Very Rare Charm Decays

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The 12th Flavor Physics & CP Violation, 25-30 May 2014, Marseille, France

How rare is VERY rare ?

$D^0 \to \mu^+ e^-$
$D^0 \to p e^-$
$D^+_{(s)} \to h^+ \mu^+ e^-$

$D^+_{(s)} \to \pi^+ l^+ l^-$
$D^+_{(s)} \to K^+ l^+ l^-$
$D^0 \to K^- \pi^+ l^+ l^-$
$D^0 \to K^{*0} l^+ l^-$

$D^0 \to \pi^- \pi^+ V(\to ll)$
$D^0 \to \rho\ V(\to ll)$
$D^0 \to K^+ K^- V(\to ll)$
$D^0 \to \phi\ V(\to ll)$

$D^0 \to K^{*0} \gamma$
$D^0 \to (\phi, \rho, \omega)\ \gamma$
$D^+_s \to \pi^+ \phi(\to ll)$

LFV, LNV, BNV | FCNC | VMD | Radiative

0 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4}

$D^+_{(s)} \to h^- l^+ l^+$
$D^0 \to X^0 \mu^+ e^-$
$D^0 \to X^{--} l^+ l^+$

$D^0 \to \mu\mu$
$D^0 \to ee$

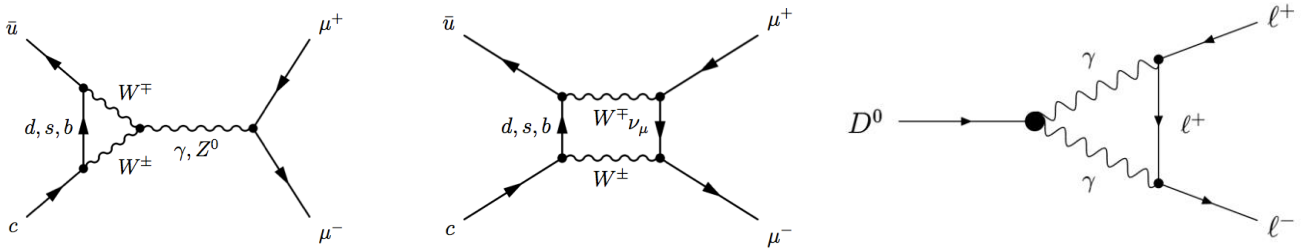
$D^0 \to \pi^- \pi^+ l^+ l^-$
$D^0 \to \rho\ l^+ l^-$
$D^0 \to K^+ K^- l^+ l^-$
$D^0 \to \phi\ l^+ l^-$

$D^0 \to K^+ \pi^- V(\to ll)$
$D^0 \to \bar{K}^{*0} V(\to ll)$
$D^0 \to \gamma\gamma$

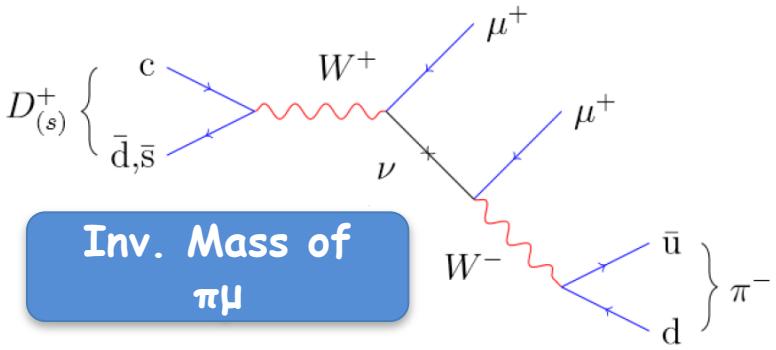
$D^+ \to \pi^+ \phi(\to ll)$
$D^0 \to K^- \pi^+ V(\to ll)$
$D^0 \to K^{*0} V(\to ll)$

Why rare decays so charming ?

- Rare decay helps to constrain effects from New Physics
- Flavor Changing Neutral Currents (FCNC) are highly suppressed in the Standard model (SM), possibly only via loops



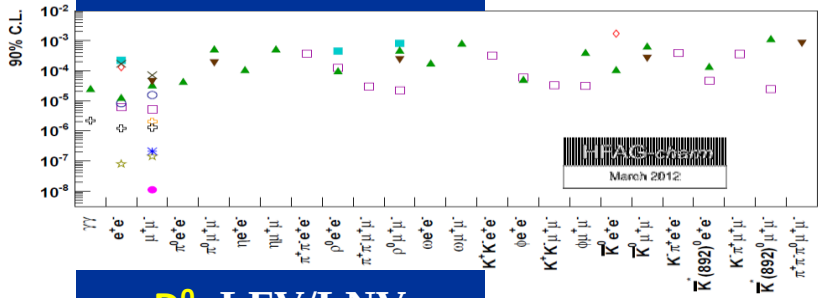
- Indirect: New particles (virtual, high mass) enter loops → enhance BFs → New Physics !
- Direct: New particles (real) can enhance BFs significantly → New Physics !



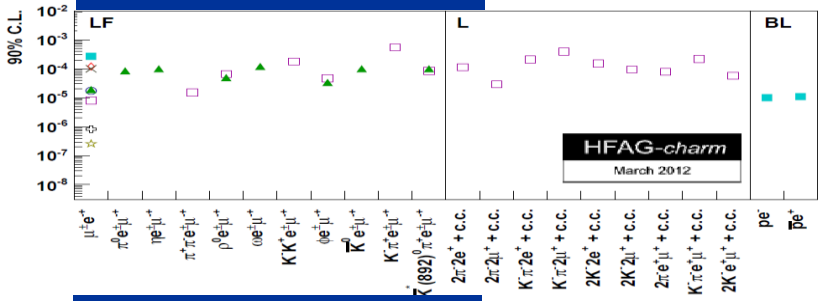
- Charm is complementary to the B and K sectors: it's a unique window on NP affecting the up-type quark dynamics

Experimental status up to 2012

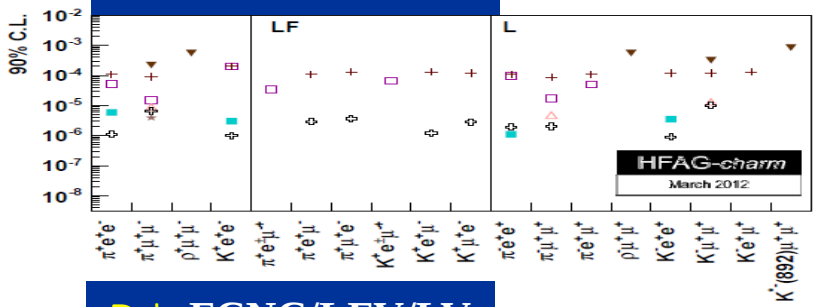
D^0: FCNC



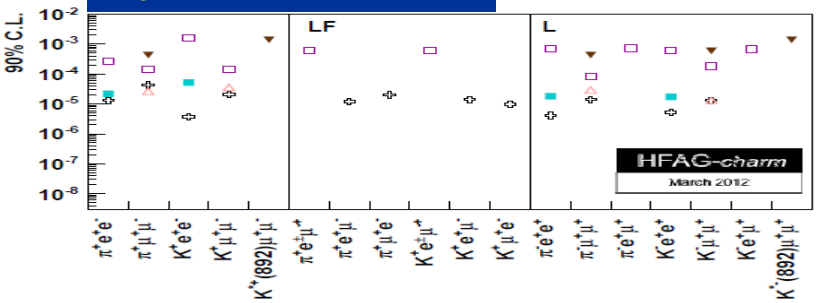
D^0: LFV/LNV



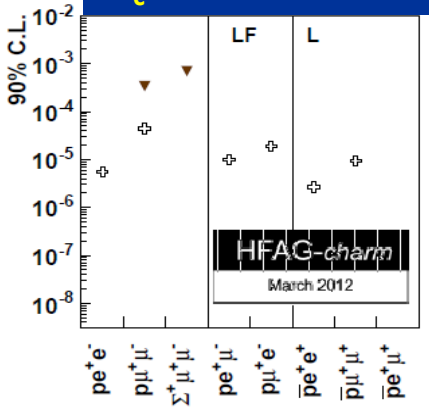
D^+: FCNC/LFV/LV

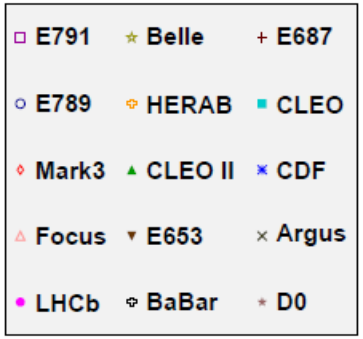


D_s^+: FCNC/LFV/LV



Λ_c^+: FCNC/LFV/LV





HFAG, arXiv: 1207.1158

HFAG2012:
No surprising yet

What's new?

☐ FCNC:

- ✓ $D^0 \to \mu^+\mu^-$ @ LHCb, PLB725 (2013) 15
- ✓ $D^0 \to ll'$ @ Babar, PRD86 (2012) 032001
- ✓ $D^0 \to \gamma\gamma$ @ Babar, PRD85 (2012) 091107
  @ BESIII, 1208.4744 (2012)
- ✓ $D^0 \to \pi^+\pi^-\mu^+\mu^-$ @ LHCb, PLB728 (2014) 234
- ✓ $D_{(S)}^+ \to \pi^+\mu^+\mu^-$ @ LHCb, PLB724 (2013) 203

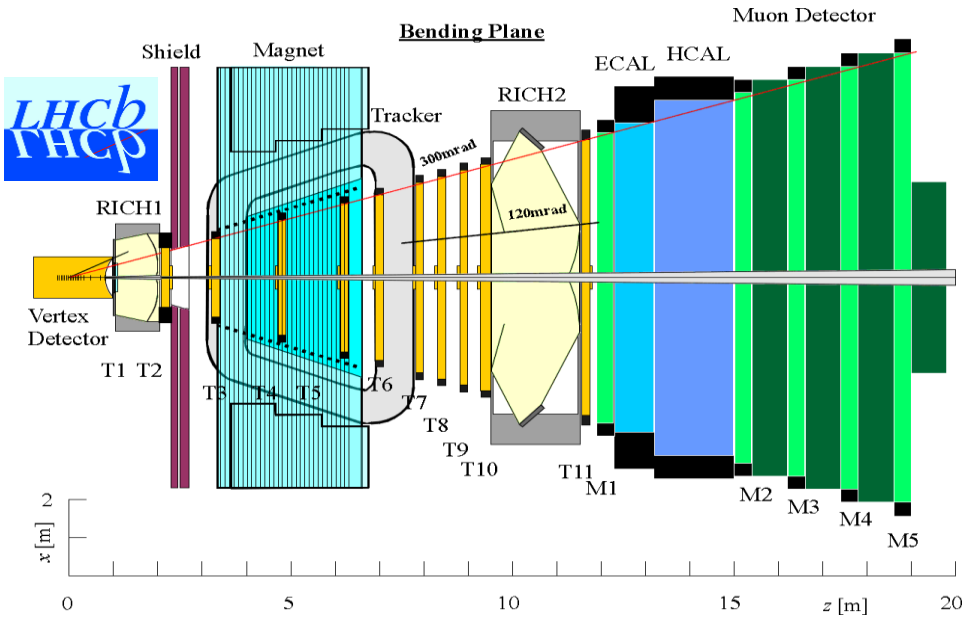
☐ LNV:

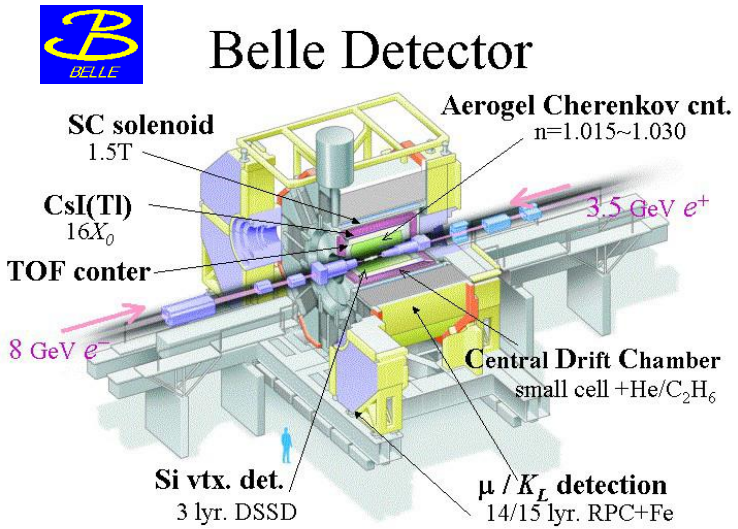
- ✓ $D_{(S)}^+ \to \pi^-\mu^+\mu^+$ @ LHCb, PLB724 (2013) 203

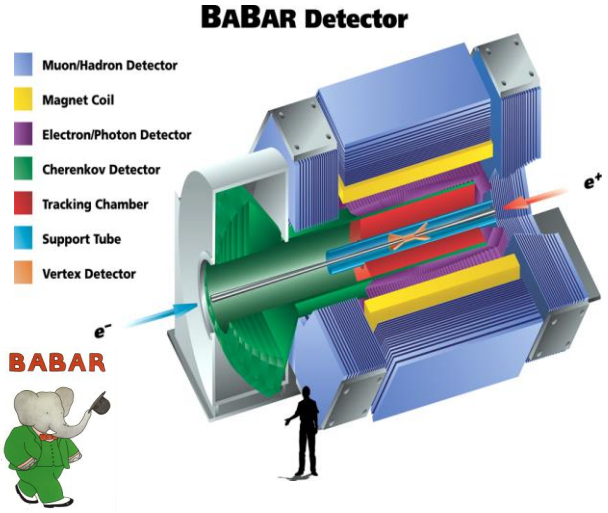
☐ LFV: latest results @Babar, 2011 ($D_{(S)}^+$ and Λ_c^+)

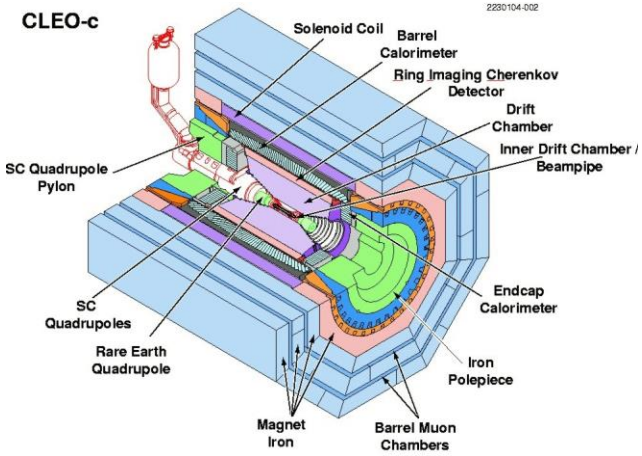
☐ BNV: latest results @ CLEOc, 2009 ($D^0 \to pe^-/p^{bar}e^+$)

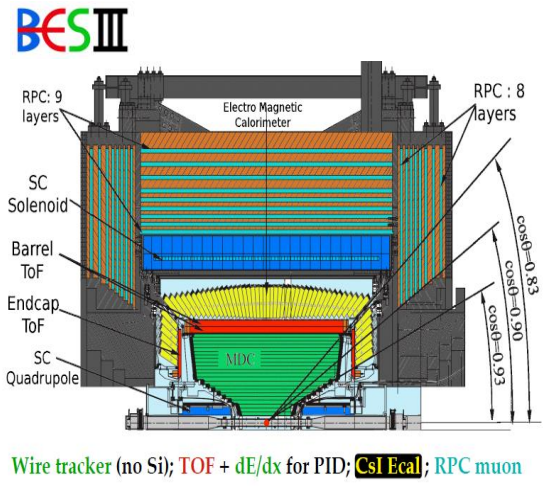
Heavy Flavor Factories





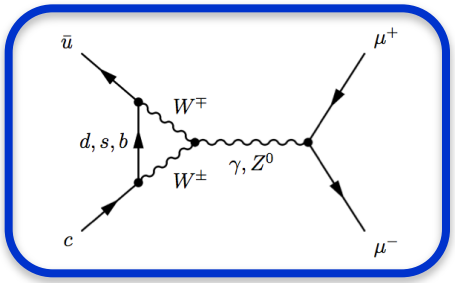


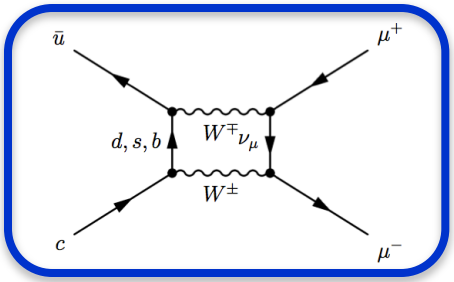


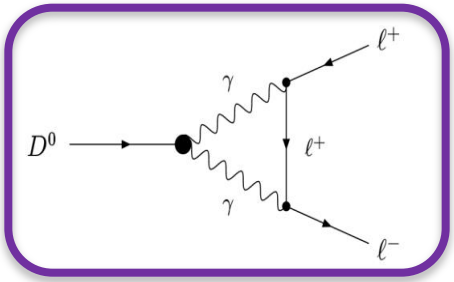


$D^0 \to l^+ l^-$

- Within Standard Model







$B_{SM}^{FCNC} \sim 10^{-18}$ [PRD66 (2002) 014009]
(helicity, in addition to GIM, suppressed)

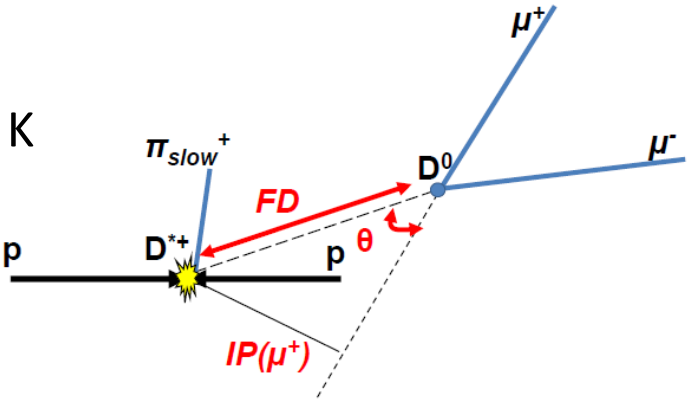
$B_{SM}^{RES.} \sim 10^{-11}$ [PRD66 (2002) 014009]
(10^{-5} times $B(D^0 \to \gamma\gamma)$)

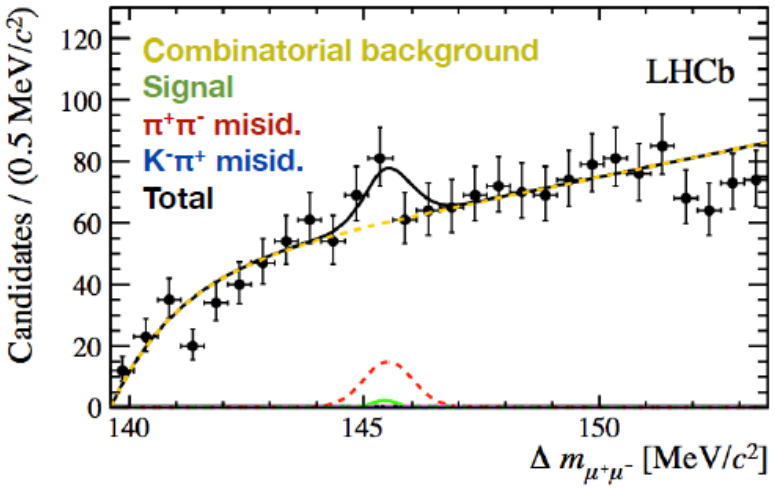
- Beyond Standard Model
  - NP (i.e. R-parity violating) may increase *BF to ~10^{-10} [arXiv: 1212.4849]*

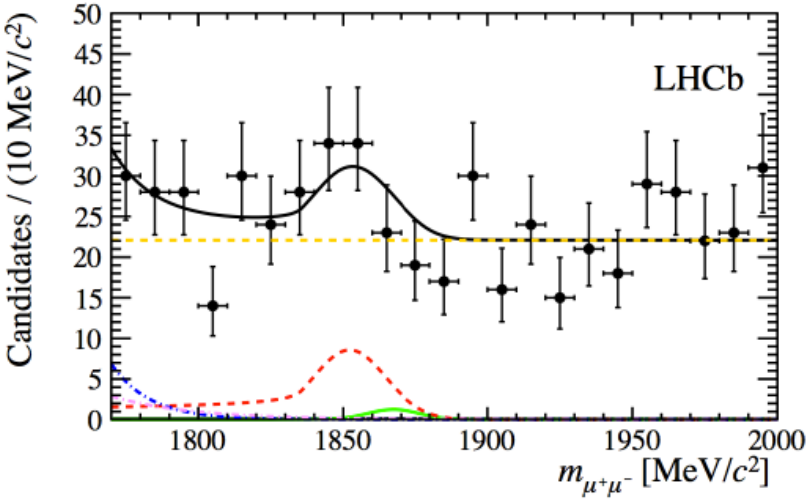
$D^0 \to \mu^+\mu^-$ @ LHCb

- Use D^0 from D^{*+} decay, $D^{*+} \to D^0(\to \mu^+\mu^-)\pi^+_s$
- Normalization channel : $D^{*+} \to D^0(\to \pi^+\pi^-)\pi^+_s$
- Peaking bkgs : $D^{*+} \to D^0(\to h^+h^-)\pi^+_s$, where h is π or K
- 2D fit in $\Delta m_{\mu+\mu-}$ ($m_{\mu+\mu-\pi+s}$ - $m_{\mu+\mu-}$) and $m_{\mu+\mu-}$

Figures from:
Phys. Lett. B 725 (2013) 15-24







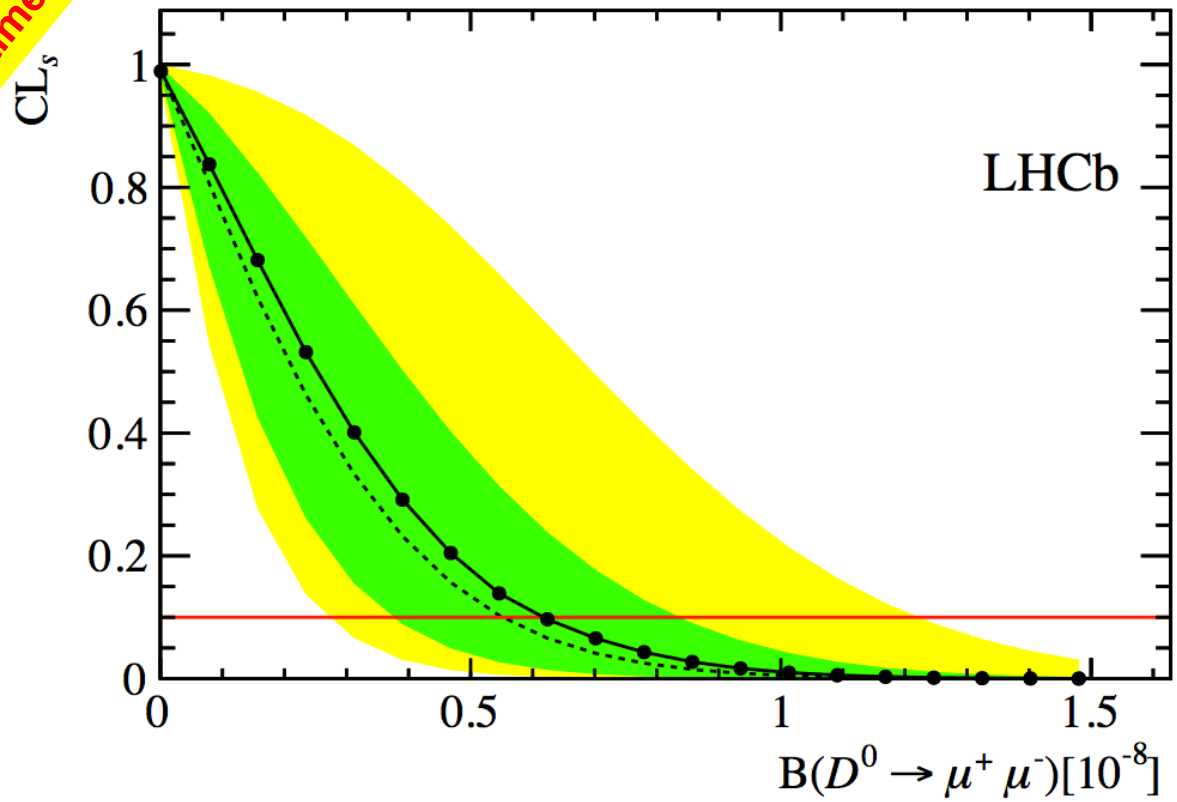
$D^0 \to \mu^+\mu^-$ @ LHCb

Figures from:
Phys. Lett. B 725 (2013) 15-24

- No observed signal, set upper limit

~ 20 times better

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

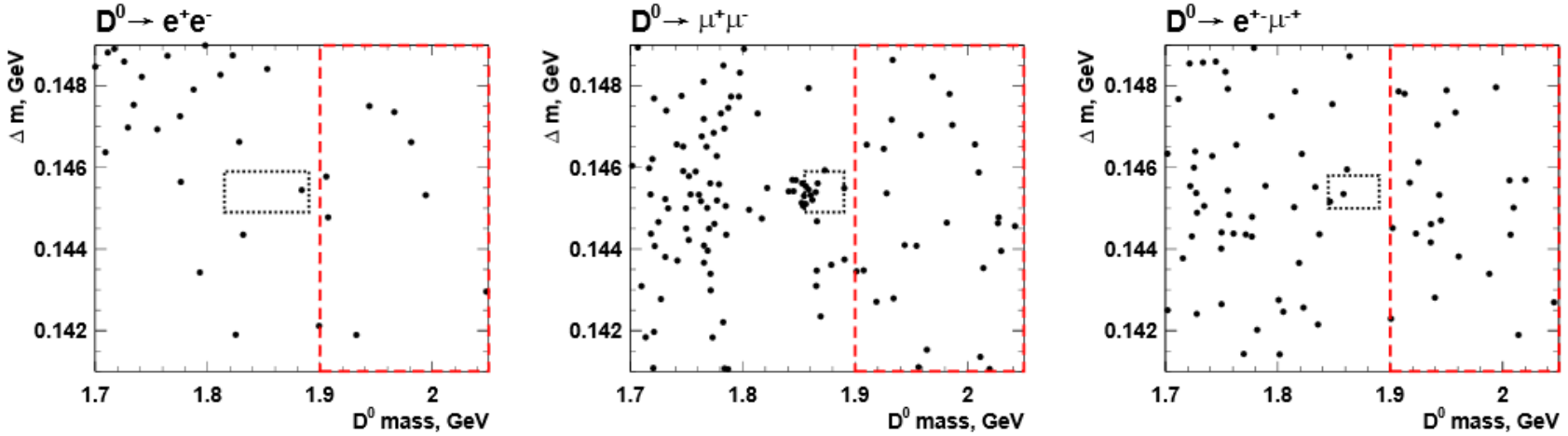


$D^0 \to l^+ l^-$ @ BaBar

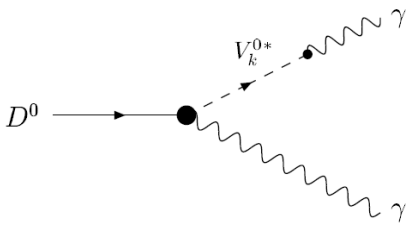
Figures from:
Phys. Rev. D 86 (2012) 032002

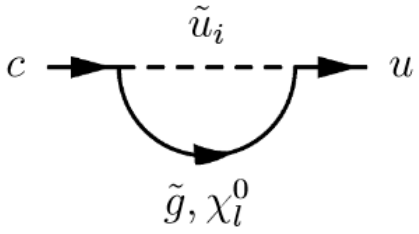
- D^0 reconstructed in e^+e^-, $\mu^+\mu^-$ (FCNC) and $e^{\mp}\mu^{\pm}$(LFV)
- Normalized to the $\pi^+\pi^-$ mode, and the $K^-\pi^+$ mode used to do misID
- Multivariate methods (Fisher) used to reject large amount of combinatorial events. $\cos\theta_H$ used as well to reject BB events
- Excess is not statistically significant and compatible with upward bkgs fluctuation.

BF($D^0 \to e^+e^-$)<1.7x10^{-7} @90% **BF($D^0 \to \mu^+\mu^-$) in [0.6,8.1]x10^{-7} @90%** **BF($D^0 \to e^+\mu^-$)<3.3x10^{-7} @90%**



$D^0 \to \gamma\gamma$ @ Babar





- Forbidden at tree level

→ GIM suppressed.

→ Short distance: BF~10^{-11} [PRD66 (2002) 014009]

→ Long distance due to Vector Meson Dominance: BF~10^{-8} [PRD66 (2002) 014009]

→ MSSM enhancement up to BF~10^{-6} [PLB500(2001)304], i.e. c→uγ via gluino exchange

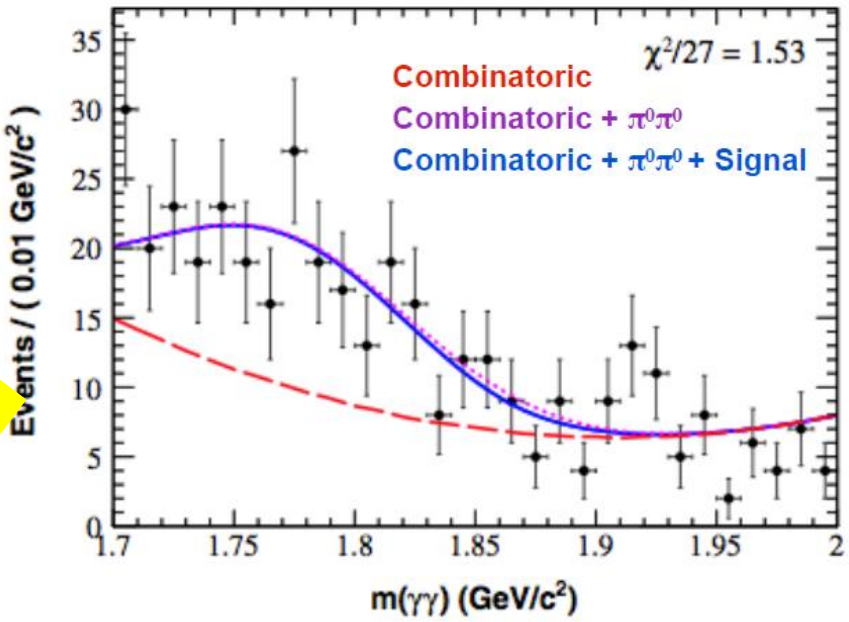
→ $D^0 \to K_S\pi^0$ used for normalization

→ $D^0 \to \pi^0\pi^0$ largest background. Studied using MC samples

→ Signal yield slightly negative and compatible with no signal observation

BF<2.4x10^{-6} @90% C

~ 10 times better

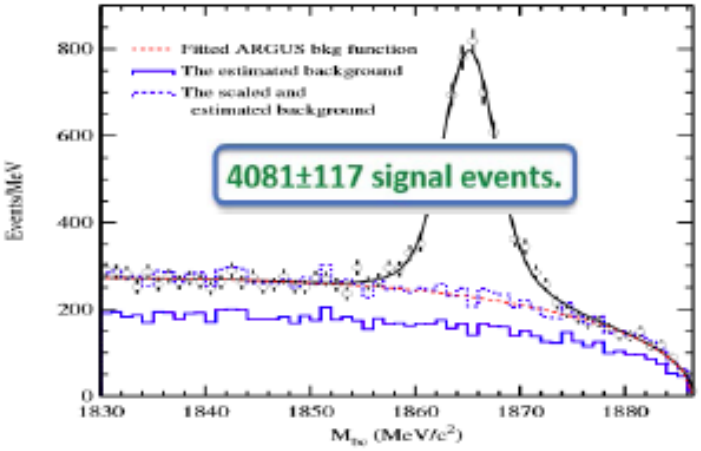


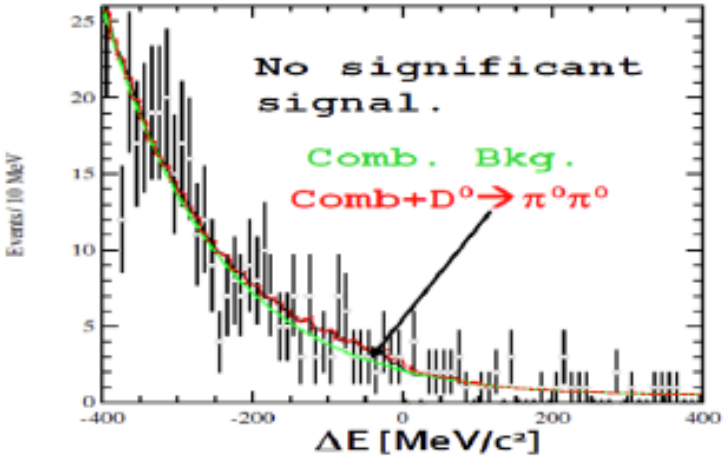
Phys. Rev. D 85 (2012) 091107R

$D^0 \to \gamma\gamma$ @ BESIII

Figures from:
arXiv: 1208.4744

- Ddbar pairs produced just above threshold, straight forward analysis
  1. Reconstruct only one of the two D^0s from $\psi(3770)$ decay with two γs or π^0s for $D^0 \to \gamma\gamma$ or $D^0 \to \pi^0\pi^0$, respectively, where $\pi^0 \to \gamma\gamma$
  2. Conservation of energy and momentum is required
     $\Delta E = E_{candidate} - E_{beam}$ should be consistent with zero
     $M_{BC} = \sqrt{(E_{Beam}^2 - p_{candidate}^2)}$ should be consistent with M_{D0}
- Normalized to $D^0 \to \pi^0\pi^0$
- Detail selection criteria are tuned based on MC samples
- Almost catch up with BaBar's results although 10 times less D^0 produced (21M)



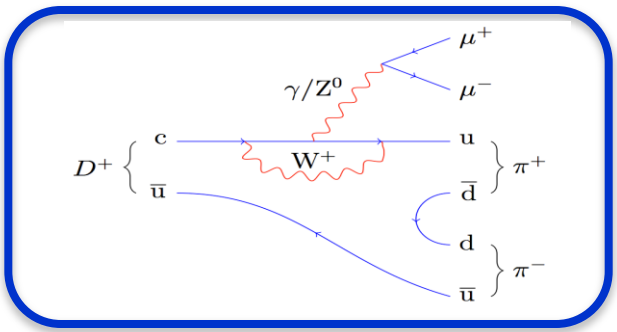


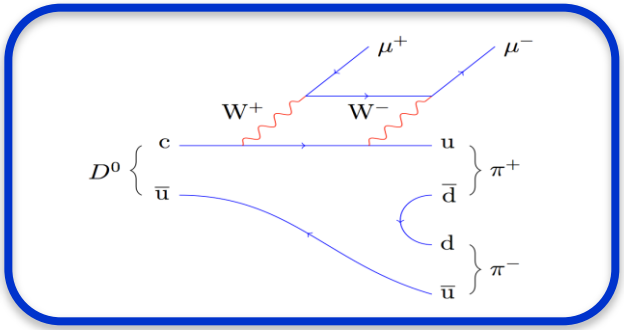
BF<4.7x10^{-6} @90% CL

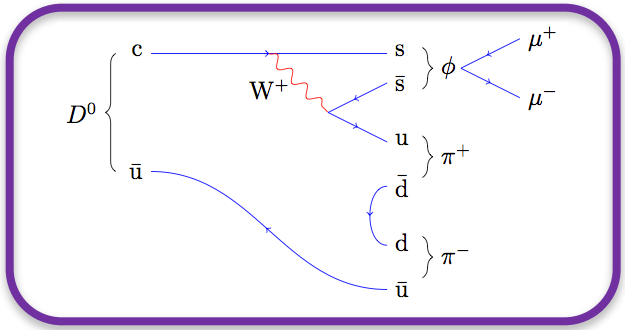
CLEO-c (6M D^0), BF<8.63x10^{-6} @90% CL

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

- Within Standard Model (i.g. $\pi^+\pi^-\mu^+\mu^-$, several experiments)



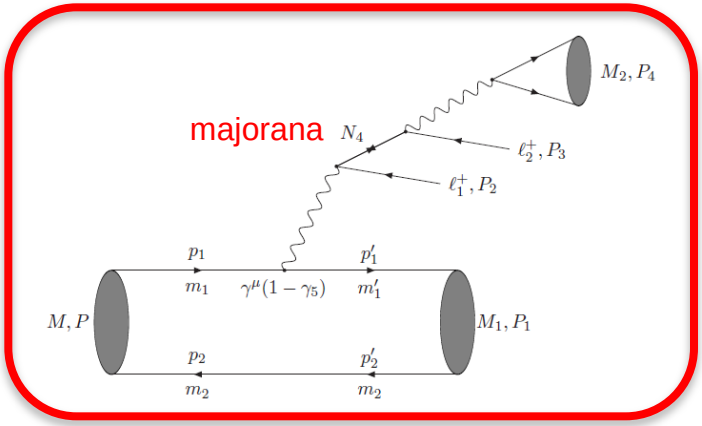


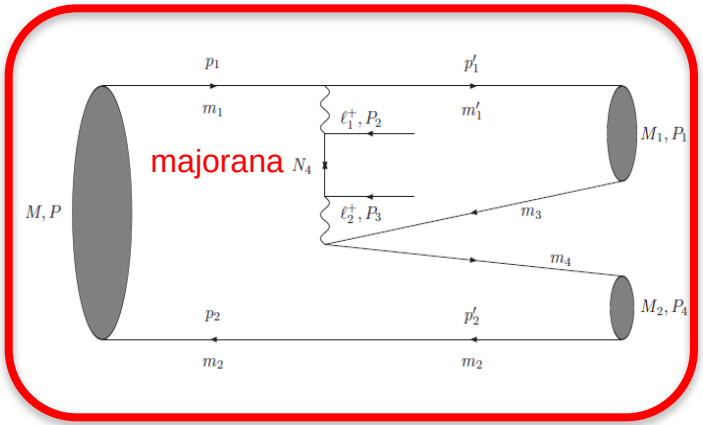


B_{SM}^{FCNC} ~ 10^{-18} [JHEP 1304(2002)135]

$B_{SM}^{RES.}$ ~ 10^{-7} [PRD85 (2012)122002]

- Beyond Standard Model (i.g. $K^-\pi^-\mu^+\mu^+$ and similar channels)



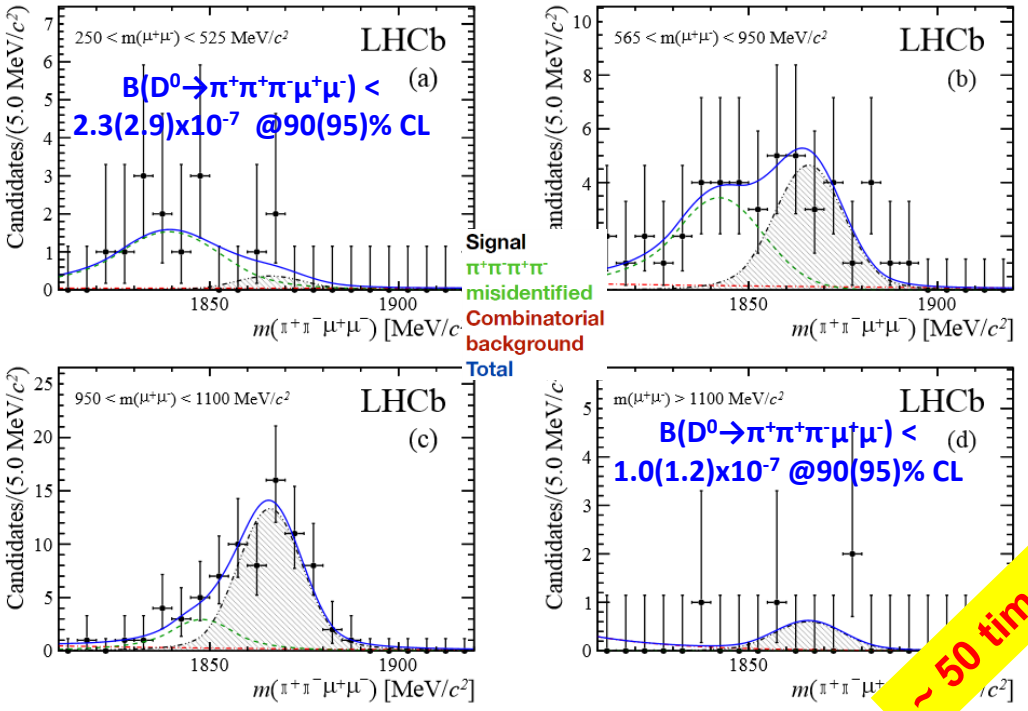


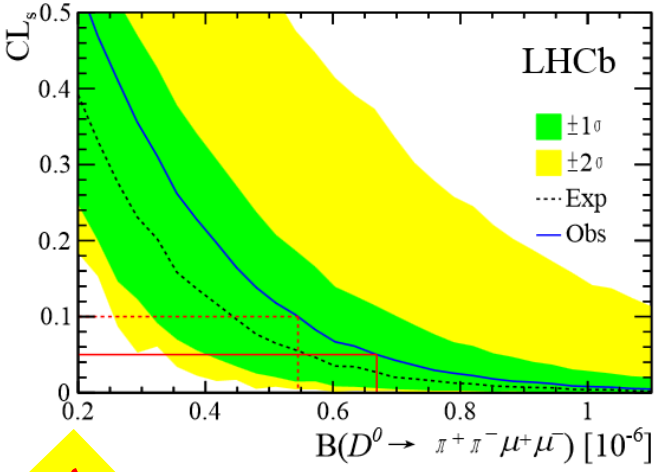
[JHEP 1308(2013) 66]

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

- Use D^0 from D^{*+} decay, $D^{*+} \to D^0(\to \pi^+\pi^-\mu^+\mu^-)\pi_s^+$
- Normalization channel : $D^0 \to \pi^+\pi^-(\mu^+\mu^-)_\phi$
- Peaking background : $D^0 \to \pi^+\pi^-\pi^+\pi^-$
- 2D fit to $m_{\pi+\pi-\mu+\mu-}$ and Δm ($m_{\pi+\pi-\mu+\mu-\pi+s}$ - $m_{\pi+\pi-\mu+\mu-}$) in each $m_{\mu+\mu-}$ bin

Range description	$m(\mu^+\mu^-)$ [MeV/c^2]
low-$m(\mu^+\mu^-)$	$250 - 525$
ρ/ω	$565 - 950$
ϕ	$950 - 1100$
high-$m(\mu^+\mu^-)$	> 1100





~ 50 times better

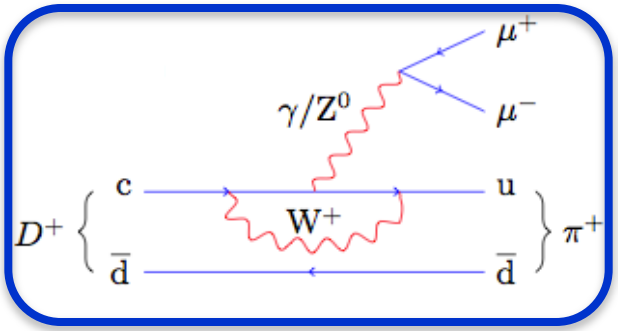
No observed signal, total results :
$B(D^0 \to \pi^+\pi^-\mu^+\mu^-) < 5.5(6.7)\times10^{-7}$ @90(95)% CL

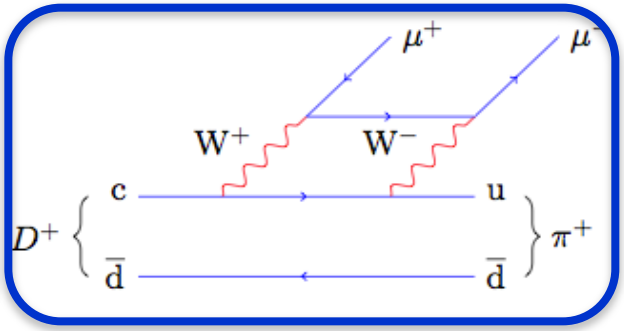
Figures from: Phys. Lett B 728 (2014) 234

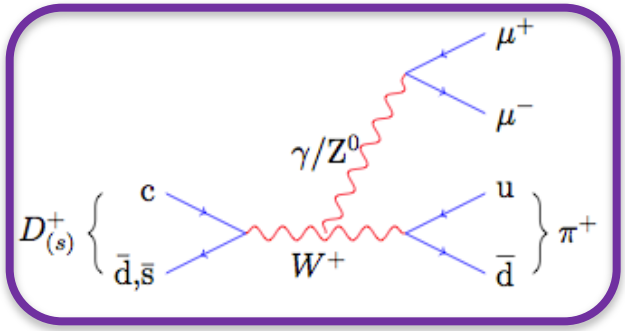
$D_{(S)}^{+} \to \pi^{\pm} \mu^{\mp} \mu^{+}$

- FCNC : $D_{(S)}^{+} \to \pi^{+} \mu^{+} \mu^{-}$ highly suppressed in SM by GIM mechanism $BF_{th} \sim 10^{-9}$ [PRD64 (2001) 114009]

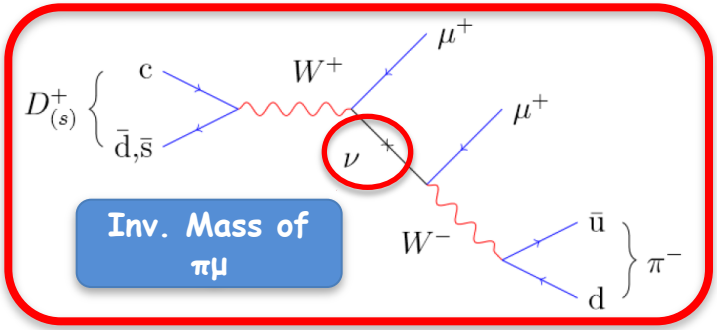
while can be enhanced by physics BSM [PRD 76 (2007) 76074010]

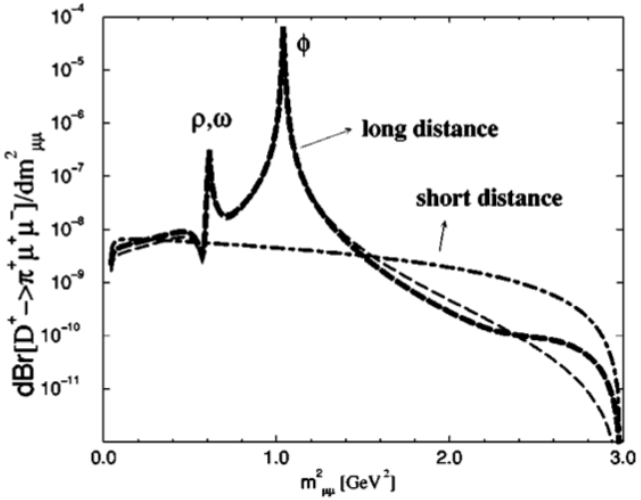






- ✓ Known resonances in $\mu^+\mu^-$ spectrum
- ✓ B(res.) ~ 10^{-6} (via ϕ) to 10^{-8} (via η and ρ/ω)
- ✓ Search for non-resonant signal away from resonances





- LNV : $D_{(S)}^{+} \to \pi^{-} \mu^{+} \mu^{+}$ forbidden in SM but allowed in models including Majorana neutrino

[EPJC71 (2011) 1715]

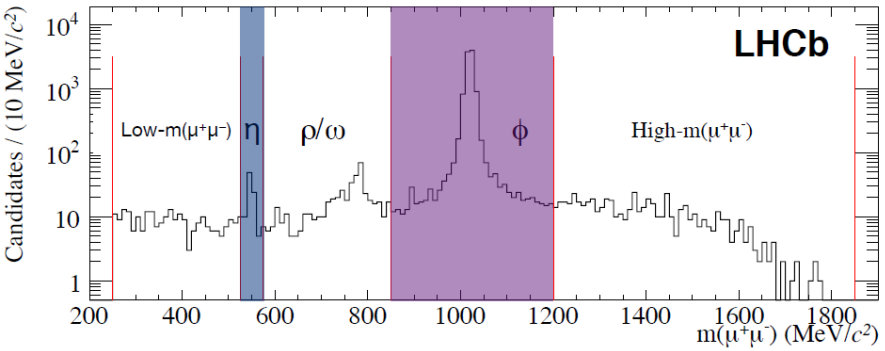
$D_{(s)}^{+} \to \pi^{+}\mu^{+}\mu^{-}$ @ LHCb

→ Peaking background : $D_{(s)}^{+} \to \pi^{+}\pi^{+}\pi^{-}$

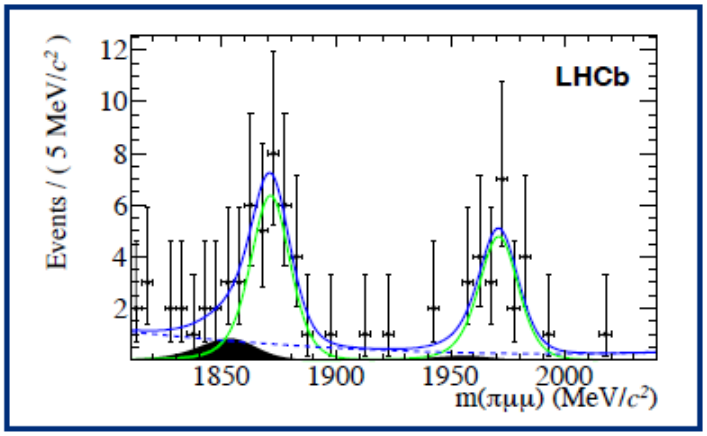
→ Normalization channel : $D_{(s)}^{+} \to \pi^{+}(\mu^{+}\mu^{-})_{\varphi}$

→ Analysis performed in regions of $q^2=M^2(\mu+\mu-)$

→ Simultaneous fit to $m_{\pi+\mu+\mu-}$ in each $m_{\mu+\mu-}$ region

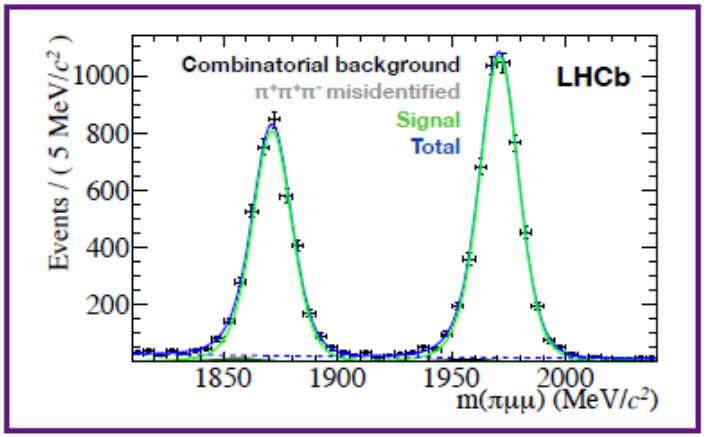


$D^{+}_{(s)} \to \pi^{+}(\mu^{+}\mu^{-})_{\eta}$ demonstrates ability to observe signals with $\mathcal{B} \sim 10^{-8}$



Signal
misID cross-feed
Combinatorial bkg

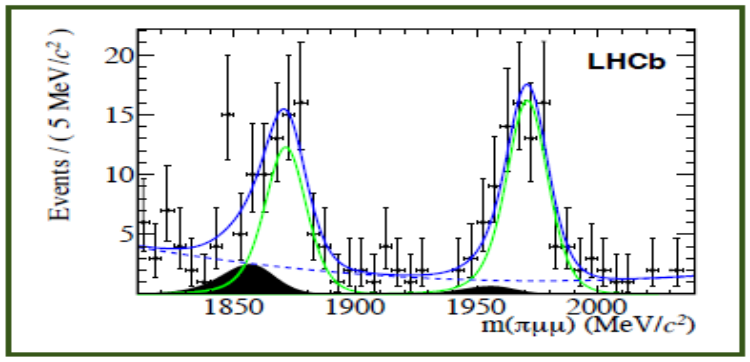
$D^{+}_{(s)} \to \pi^{+}(\mu^{+}\mu^{-})_{\phi}$ with $\mathcal{B} \sim 10^{-6}$ used to normalise yield

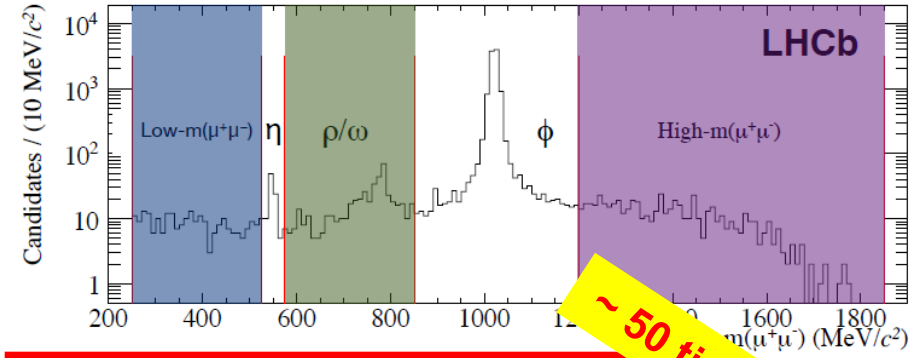


Figures from: Phys. Lett B 724 (2013) 203

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

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





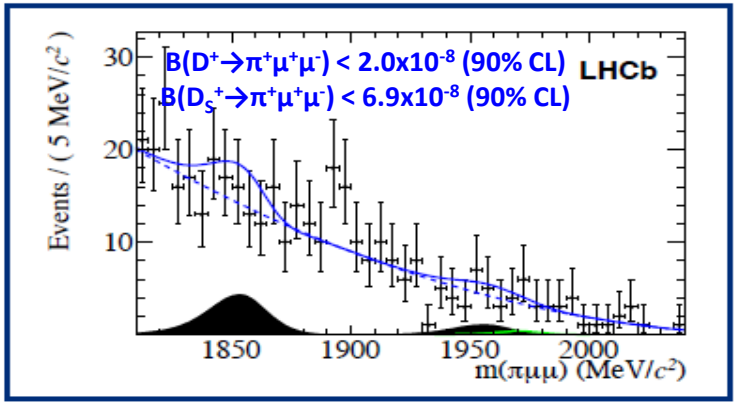
~ 50 times better

No observed signal, total results :

$B(D^{+}\to\pi^{+}\mu^{+}\mu^{-}) < 7.3(8.3)\times10^{-8}$ @90(95)% CL

$B(D_S^{+}\to\pi^{+}\mu^{+}\mu^{-}) < 4.1(4.8)\times10^{-7}$ @90(95)% CL

Low-m($\mu^{+}\mu^{-}$) region

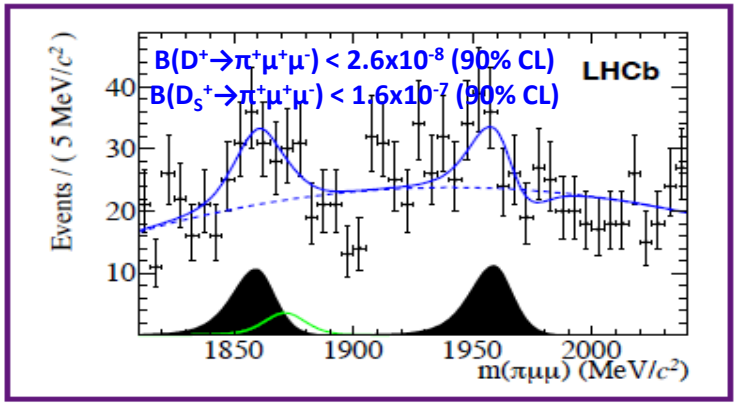


Signal

misID cross-feed

Combinatorial bkg

High-m($\mu^{+}\mu^{-}$) region



10

FCNC sensitive to NP constrained to regions far from the resonances: low and high q2 values

$D_{(S)}^{+} \to \pi^{-}\mu^{+}\mu^{+}$ @ LHCb

→ Split in 4 bins in $M_{\mu^+\pi^-}$ to improve sensitivity

→ Analysis performed in regions of $q^2=M^2(\mu^+\pi^-)$

→ Peaking background : $D_{(s)}^{+} \to \pi^+\pi^+\pi^-$

Figures from:

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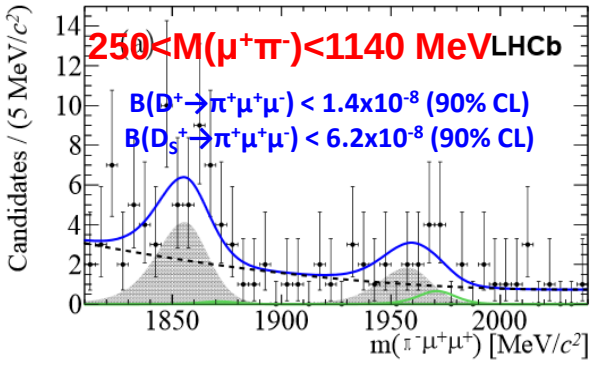

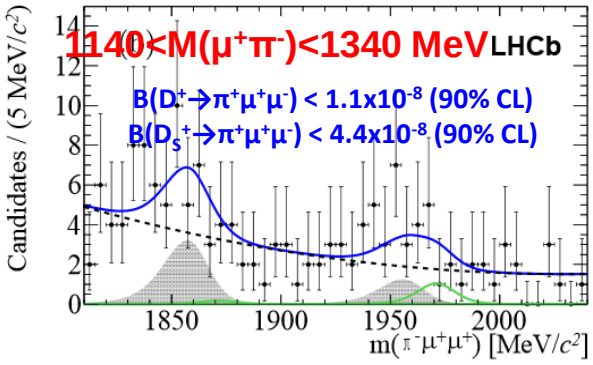

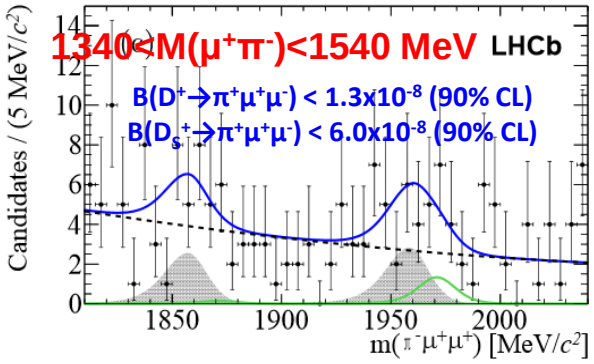

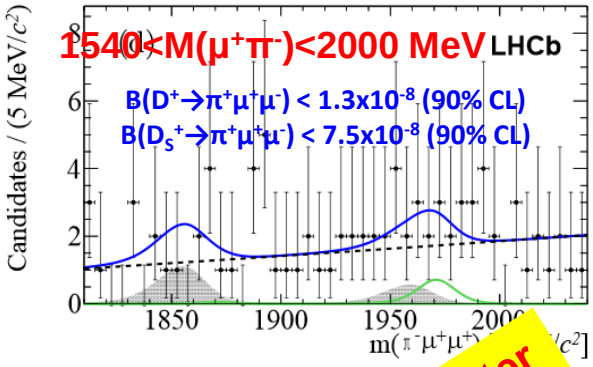

Bin description	$m(\mu^+x^-)$ range [MeV/c^2]
ϕ	850 – 1250
bin 1	250 – 1140
bin 2	1140 – 1340
bin 3	1340 – 1550
bin 4	1540 – 2000

~ 50 times better

No observed signal, total results :

$B(D^+\to\pi^+\mu^+\mu^-) < 2.2(2.5)\times10^{-8}$ @90(95)% CL

$B(D_S^+\to\pi^+\mu^+\mu^-) < 1.2(1.4)\times10^{-7}$ @90(95)% CL

Summary

- The most recent very rare charm decays are presented;
- Upper limits still above SM predictions .
- Rare charm decays are good tools for searching the NP;
- No NP effects have been seen yet .
- New results and new modes (i.e. electron channels) are expected next year (new LHCb run/BESIII ?)


Thank you !