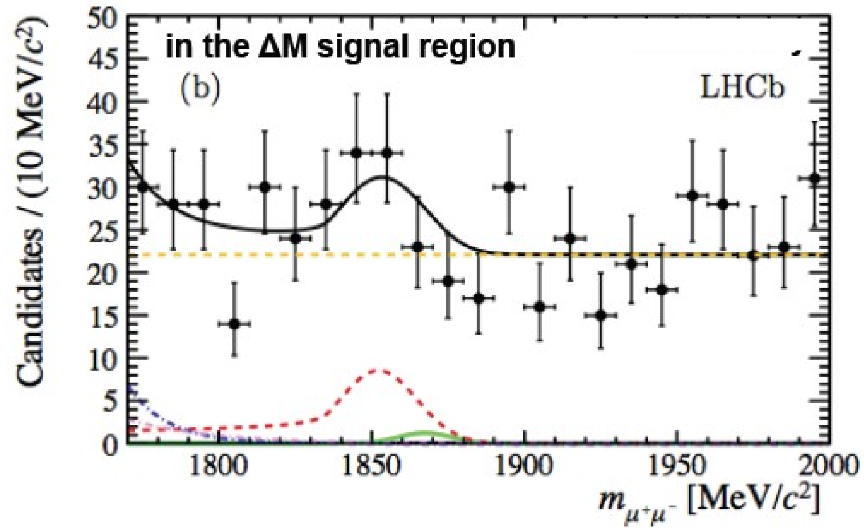
- Selection based typical features of the signal.
  - An MVA to keep the combi. Bkg. under control
  - Tight muon-ID criteria against $D^0 \to \pi^+\pi^- \to \mu^+\mu^-$ (Hadronic BF's typically >10^4 larger than signals)
- Critical aspects of efficiency determination based on data-driven methods (large control samples).

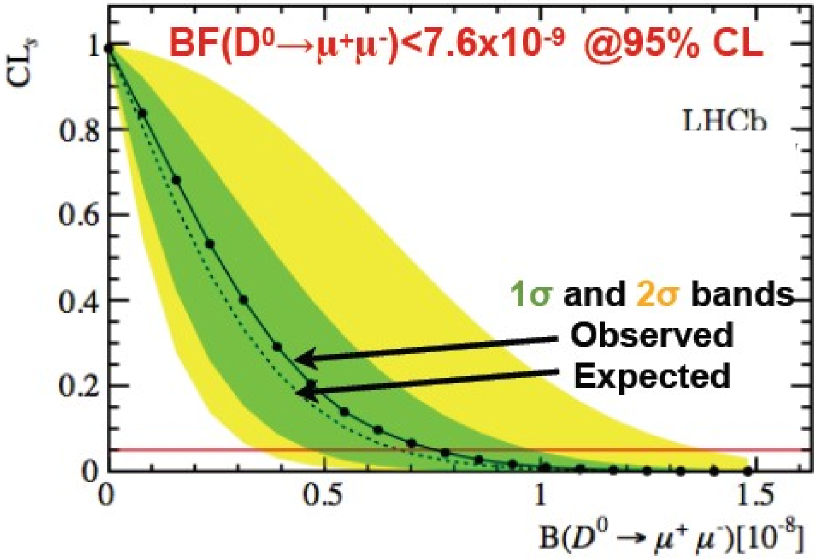


$D^0 \to \mu^+\mu^-$

1 fb^{-1} of pp collisions @ $\sqrt{s}$=7TeV
arXiv:1305.5059
Phys. Lett. B 725 (2013) 15-24







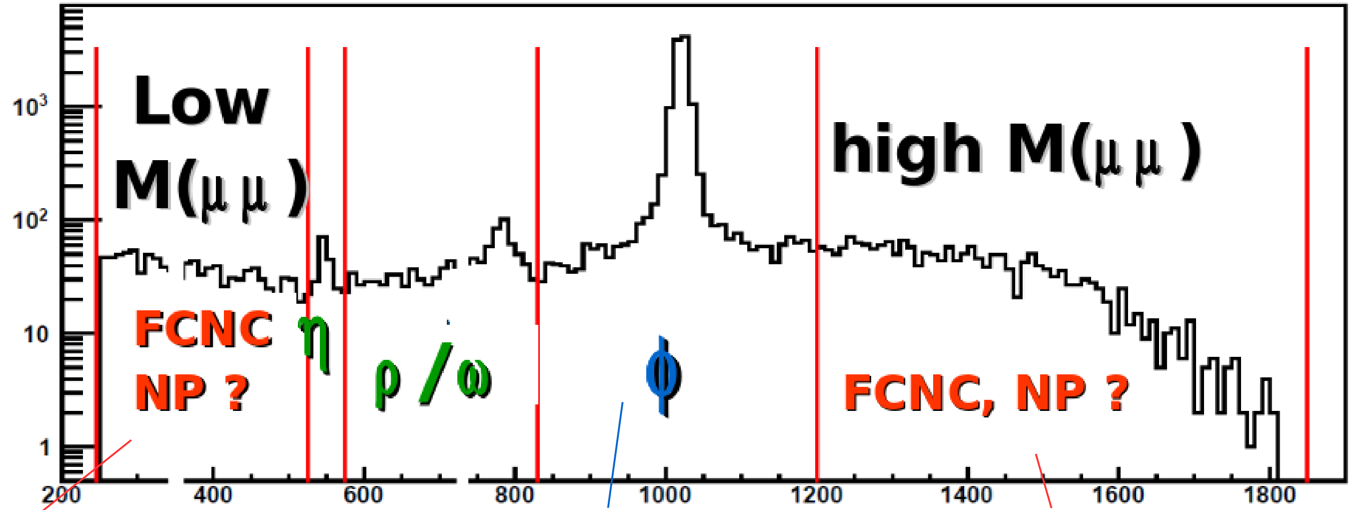
$BF(D^0 \to \mu\mu) < 6.2\ (7.6) \cdot 10^{-9}$
@ 90% (95%) CL

Best limit !
Still ~100× SM

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

1 fb^{-1} of pp collision s@ $\sqrt{s}$=7TeV

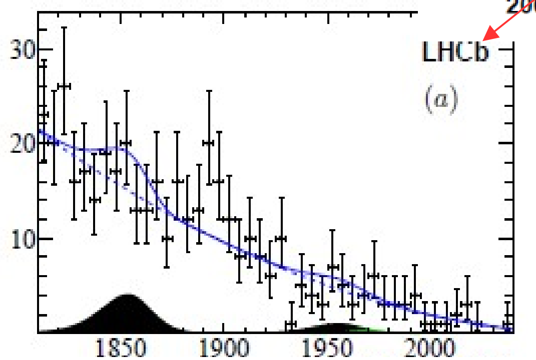
arXiv:1304.6365,
Phys. Lett. B 724 (2013) 203-212



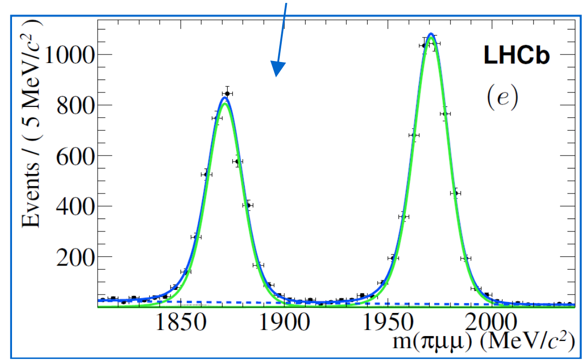
$D^+_{(s)} \to \pi^+ \phi\ (\mu^+\mu^-)$

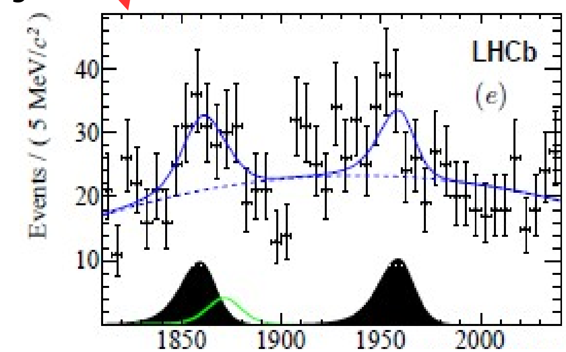
M(μμ) MeV/c

→ normalisation mode + signal proxy to optimize analysis



$M(D^+_{(s)})$ MeV/c





$M(D^+_{(s)})$ MeV/c

Signal
Comb. background:
Peaking backgrounds: $D^+_S \to \pi^+\pi^+\pi^-$

Limits 90(95%) C.L.: few 10^{-8}(10^{-7}) for D^+(D_s)

Region	$B(D^+ \to \pi^+\mu^+\mu^-)$	$B(D_s \to \pi^+\mu^+\mu^-)$
Low M(μμ)	2.0 (2.5) $\times 10^{-8}$	6.9 (7.7) $\times 10^{-8}$
High M(μμ)	2.6 (2.9) $\times 10^{-8}$	16.0 (18.6) $\times 10^{-8}$
Total	7.3 (8.3) $\times 10^{-8}$	41.0 (47.7) $\times 10^{-8}$

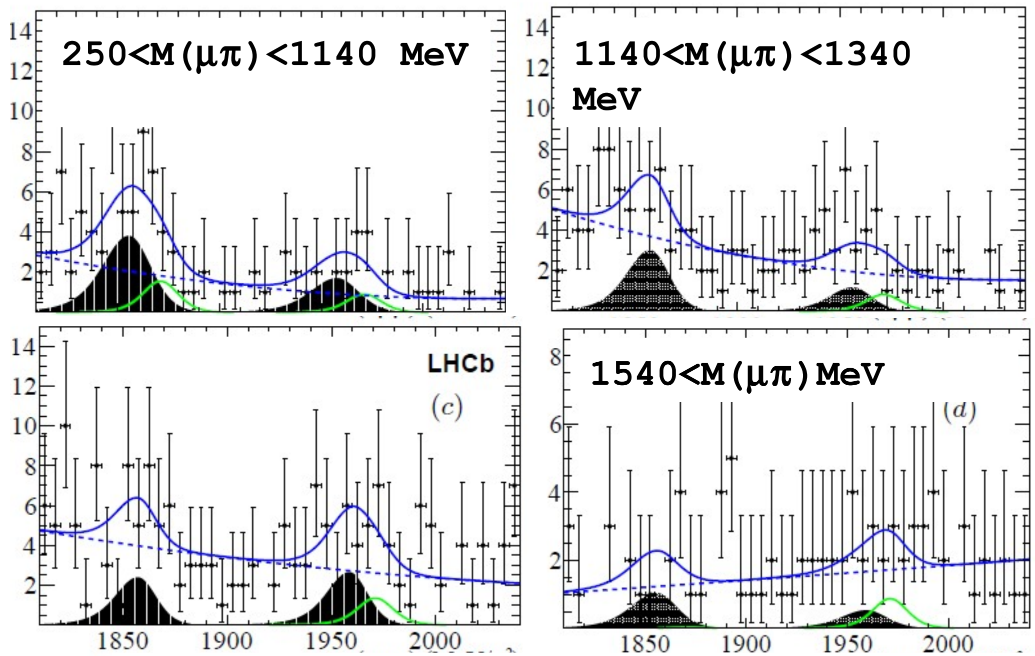
~ 1 order of magnitude above largest NP predictions.

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

1 fb^{-1} of pp collisions @ $\sqrt{s}$=7TeV

arXiv:1304.6365,
Phys. Lett. B 724 (2013) 203-212

Limits in four regions where a majorana ν could peak



M(πμμ) [MeV/c²]   M(πμμ) [MeV/c²]

Signal
Comb. background:
Peaking backgrounds: $D^+_S \to \pi^+\pi^+\pi^-$

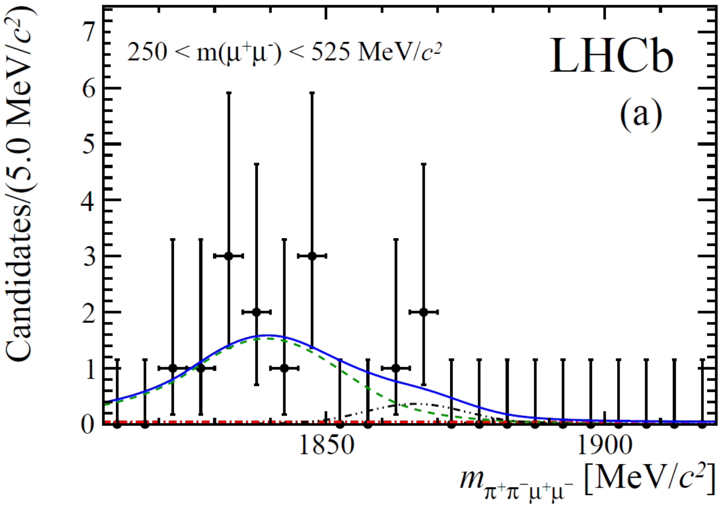
Limits 90(95%) C.L.: few 10^{-8}(10^{-7}) for D^+(D_s)

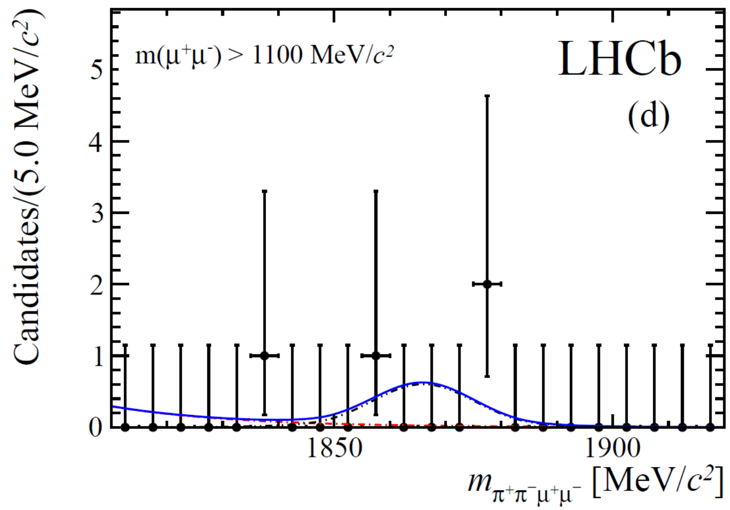
Region	$B(D^+ \to \pi^+\mu^+\mu^-)$	$B(D_s \to \pi^+\mu^+\mu^-)$
Total	2.2 (2.5) $\times 10^{-8}$	12.0 (14.1) $\times 10^{-8}$

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

1 fb^{-1} of pp collisions @ $\sqrt{s}$=7TeV
arXiv:1310.2535

- Normalized to $D^0 \to \pi^+\pi^- \phi(\mu^+\mu^-)$: $B=(5.2\pm1.1)\times10^{-7}$ derived from the ampl. ana. of $D^0 \to \pi^+\pi^- K^+K^-$ []





- Signal
- $D^0 \to \pi\pi\pi\pi$
- Comb.Bkg.

Upper limit	Bin	90% [$\times10^{-7}$]	95% [$\times10^{-7}$]
	low-$m(\mu^+\mu^-)$	2.3	2.9
$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-)$	high-$m(\mu^+\mu^-)$	1.0	1.2
	Total	5.5	6.7

U.L. at a few 10^{-7}
Still ~2 orders of magnitude above NP predictions.

In the future ?

Near future (2015-2016)

Expect a 1st study, or an update, of these modes with Run I data:

- Update of $D^0 \to \mu^+\mu^-$.
- Measurement of $D^0 \to K^-\pi^+ \mu^+\mu^-$ in the ρ/ω region of $m(\mu\mu)$. Provides normalization mode to other $D^0 \to h^+h'^{(-)}\mu^+\mu^-$ studies. Olga Kochebina's PhD thesis.
- First study of $D^0 \to K^+K^- \mu^+\mu^-$, $D^0 \to K^-\pi^+ \mu^+\mu^-$, $D^0 \to K^+\pi^- \mu^+\mu^-$. Measure partial BF's both in resonant and low/high $m(\mu\mu)$ regions.
- Update of $D^0 \to \pi^+\pi^- \mu^+\mu^-$.
- Update of $D^+_{(s)} \to \pi^+\mu^+\mu^-$.

  Extension to $D^+_{(s)} \to K^+\mu^+\mu^-$.
- First study of LFV in $D^0 \to \mu e$.
- First study of $\Lambda_c \to p\mu\mu$.
- First study of $D^0 \to \phi\gamma$.

Not sure to have the manpower for all...

Possible Upper Limits in future datasets

Based on the results shown on the previous slides, we 'guestimate' future sensitivities:

- Assume same efficiencies & S/B (possible improvements shouldn't change order of mags.)
- Scale according to rise in Lumi and X-sections.

In already published modes we expect to be sensitive to NP at the level of

Modes	Run I	Run II	Upgrade	Comments
$D^0 \to \mu^+\mu^-$	few 10^{-9}	fewer 10^{-9}	few 10^{-10}	Also improvements in the analysis
$D^+ \to \pi^+\mu^+\mu^-$	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_s shorter lived + less produced
$D^0 \to h^+h'^{(-)}\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	few 10^{-8}	Also improvements in the analysis

Work started on 3 new modes, including 2 challenging final states. NP Sensitivity:

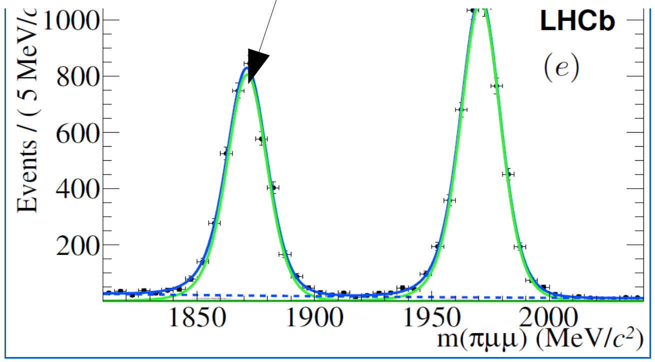
$\Lambda_c \to p\mu\mu$	few 10^{-7}	fewer 10^{-7}	few 10^{-8}	
$D^0 \to \mu e$	few 10^{-8}	fewer 10^{-8}	few 10^{-9}	Harder than $\mu\mu$: electron! Possible in Upgrade conditions ?
$\sigma A_{CP}(D^0 \to \phi\gamma)$	10%	5%	?	Soft photon ! Very hard to tell from $D^0 \to \phi\pi^0$ Possible in Upgrade conditions ?

Sensitivities to asymmetries in multi-body rares modes

They can be estimated for various datasets from:

- Yields in 1 fb^{-1} (ex: ~3000 $D^+ \to \pi^+\mu\mu$, ~150 $D^0 \to \pi^+\pi^-\mu\mu$)
- The background yields (vary between modes).
- The luminosities, X-sections, Branching ratios [PDG, 3].
- The MC efficiencies.

$D^+ \to \pi^+ \mu\mu$ in $\phi(\mu\mu)$ region, 1fb^{-1}



arXiv:1304.6365, Phys. Lett. B 724 (2013) 203-212

	BF×10^6	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%**

- **O(1%) asymmetries hard to measure even with the upgrade. Possible in $D^+ \to \pi^+\mu\mu$.**
- **O(5%) asymmetries may be detectable with $D^0 \to \pi^+\pi^-\mu\mu$.**
- **Other modes ? Hope if actual BF's larger than theoretical predictions, if improvements in the analysis (ex: better trigger for the Upgrade), ...**

Questions to theorists...

Priorities ?

Possible plan in the next few years (with LHCb Run I and Run II): Update or first study of BF's in

- $D^0 \to \mu^+\mu^-$
- $D^0 \to h^+h'^{(-)}\mu^+\mu^-$ (h,h'=K,π)
- $D^0 \to \mu e$
- $D^+_{(s)} \to h^+\mu^+\mu^-$ (h=K,π)
- $\Lambda_c \to p\mu\mu$
- $D^0 \to \phi\gamma$

Note: this list is not meant to be exhaustive.

1st asymmetries studies can be tried with Run II, but more in our plans for the Upgrade.

→ Did we miss above any promising mode you regard as a priority ?

→ Any priority among the modes above ?

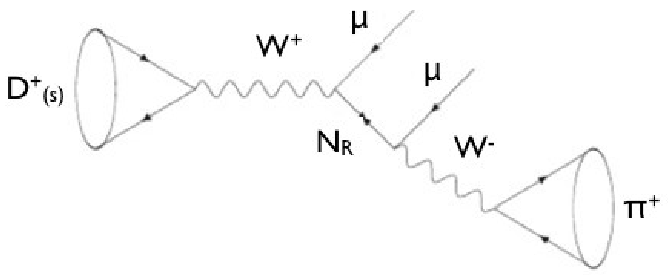
Lepton Number and Flavor Violation

Most of our studies focus on FCNC decays.

One excursion in the LNF world: $D^+_{(s)} \rightarrow \pi^- \mu^+ \mu^+$

→ Is it useful to update this decay ?

→ Can it bring better constraints than searches in B decays (or elsewhere) ?



Currently preparing our first search for LFV in charm: $D^0 \rightarrow \mu e$.

→ Is it worth searching for other LFV charm modes (Ex: $D \rightarrow (h^+)h'^- \mu e$) ?

FCNC modes: Interplay between modes, between observables ?

Taken individually, most of the modes we study can't reach easily the predicted NP-induced BF's and Asymmetries.

LHCb is able to study lots of modes and lots of observables (2-, 3-, 4-decays, BF's, CP and angular asymmetries)

→ Shall we try to combine all available info. to precisely assert how constrained NP is ?

→ Isn't it THE way to follow now in rare charm ?

→ Any limitation in this due to QCD-related σ_{th} ?

Asymmetries depend on the size of NP contributions (ex: size of C10 that generates A_{FB})

→ Could asymmetries become hopeless once U.L.'s reach a few 10^{-10} in $D^0 \to \mu\mu$ and a few 10^{-9} in $D \to (h^+)h'^- \mu\mu$ (i.e. during the upgrade) ?

$D^0 \to \mu\mu$ seems to provide the most stringent constraints. With an overlap with multibody modes (example in back-up)

→ Will Multibody decays remain useful regardless of the U.L. on $D^0 \to \mu\mu$?

Corollary: during Run II, should we spend more efforts on the improvement of our sensitivity to this mode than on other studies ?

FCNC modes: NP models ?

The NP studies we are familiar with are

- Extra up quark singlet [7]
- Littlest Higgs model [6], with T-parity [2]
- SUSY with and without R-parity [1,8,4]
- Leptoquarks [9]
- RS model with Extra Warped Dimension [5]
- Generic Z(') models [3]

[7] S. Fajfer *et al*, Phys. Rev. D76 (2007) 074010, arXiv:0706.1133.
[6] S. Fajfer *et al*, Conf. Proc. C060726 (2006) 811, arXiv:hep-ph/0610032 and Phys. Rev. D73 (2006) 054026, arXiv:hep-ph/0511048.
[2] A. Paul *et al.*, Phys. Rev. D83 (2011) 114006, arXiv:1101.6053.
[8] G. F. Giudice *et al*, JHEP 1204 (2012) 060, arXiv:1201.6204.
[4] S. Fajfer *et al*, Phys. Rev. D87 (2013) 054026, arXiv:1208.0759.
[9] S. Fajfer *et al*, Phys. Rev. D79 (2009) 017502, arXiv:0810.4858.
[5] A. Paul *et al*, arXiv:1212.4849.
[3] L. Cappiello *et al*, JHEP 1304 (2013) 135, arXiv:1209.4235.

Most of them predict "modest" effects in $D \to (h^+)h'^- \mu\mu$ modes

- B^{SD} hardly exceed a few 10^{-9}.
- Asymmetries O(1%), ie rarely more than 5%.

Previous slides: detecting this is unlikely with LHCb Run II. Still hard with the Upgrade.

→ Any model we missed, that would predict more ?

→ Any new observable ?

→ Is one of the models above out of the game due to recent experimental constraints ?

FCNC: more sensitive observables ?

<u>**Example**</u>**: Ref [4] studied 2 CPV observables based on A_{CP}**

$$A_{CP}(m_1, m_2) = \frac{\Gamma(m_1 < m_{\ell\ell} < m_2) - \bar{\Gamma}(m_1 < m_{\ell\ell} < m_2)}{\Gamma(m_1 < m_{\ell\ell} < m_2) + \bar{\Gamma}(m_1 < m_{\ell\ell} < m_2)}$$

$$C^{\phi}_{CP} \equiv A_{CP}(m_\phi - 20\,\mathrm{MeV}, m_\phi + 20\,\mathrm{MeV})$$

Φ resonance: lots of stat, but A_{CP} <1%

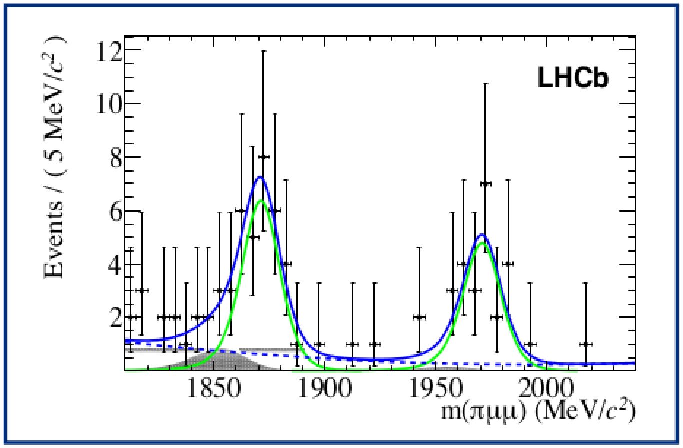
$$S^{\phi}_{CP} \equiv A_{CP}(m_\phi - 40\,\mathrm{MeV}, m_\phi - 20\,\mathrm{MeV}) - A_{CP}(m_\phi + 20\,\mathrm{MeV}, m_\phi + 40\,\mathrm{MeV})$$

Wings of Φ resonance: Up to 5%, but low stat.

The asymmetry seems maximal where A_{SD} is less clouded by A_{LD} .
On the other end: lower stat here thus lower sensitivity.

Ideas of observables that would allow an optimal trade-off ?

Ex: $\eta(\mu\mu)$ region in $D^+ \to \pi^+ \mu^+ \mu^-$ contains ~100 events in 1 fb-1. Could be sensitive to asymmetries O(5%) with the upgrade.



Generically:

- **~3% asymmetries in the ϕ region of $D^+ \to \pi^+\mu^+\mu^-$ woud be measurable in Run II.**
- **Elsewhere: need >10% effects.**

Note: for any new idea, we will be happy to determine LHCb's sensitivity for Run II and Upgrade.

Other ideas...

In LHCb's Run I

- O(100) $D^+ \to \pi^+\eta(\mu^+\mu^-)$, $D^+ \to \pi^+\rho(\mu^+\mu^-)$, $D^0 \to \pi^+\pi^-\phi(\mu^+\mu^-)$reconstructed
- O(1000) $D^+ \to \pi^+\phi(\mu^+\mu^-)$, $D^0 \to K^-\pi^+\rho(\mu^+\mu^-)$, $D^0 \to K^-\pi^+\omega(\mu^+\mu^-)$
- O(10) $D^0 \to K^-\pi^+\eta(\mu^+\mu^-)$, $D^0 \to K^-\pi^+\eta'(\mu^+\mu^-)$

~4 times more with Run II, 40 times more with the Upgrade

These modes have been studied in hadronic final states (sometimes with complicated amplitude analyses).

→ Can it help to now have them as well in dimuon final states ?

At LHCb, charm is becoming a clean and prolific $(\eta,\rho,\omega,\phi,\eta') \to \mu\mu$ **factory.**

→ Is there something to learn there ?

Back-up slides

Questions

- **A large fraction of the models we're aware of have only a limited effect on B^{SD} in $D\to (h^+)h'^- \mu\mu$ modes (hardly reach 10^{-8}). What models do better than that ?**

- **Constraints from $B(D^0 \to \mu\mu)$ on NP effects in $D\to (h^+)h'^- \mu\mu$?**

  Is it still possible to find $B^{SD}(D\to (h^+)h'^- \mu\mu)\sim 10^{-9}$ or 10^{-8} if $B(D^0\to \mu\mu) < 10^{-9}$? 10^{-10} ?

  Are there models that impact only one of the two modes ?
  Ex: models generating effects on C7 and C9,C10 independently ?

Ex: Talk by Nejc Kosnic at the 2013 implication workshop:
RPV SUSY via C9, C10 hard to detect even with the Upgrade.

$\boxed{|\lambda_b \delta C_9^{\mathrm{RPV}}|, |\lambda_b \delta C_{10}^{\mathrm{RPV}}| < 1.2}$ Stronger than from semileptonic decay!

Repercussion on $D^+ \to \pi^+\mu^+\mu^-$ of constraints from $D^0 \to \mu\mu$ on RPV SUSY

Decay	Bin	90% [$\times 10^{-8}$]	
$D^+ \to \pi^+\mu^+\mu^-$	low-$m(\mu^+\mu^-)$	2.0	0.18
	high-$m(\mu^+\mu^-)$	2.6	0.60
	Total	7.3	1.8

More...

- $D^0 \to \mu\mu$ constrains essentially the C9, C10 terms.
- Now seems difficult to get measurable NP in $D \to (h^+)h'^- \mu\mu$ from C9, C10 (next slide).
- C7 is sub-dominant in $D \to (h^+)h'^- \mu\mu$ BF's.

→ Are there NP models which effects on C7 are independent from those on C9 & C10, and are large enough to be seen in B($D \to (h^+)h'^- \mu\mu$) ?

→ If we reach $B^{SD}(D^+ \to \pi^+\mu^+\mu^-) <$ few 10^{-8} or 10^{-9}, is it stronger a constraint than from CP asymmetries like in [] ?