Rare charm decays at LHCb

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IOP Annual Meeting
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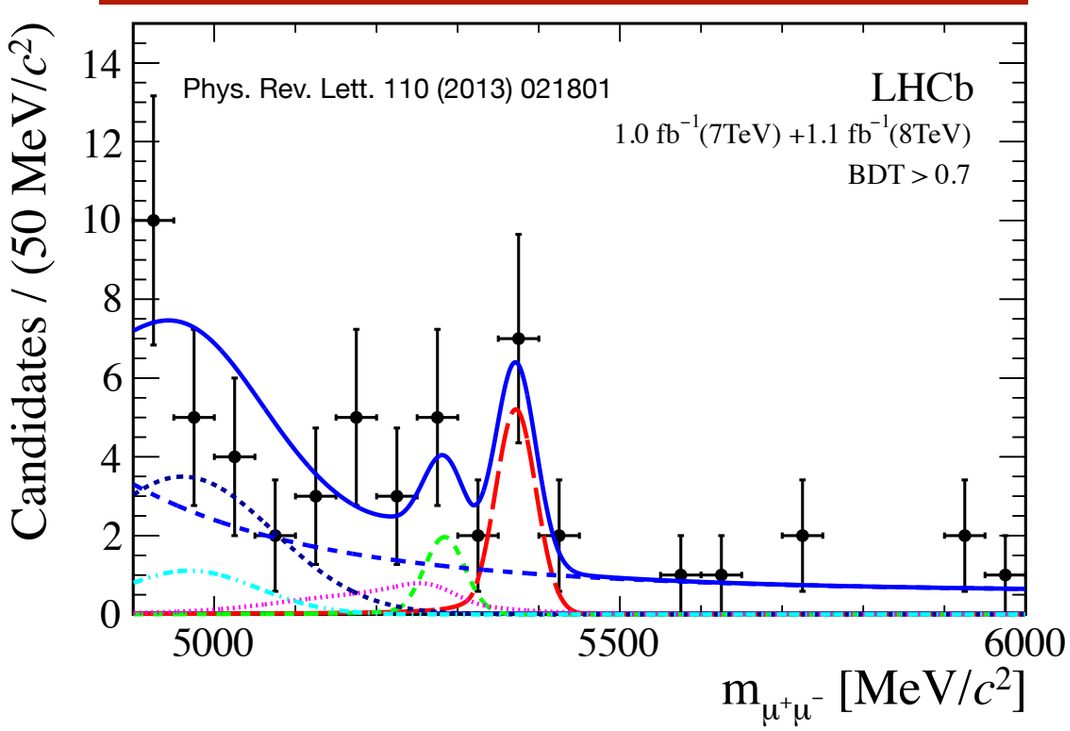
Why are rare decays useful?

✦Suppression of $K_L \to \mu^+\mu^-$ pointed to the discovery of the charm quark

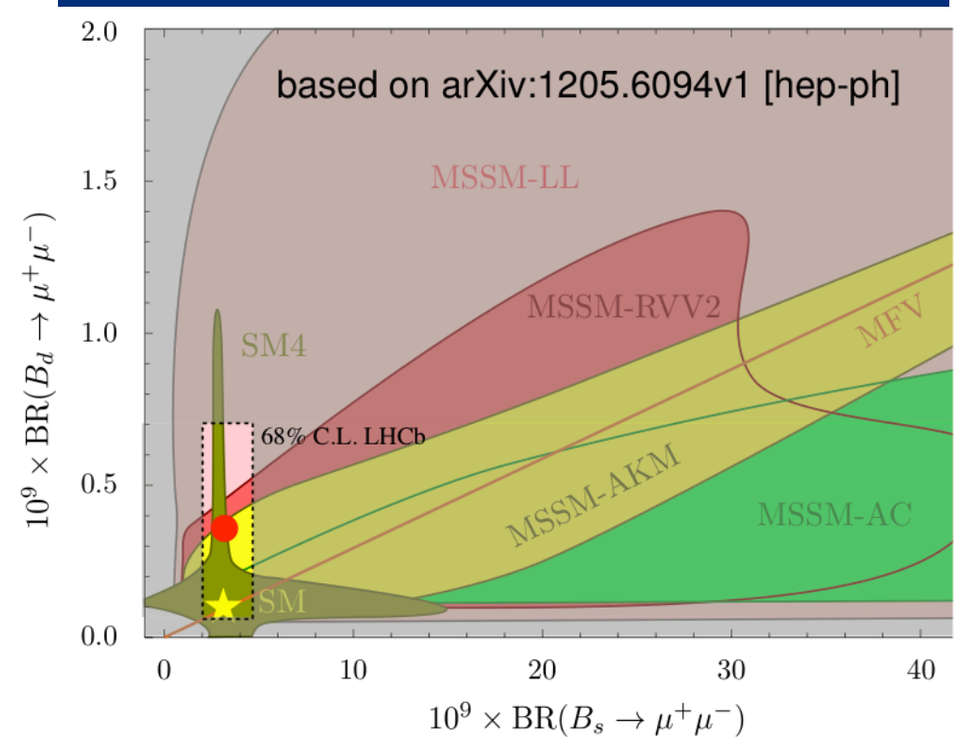
✦Indirect probe of new physics (NP)

✦For instance, $B^0_{(s)} \to \mu^+\mu^-$

Evidence of $B^0_s \to \mu^+\mu^-$ (red line)



Constraining new physics



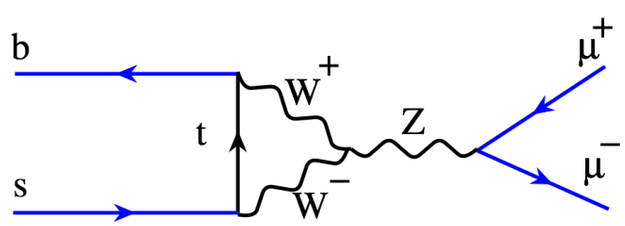
FCNC fundamentals

✦Flavour changing neutral current decays do not occur at tree level in the SM

- as γ, Z^0 and g conserve quark flavour

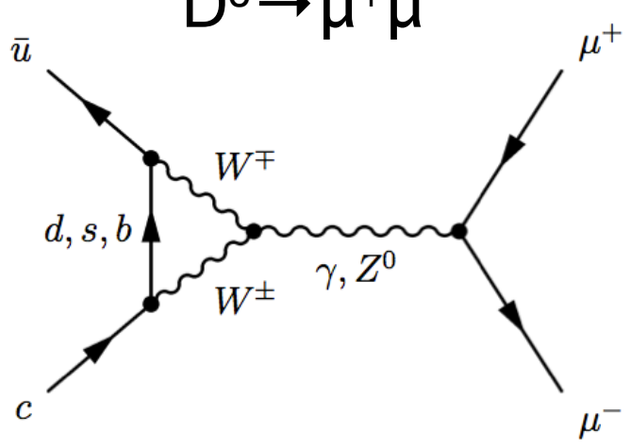
✦Transition rate driven by **mass of internal quark** and **V_{CKM} elements**

$B^0_s \to \mu^+\mu^-$



For mesons composed of **down-type** quarks
the huge mass of the top quark dominates the transition

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



For mesons composed of **up-type** quarks
GIM suppression is more exact ⇒ lower $\mathcal{B}_{SM}$

[1] LHCb-PAPER-2012-041
[2] CERN-PH-EP-2010-029

Rare charm decays

✦Not yet observed in : $D^0 \to \mu^+\mu^-$, $D^+ \to h^+\mu^+\mu^-$, $D^+ \to h^+h^-\mu^+\mu^-$, $\Lambda_c \to p^+\mu^+\mu^-$

✦Unique theatre in which to study FCNC of up-type quarks

✦NP may not affect up-type and down-type quarks in the same way

GOOD NEWS : $\sigma(c\bar{c})_{[1]}$ 20 times larger than $\sigma(b\bar{b})_{[2]}$ in LHCb's acceptance

BAD NEWS : Lower D meson trigger efficiencies counteract this

(due to their shorter flight distance, and smaller impact parameter and P_T)

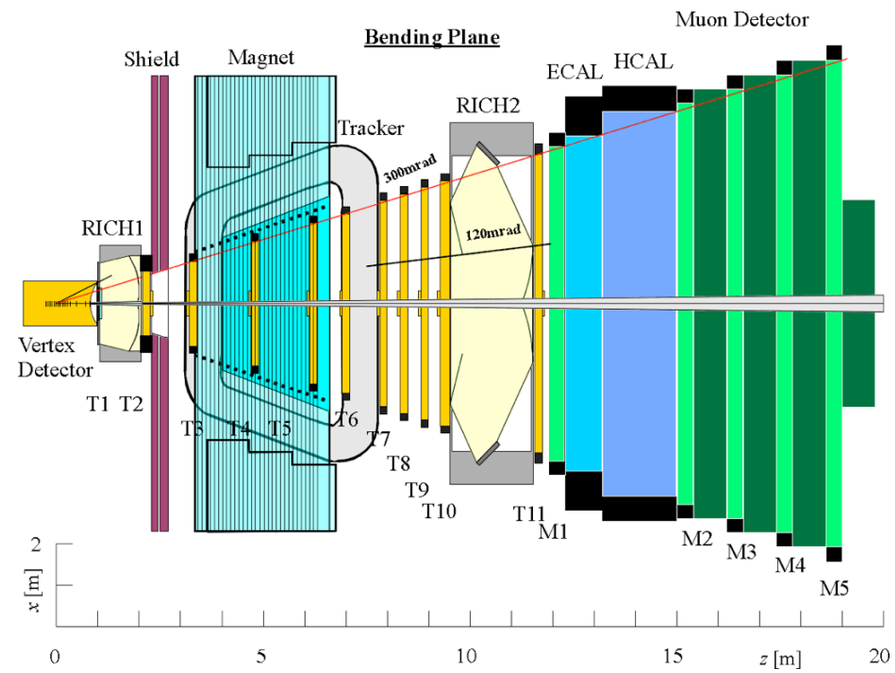
✦Overview of two analyses which both analyse 1.0 fb^{-1} of 2011 data,

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

Specialities of LHCb

✦Detector in the forward-region :

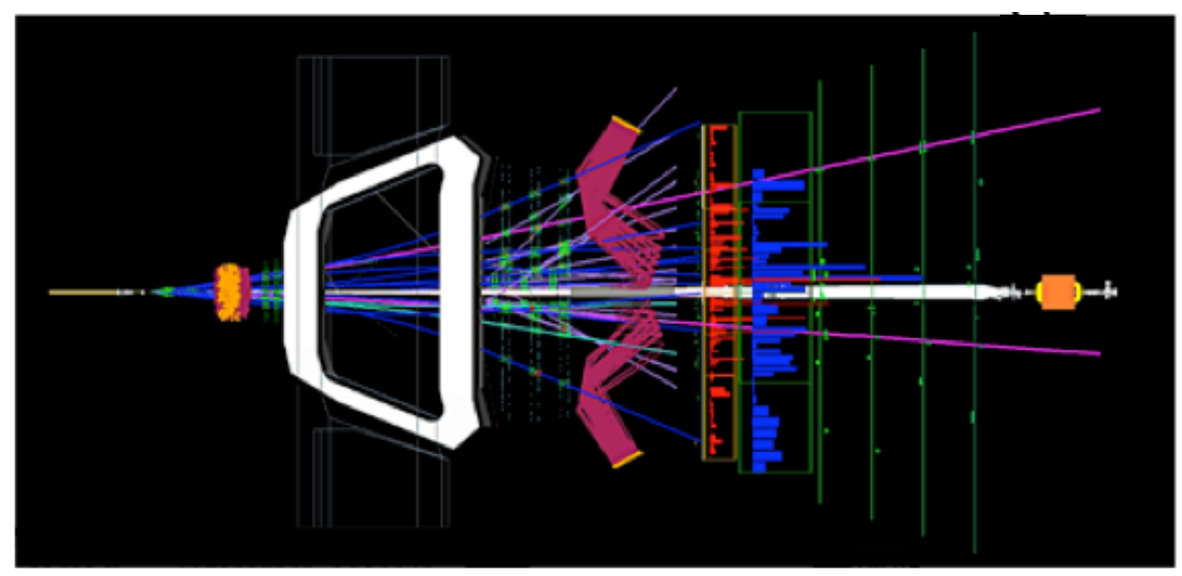
- $b\bar{b}/c\bar{c}$ predominately produced at high $|\eta|$



✦High muon efficiency :

- Low p_T trigger threshold for μ
- Low contamination, $\varepsilon(h \rightarrow \mu) < 1\%$
- High momentum resolution,

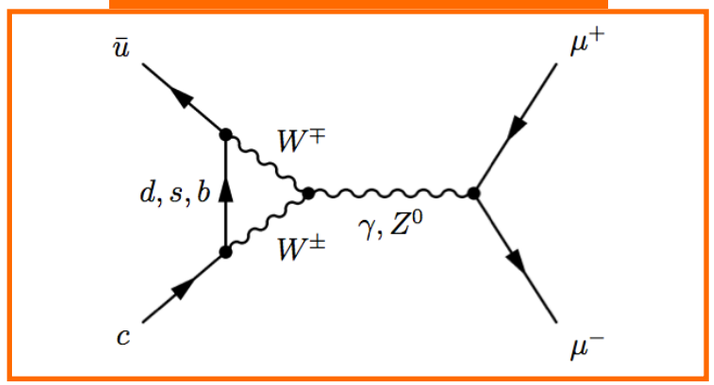
  $0.4\% < \delta p/p < 0.6\%$



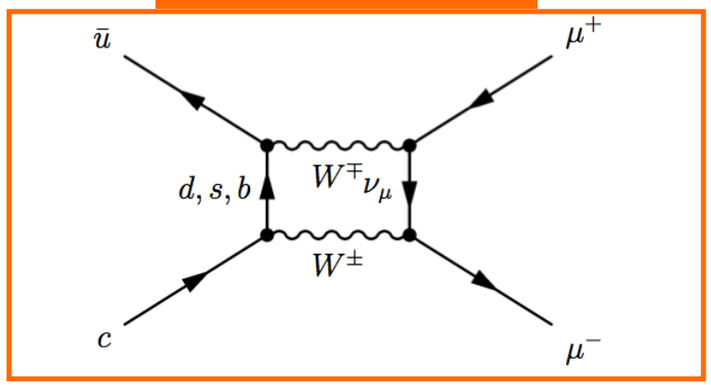
$D^0 \to \mu^+\mu^-$

[LHCb-CONF-2012-005]

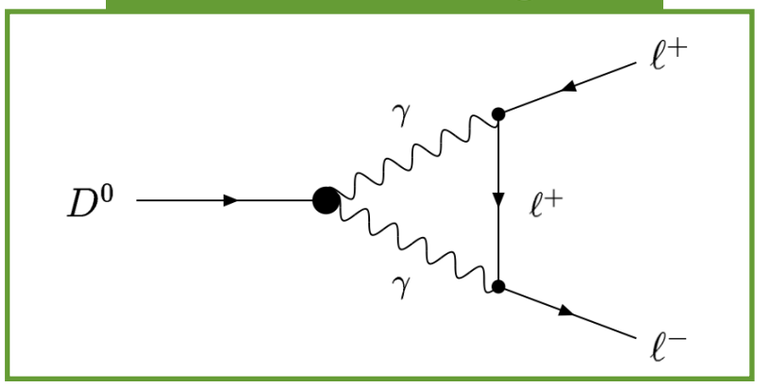
Penguin diagram



Box diagram



Resonant diagram

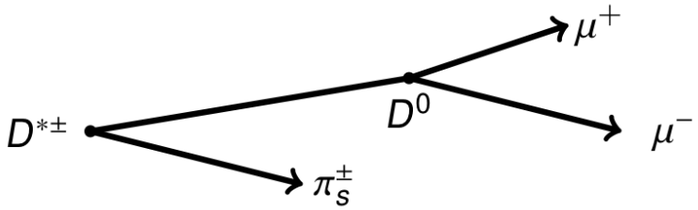


$\mathcal{B}_{SM}$(FCNC) ~ 10^{-18}
(helicity, in addition to GIM, suppressed)

$\mathcal{B}_{SM}$(res.) ~ (10^{-5}) x B($D^0 \to \gamma\gamma$)
Upper limit of 10^{-11} at 90% CL

- ✦Neither FCNC nor γγ resonance observed
- ✦NP such as R-parity violating SUSY and extra dimensions may increase $\mathcal{B}$
- ✦Direct upper limit of ~ **10^{-7}** at 90% CL (Belle) [1]

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

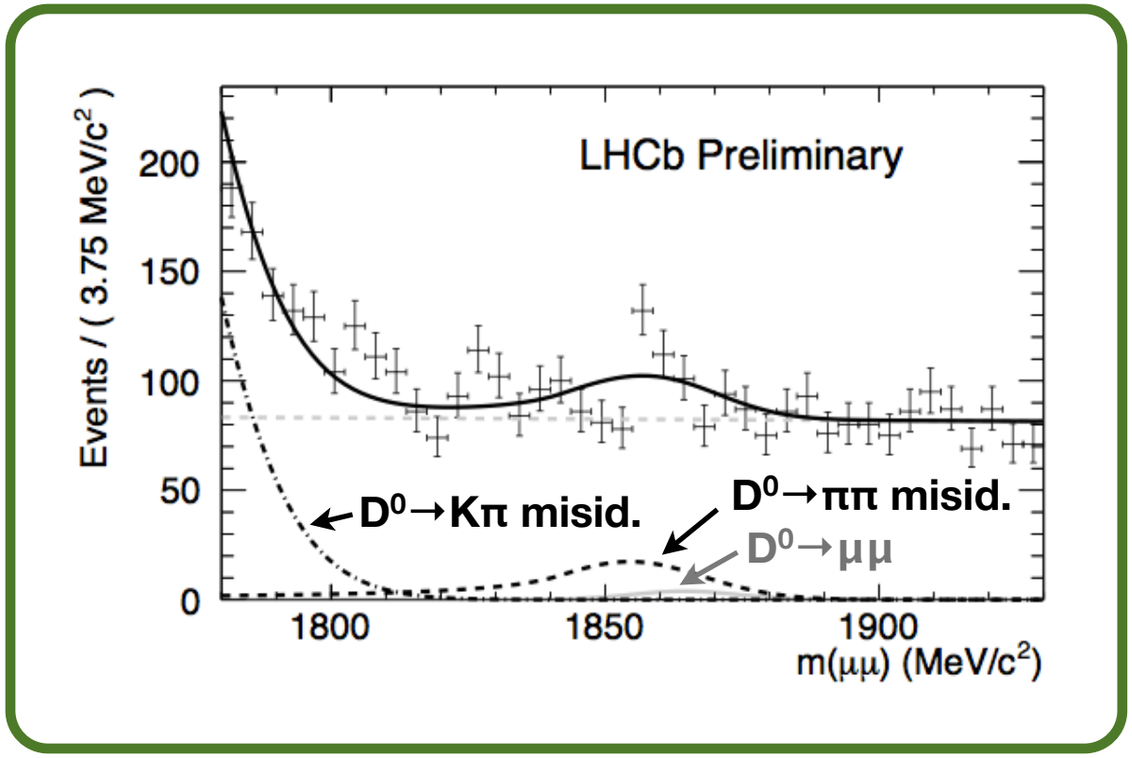


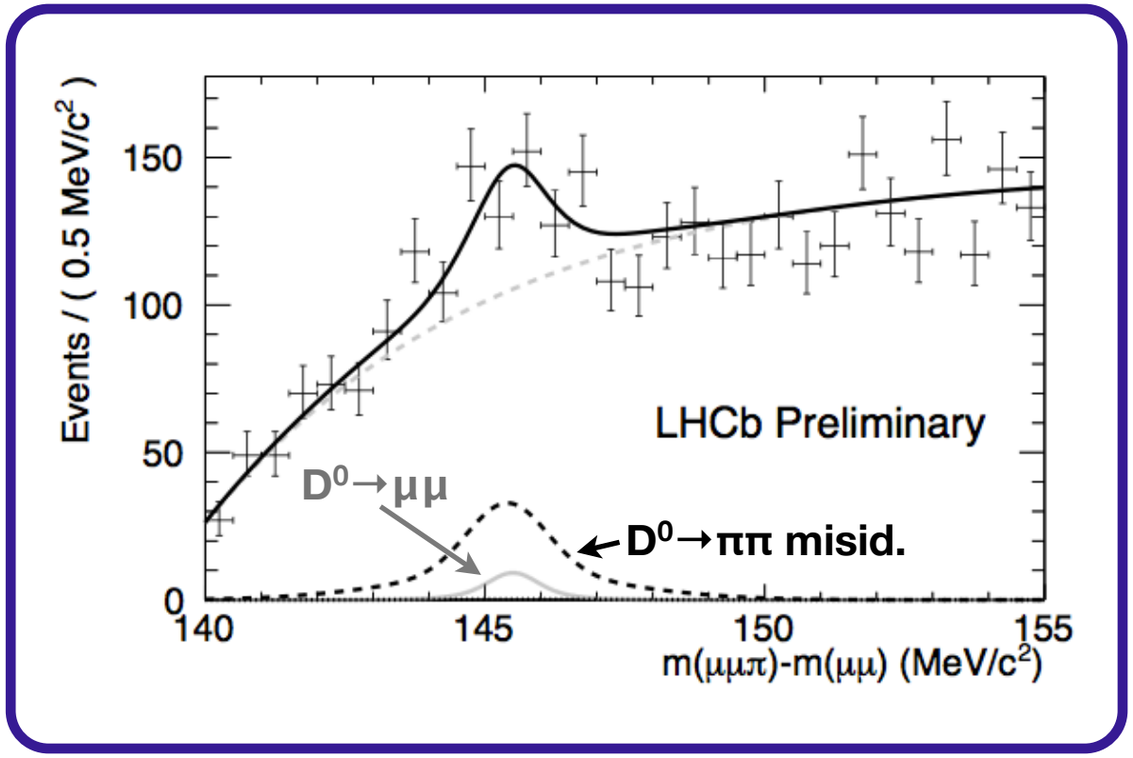
✦Use D^0 from D^{*+} decay, $D^{*+} \to D^0(\to \mu\mu)\pi^+_s$

✦Normalisation channel : $D^{*+} \to D^0(\to \pi^+\pi^-)\pi^+_s$

✦Peaking backgrounds : $D^{*+} \to D^0(\to h^+h^-)\pi^+_s$, where h is either π or K

✦2D fit in $m(\mu^+\mu^-)$ and Δm ($m(\mu^+\mu^-\pi_s)$-$m(\mu^+\mu^-)$)

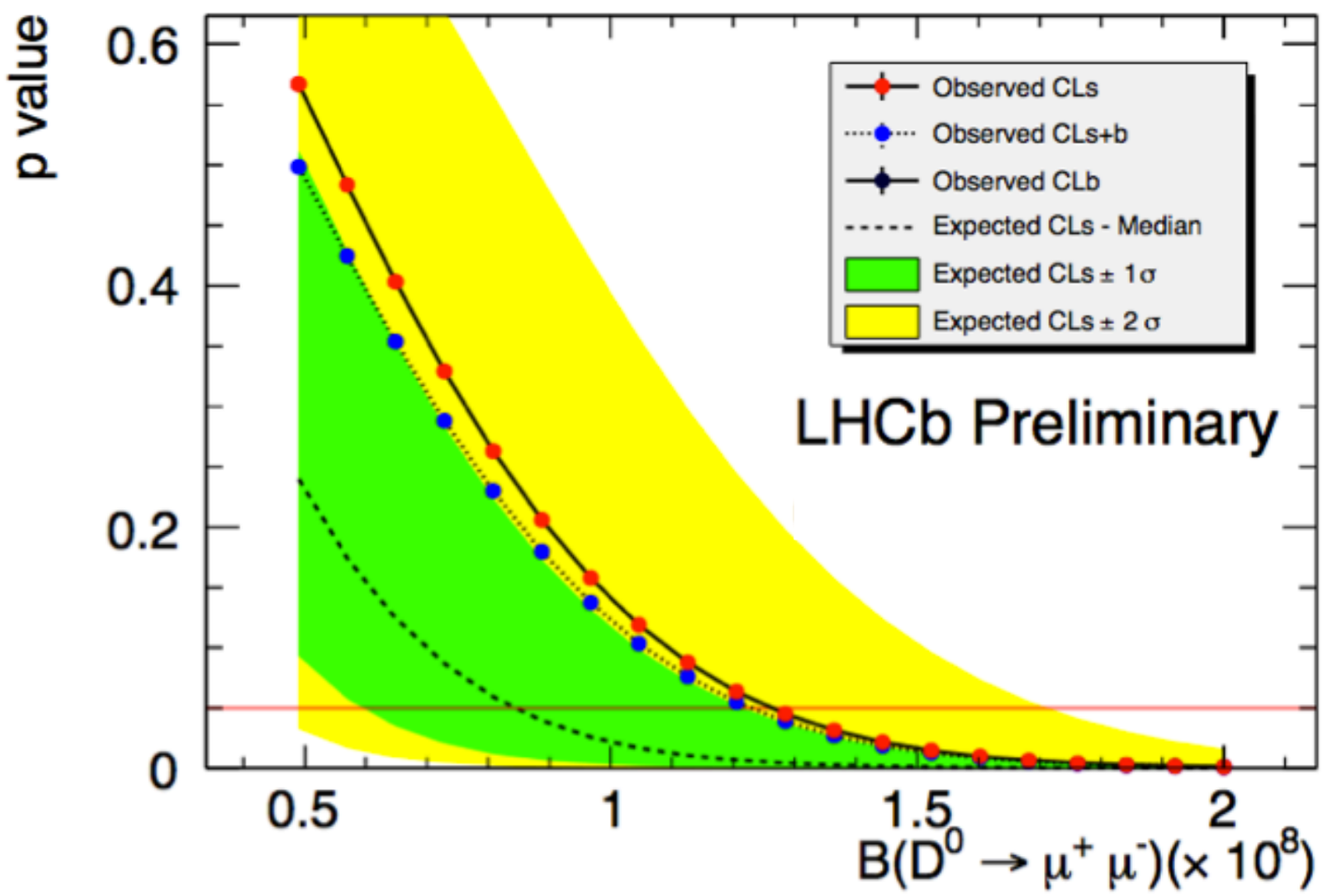




$D^0 \to \mu^+\mu^-$: Upper limits

✦No observed signal, set upper limits :

$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.1\times10^{-8}$ (90% CL)

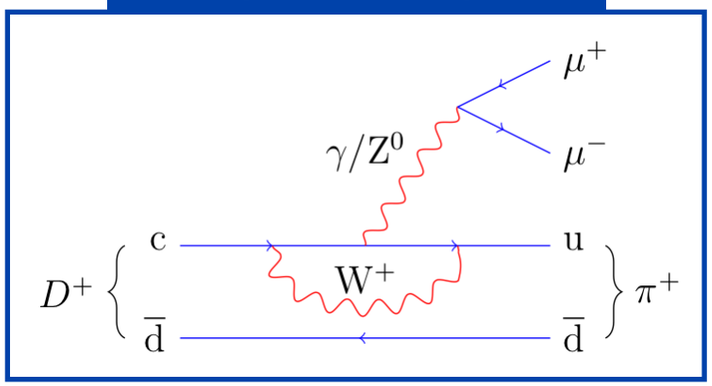


[1] Phys. Rev. D64 (2001) 114009
[2] Phys. Rev. D76 (2007) 074010
[3] Phys. Rev. D83 (2011) 114006
[4] Phys. Rev. Lett. 100 (2008) 101801

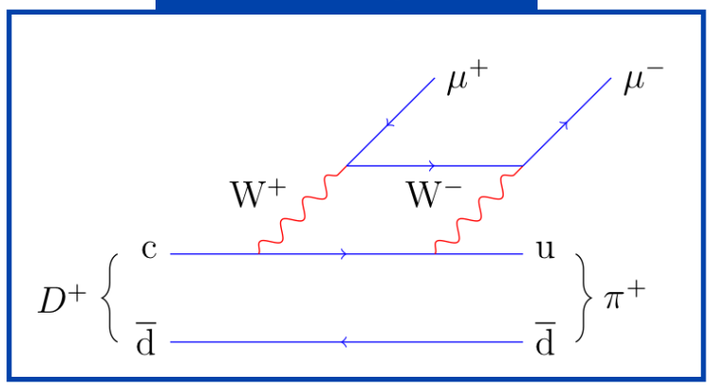
$D^+ \to \pi^+\mu^+\mu^-$

[LHCb-PAPER-2012-051]

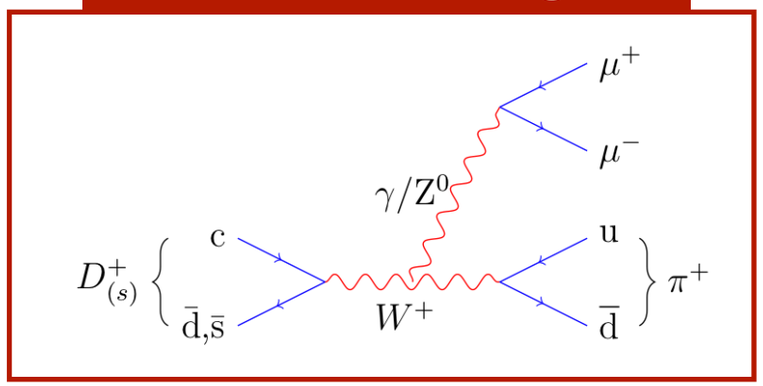
Penguin diagram



Box diagram



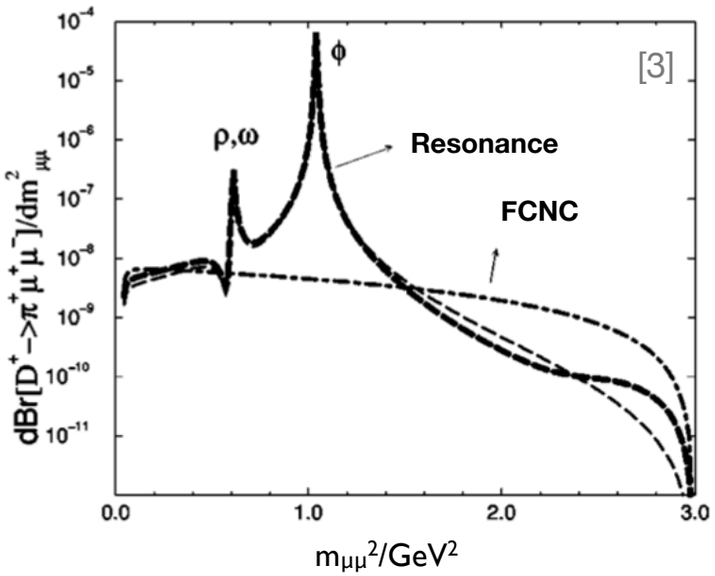
Annihilation diagram



$\mathcal{B}_{SM}$(FCNC) ~ 10^{-9} [1,2,3]
(NP may increase this to ~10^{-8} [3])

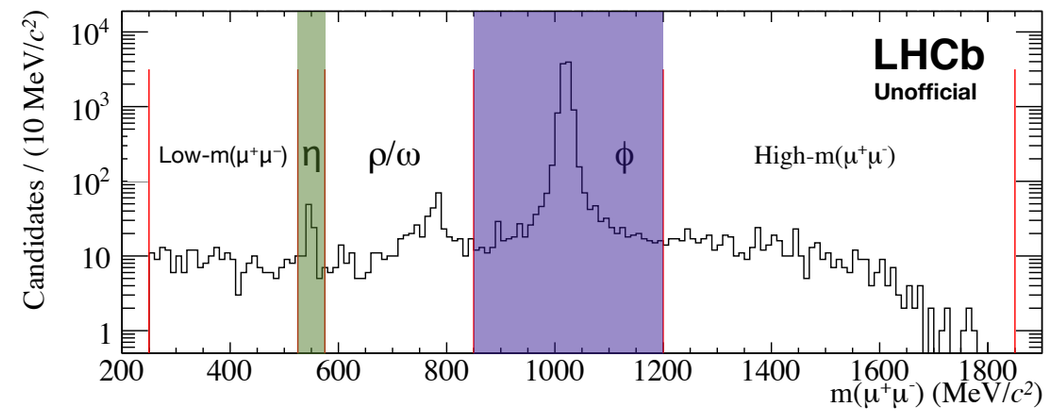
Contributes to D^+ and D^+_s decays

- ✦Known resonances in $\mu^+\mu^-$ spectrum
- ✦$\mathcal{B}$(res.) ~ $\mathbf{10^{-6}}$ (via Φ) to $\mathbf{10^{-8}}$ (via η and ρ/ω)
- ✦Non-resonant limit of ~ $\mathbf{10^{-6}}$ at 90% CL (DØ) [4]
- ✦Search for non-resonant signal away from resonances

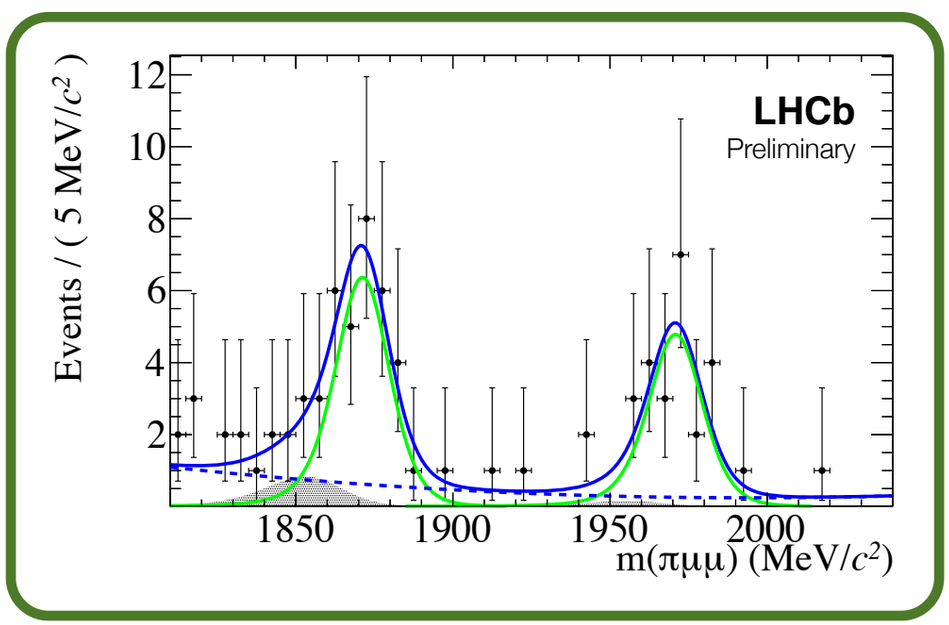


$D^+ \to \pi^+\mu^+\mu^-$: Concepts

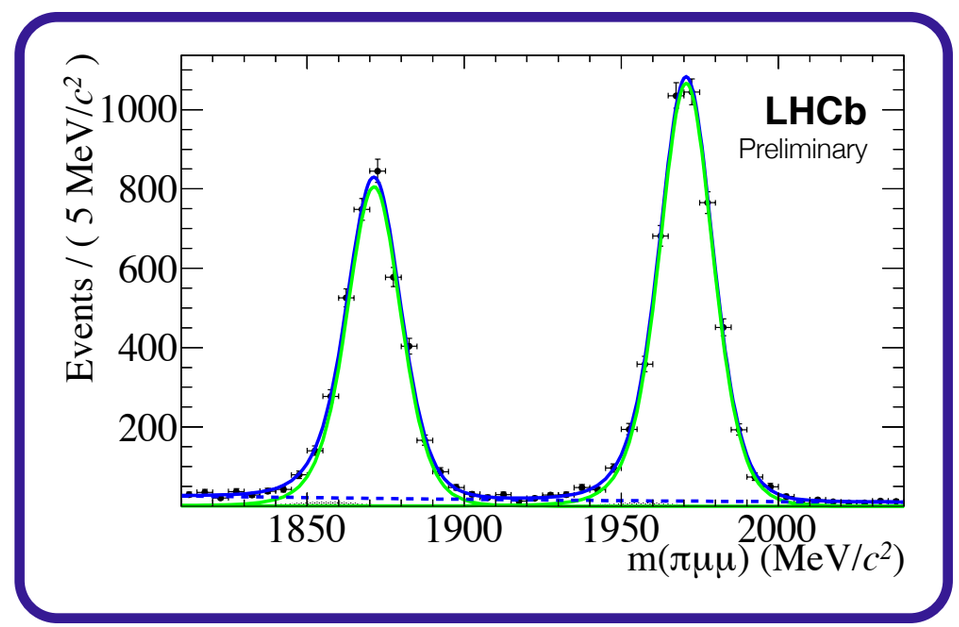
- ✦Normalisation channel : $D^+_{(s)} \to \pi^+(\mu^+\mu^-)_\phi$
- ✦Peaking backgrounds : $D^+_{(s)} \to \pi^+\pi^+\pi^-$
- ✦Simultaneous fit to $m(\pi^+\mu^+\mu^-)$ in each $m(\mu^+\mu^-)$ region



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

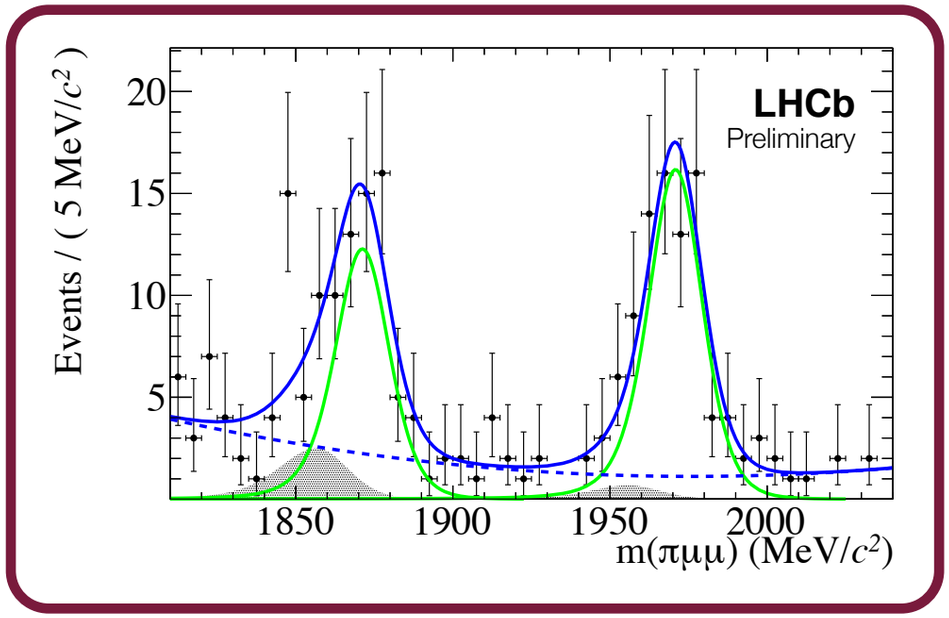


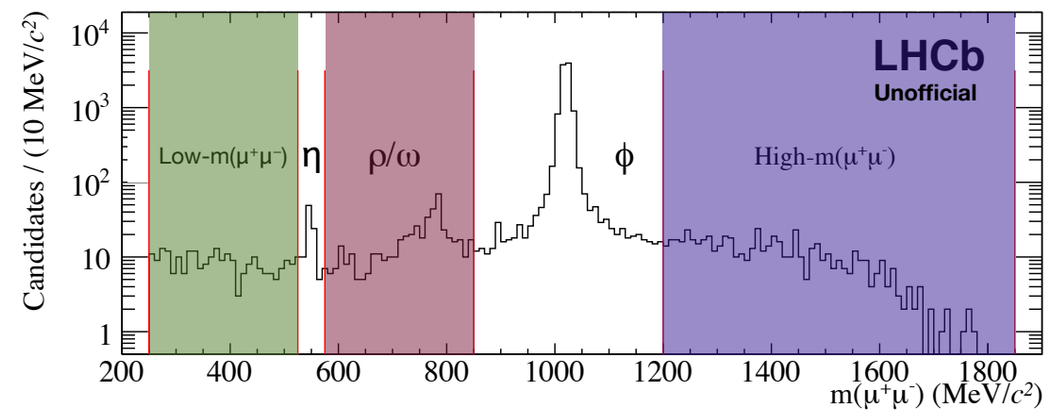
$D^+_{(s)} \to \pi^+(\mu^+\mu^-)_\phi$ with $\mathcal{B} \sim 10^{-6}$ used to normalise yield



$D^+ \to \pi^+\mu^+\mu^-$: Invariant mass fits

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



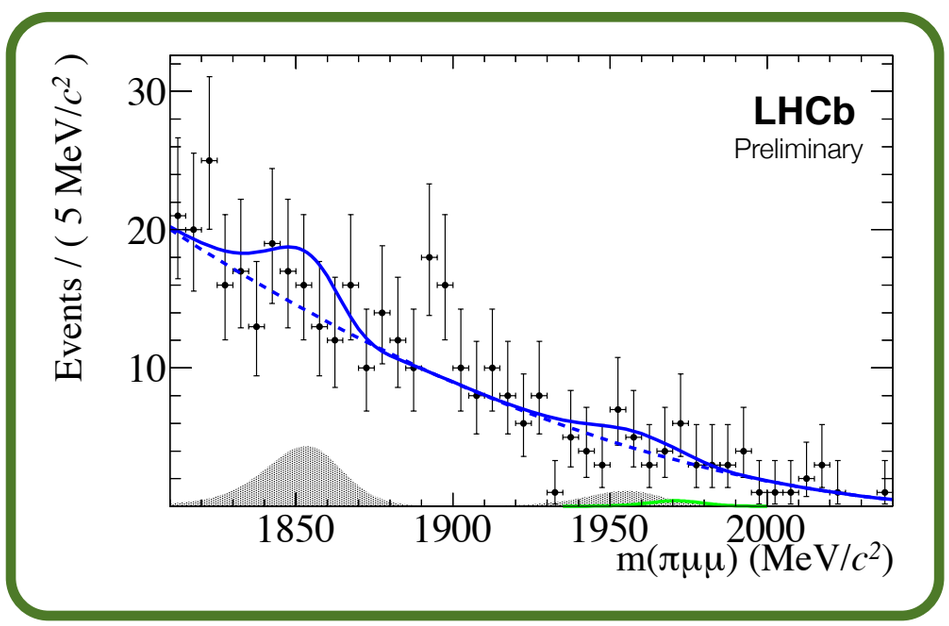


✦No observed signal, set upper limits :

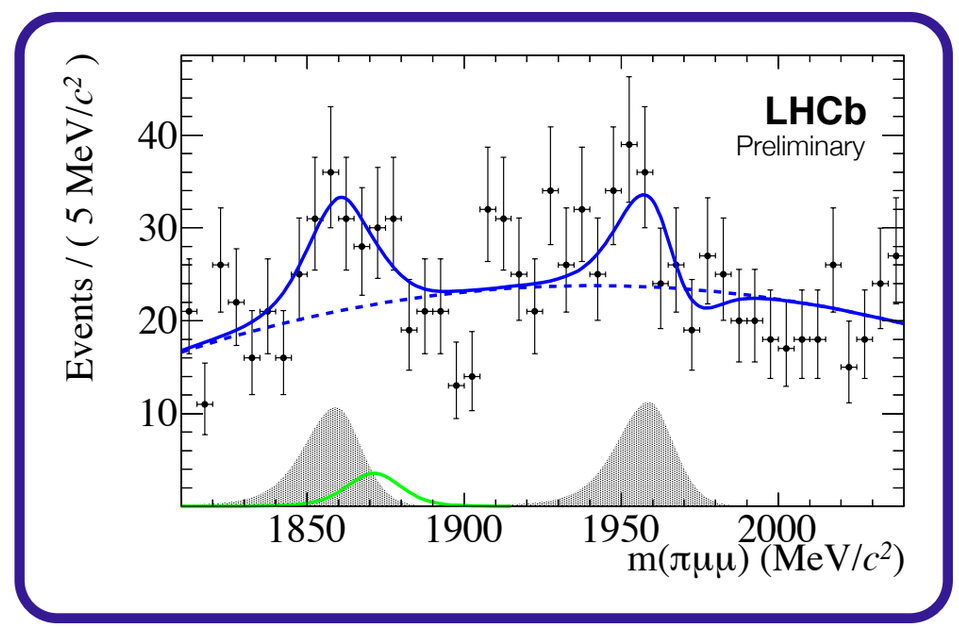
$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3\times10^{-8}$ (90% CL)

$\mathcal{B}(D^+_s \to \pi^+\mu^+\mu^-) < 4.1\times10^{-7}$ (90% CL)

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



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



In conclusion : Future predictions

✦By the end of 2017, one can imagine that :

$\mathcal{L}$ = **3** (7/8 TeV) + **5** (13 TeV + trigger and analysis improvements) **fb^{-1}**

Statistics up by factor 20...

✦Can we expect to see anything?

$D^0 \to \mu^+\mu^-$: $\mathcal{B} \sim 10^{-10}$, an order of magnitude above the indirect bound

$D^+ \to \pi^+\mu^+\mu^-$: $\mathcal{B} \sim 10^{-9}$, same magnitude as the predicted $\mathcal{B}_{SM}$(FCNC)

✦News of other analyses :

Majorana neutrino search, $\mathcal{B}_{SM}$(LNV) = 0

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

$\mathcal{B}(D^+_s \to \pi^-\mu^+\mu^+) < 1.2\times10^{-7}$ (90% CL)

$D^0 \to h^+h^-\mu^+\mu^-$: Ongoing

Extras

Effective Hamiltonian

$$\mathcal{H}_{\text{eff}}^{c\to u\ell^+\ell^-} = -\frac{4G_F}{\sqrt{2}}\left[\sum_{i=1}^{2}\left(\sum_{q=d,s} C_i^{(q)}(\mu)\mathcal{O}_i^{(q)}(\mu)\right) + \sum_{i=3}^{10} C_i'(\mu)\mathcal{O}_i'(\mu)\right]$$

i=1,2	Tree
i=3-6,8	Gluon Penguin
i=7	Photon penguin
i=9,10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

✦Used to simplify calculations (by viewing them as Fermi interactions)

- q index runs over internal quarks, i runs over possible Feynman diagrams

✦Each Feynman diagram contributes an operator with calculable SM coefficient

Short distance physics contained in Wilson coefficients C_i

Long distance (via inter-mediatory state) physics contained in operators O_i

New physics may alter Wilson coefficients or require new operators

Charm FCNC

$$\mathcal{H}_{\rm eff}^{c\to u\ell^+\ell^-} = -\frac{4G_F}{\sqrt{2}}\left[\sum_{i=1}^{2}\left(\sum_{q=d,s} C_i^{(q)}(\mu)\mathcal{O}_i^{(q)}(\mu)\right) + \sum_{i=3}^{10} C_i'(\mu)\mathcal{O}_i'(\mu)\right]$$

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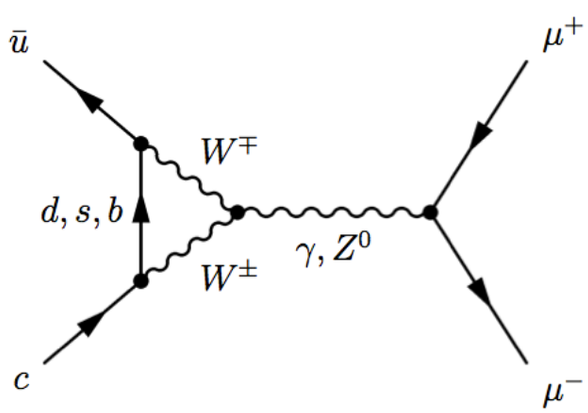
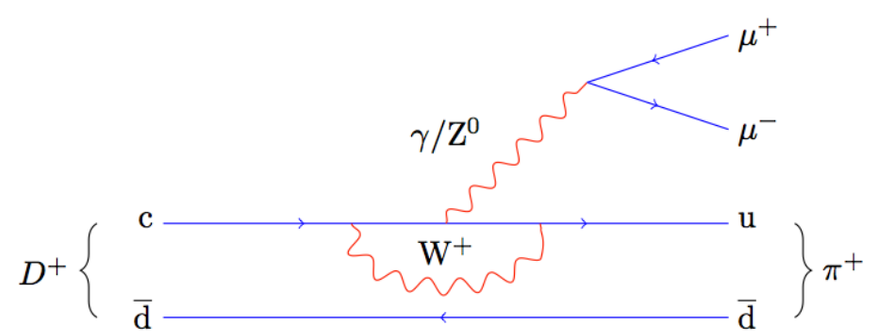
$D^0 \to \mu^+\mu^-$



C_P, C_S and C_{10}

R-parity violating SUSY

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



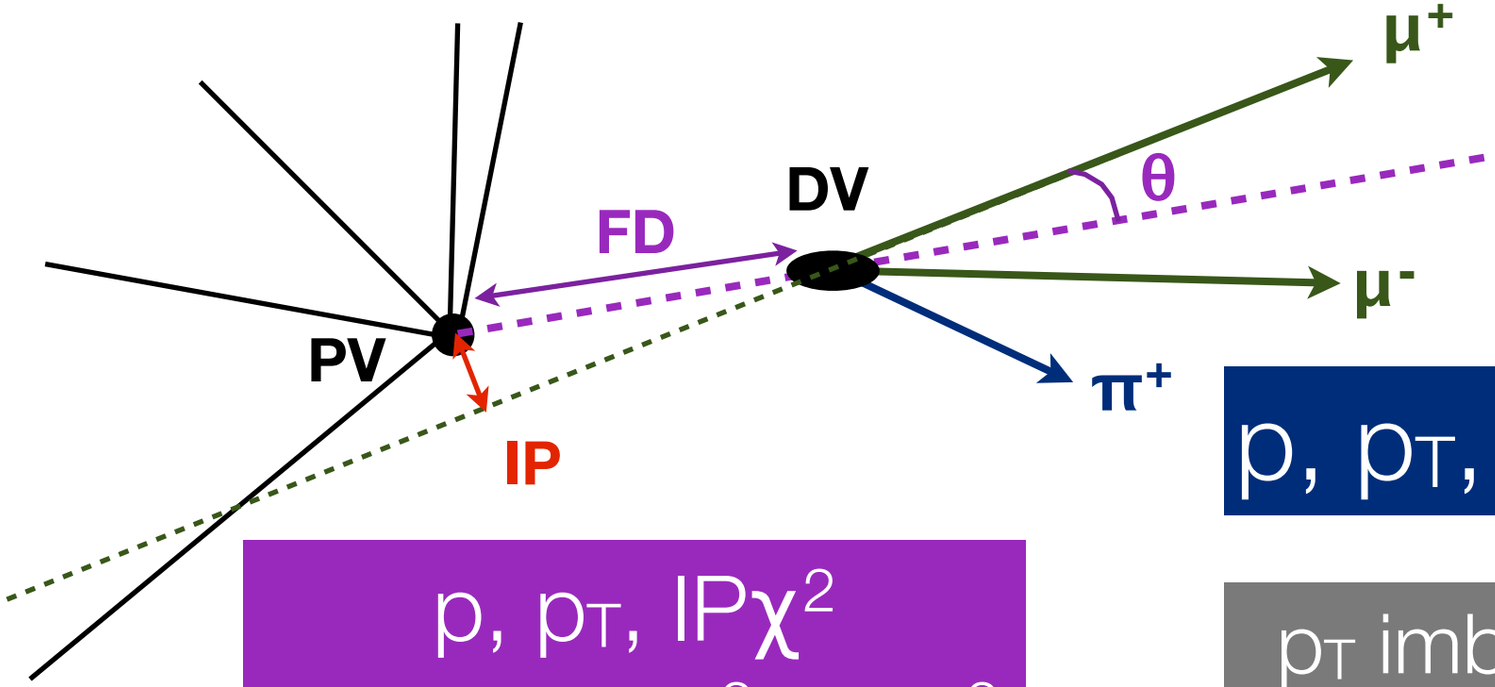
C_7, C_9 and C_{10}

R-parity conserving SUSY

BDT selection

✦Train using MC10 signal vs. 2010 data sidebands

✦BDT variables:



p, p_T, IPχ^2

p, p_T, IPχ^2

p, p_T, IPχ^2
cos(θ), FDχ^2, DVχ^2
Maximum DOCA

p_T imbalance of the D vs. other nearby tracks

$$A_{p_T} = \frac{p_T(D) - (\sum_n p)_T}{p_T(D) + (\sum_n p)_T}$$

LNV fundamentals

✦Lepton Number Violating decays have never been observed

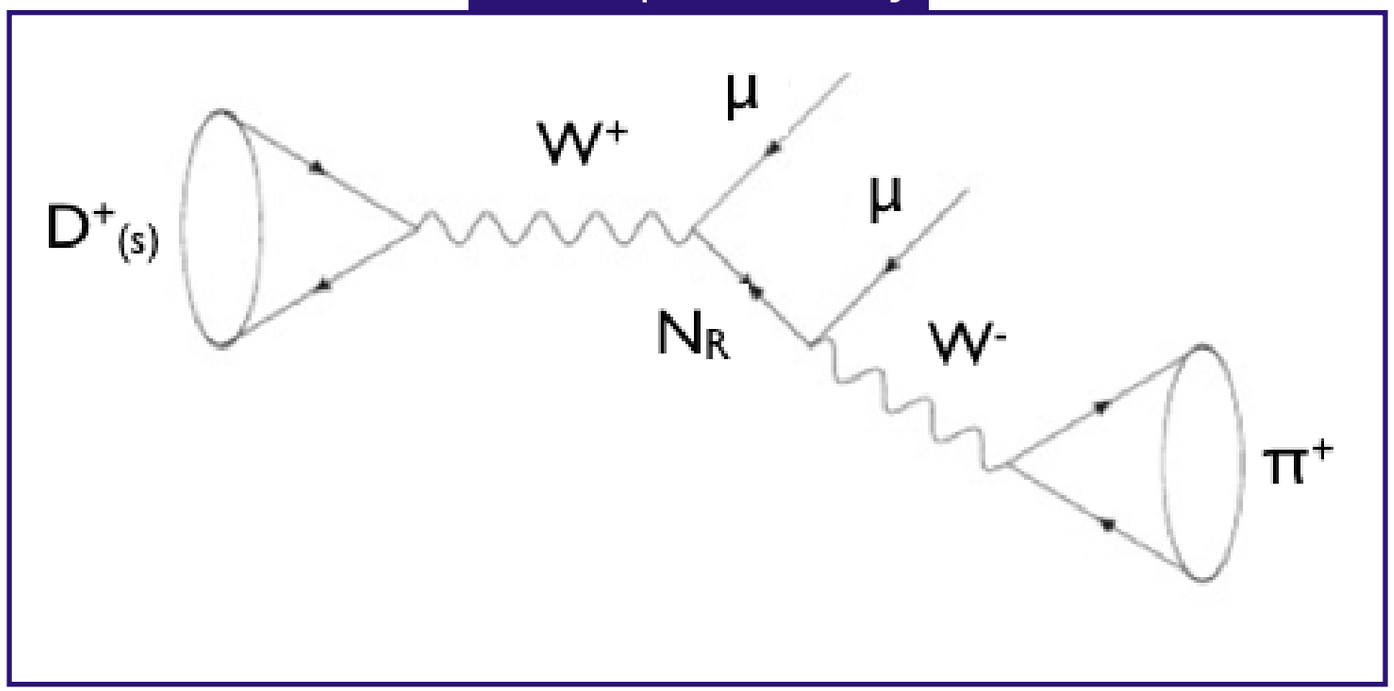
✦Mediated by non-SM particle, such as a Majorana neutrino

✦Possible decays (**analyses in bold covered in presentation**) :

Approval to go to paper :
$D^+_{(s)} \rightarrow \pi^- \mu^+ \mu^+$

Also :
$D^+_{(s)} \rightarrow K^+ \mu^- \mu^-$

Example Decay



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

[LHCb-PAPER-2012-051]

✦$m(\pi^-\mu^+)$ could peak at Majorana neutrino mass, so partition into 4 bins

✦Fold over to create unique binning

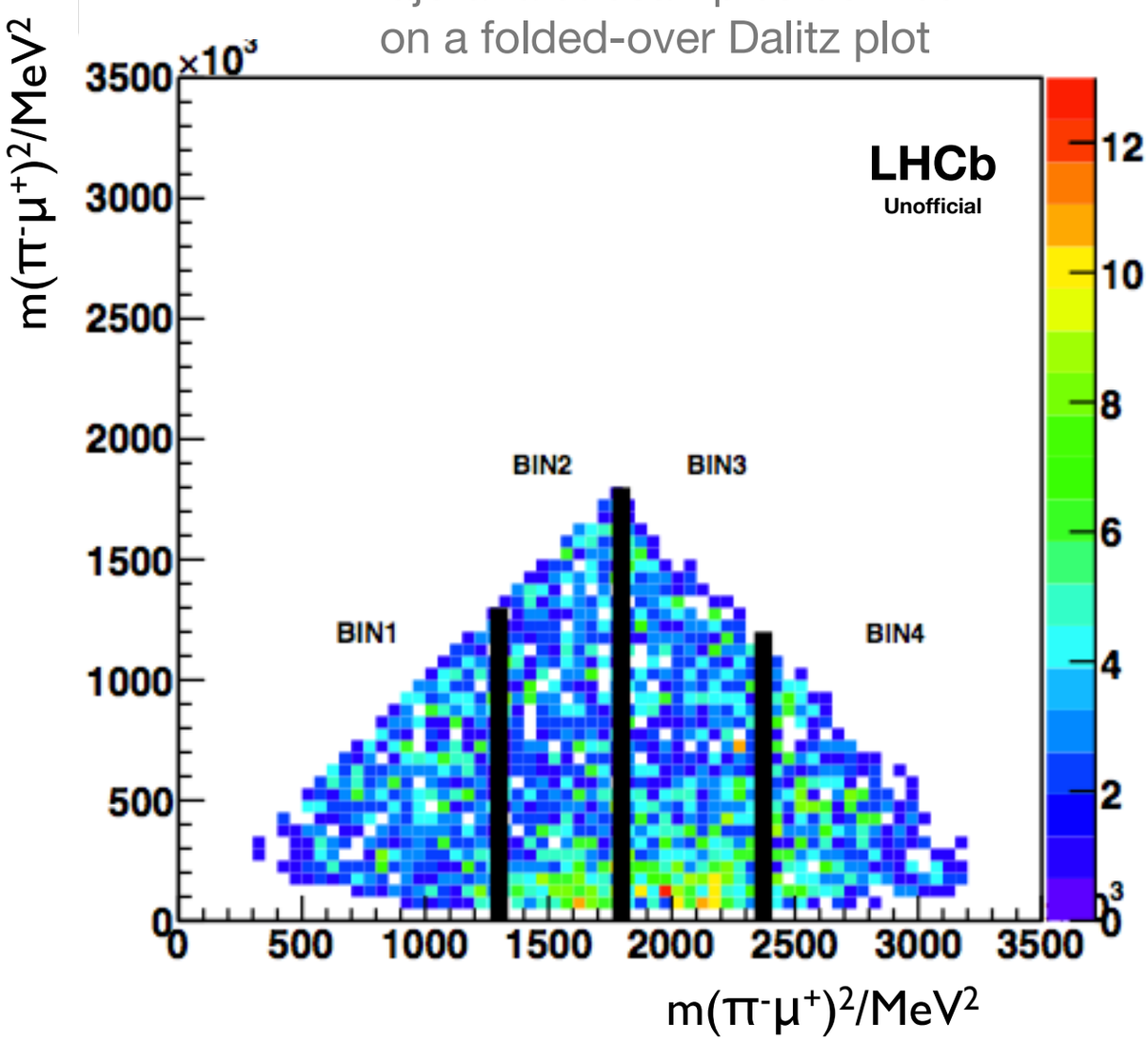
✦No $m(\mu^+\mu^+)$ resonances

✦BaBar: BF < 2.0(14) x 10^{-6} (90% C.L.)

http://arxiv.org/abs/1107.4465v1

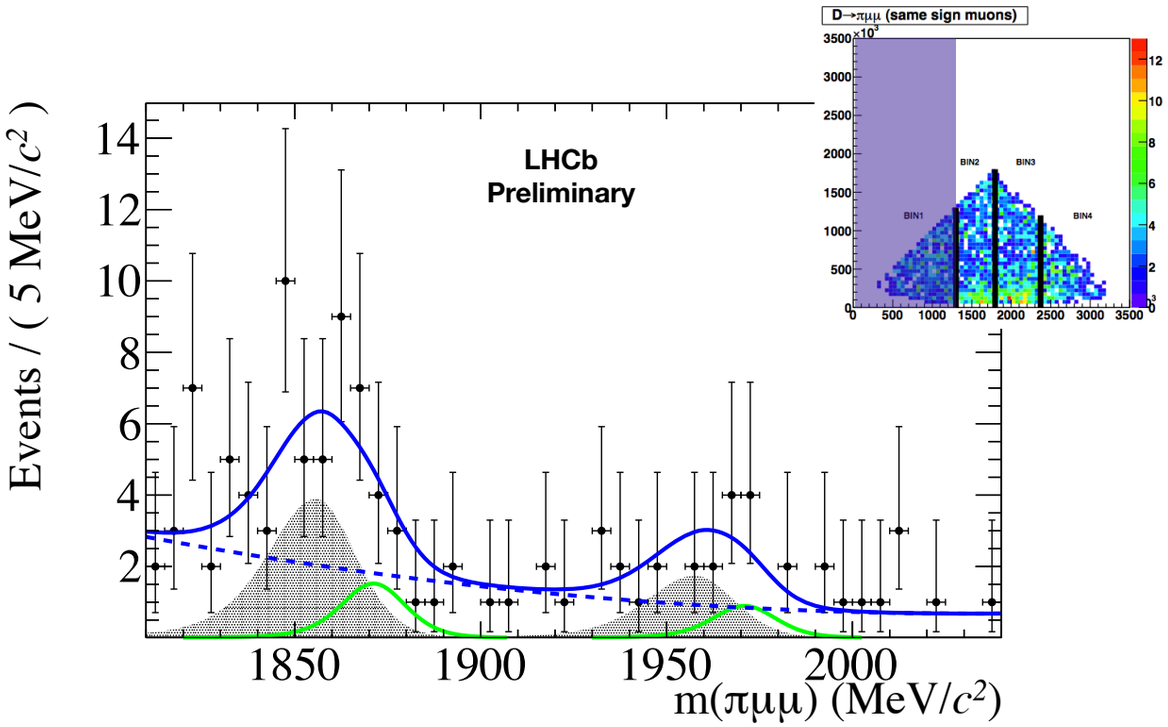
Analyse 1.0 fb^{-1} of 2011 data normalising with $D^+_{(s)} \to \pi^+(\mu^+\mu^-)_\phi$ like in the FCNC analysis

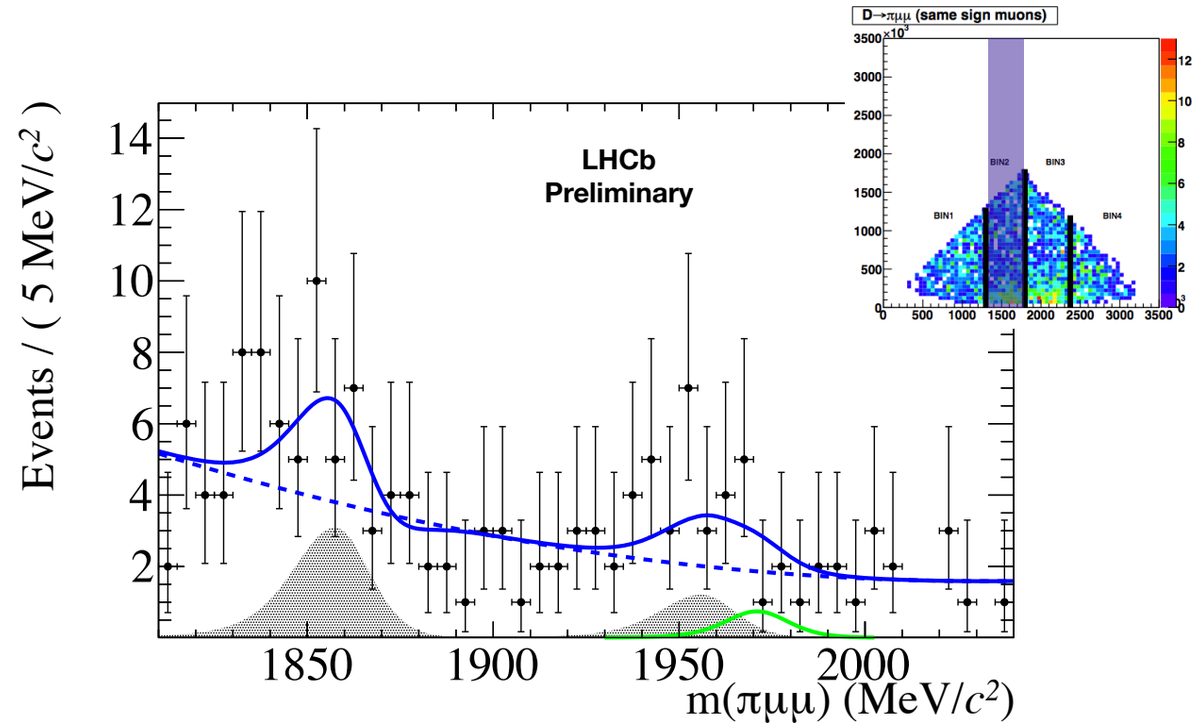
Majorana subsamples defined on a folded-over Dalitz plot

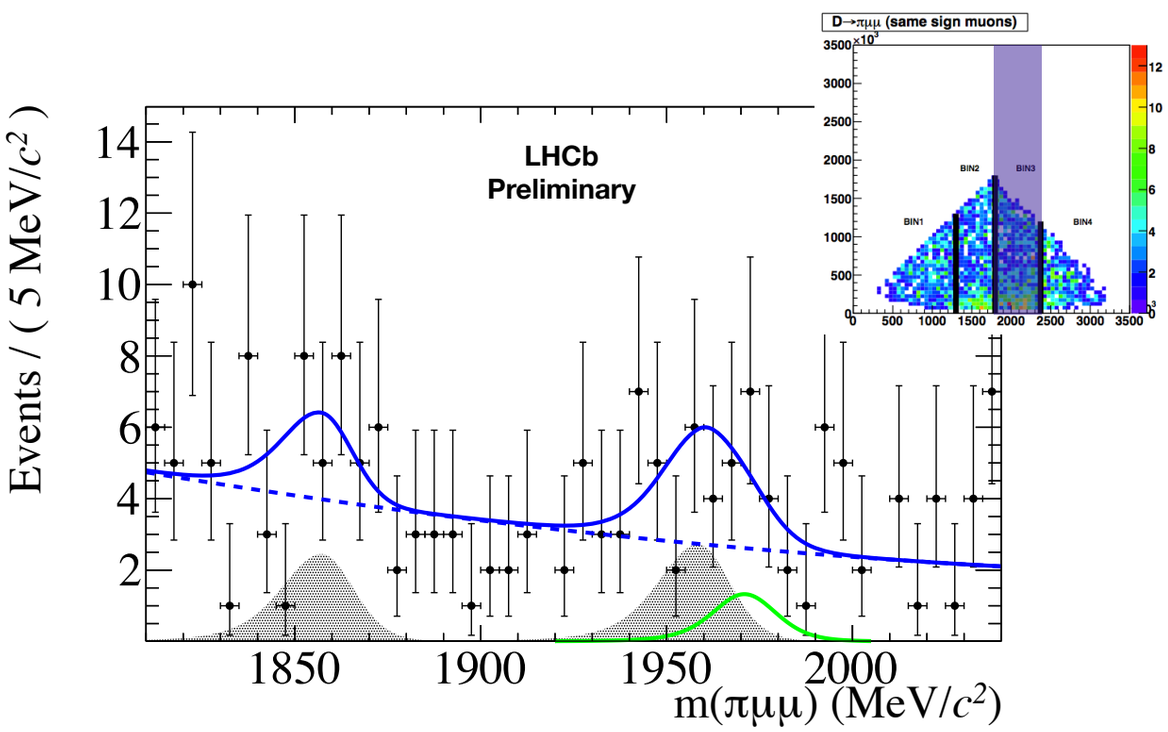


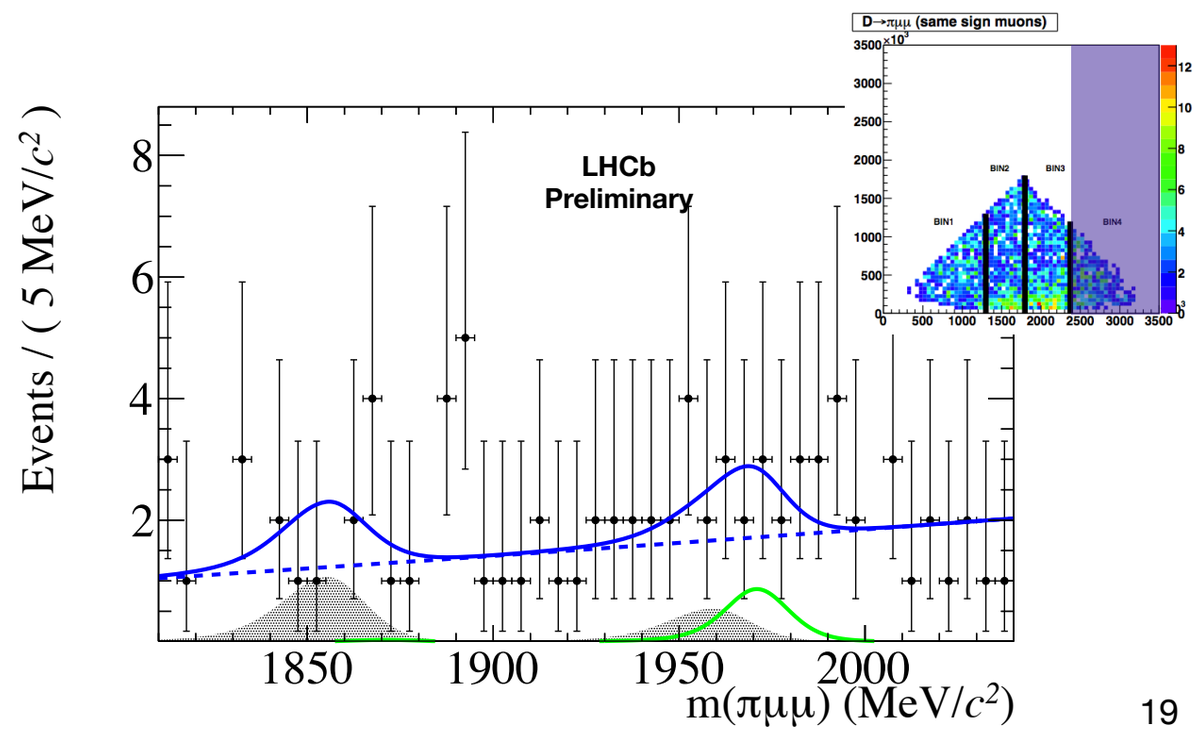
Preliminary

$D^+_{(s)} \rightarrow \pi^- \mu^+ \mu^+$: Invariant mass plots









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

✦No significant excess above the background observed

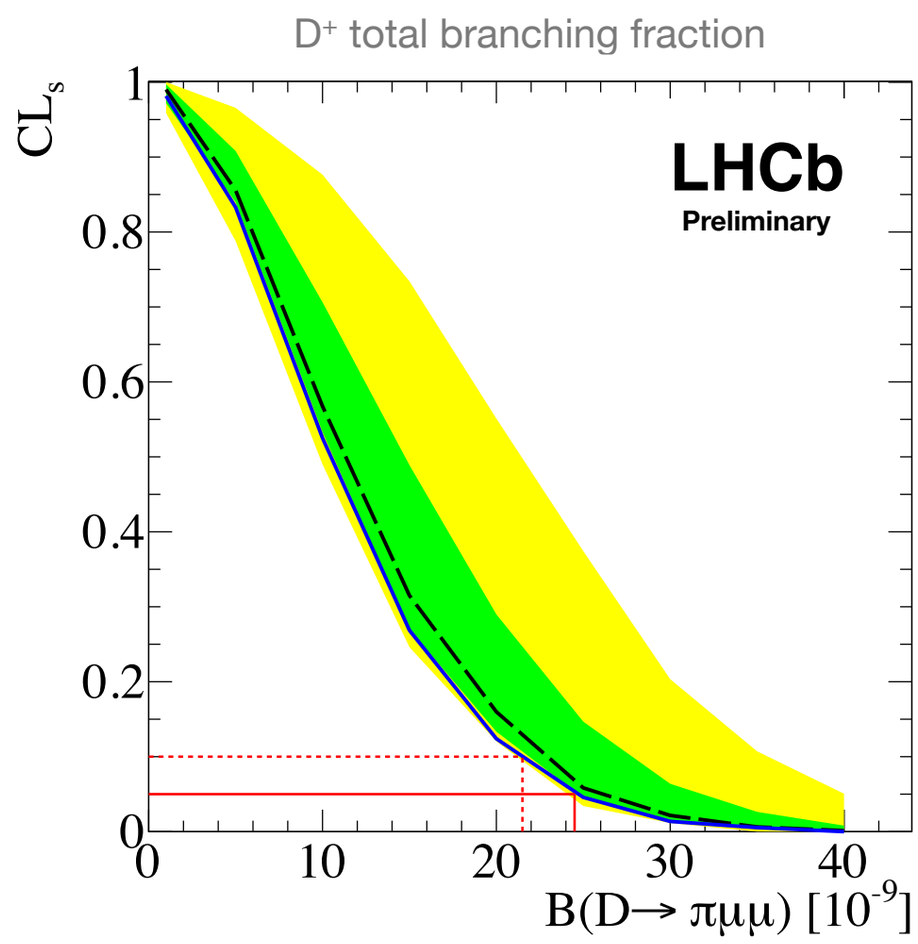
✦Upper limit set using the CLs method :

Decay	90% [$\times 10^{-8}$]	95% [$\times 10^{-8}$]
$D^+_{(s)} \to \pi^- \mu^+ \mu^+$	2.2(12.0)*	2.5(14.1)

Belle : $\mathcal{B}$ ~ **10^{-6}**

LHCb : $\mathcal{B}$ ~ **10^{-8}**

SM : $\mathcal{B}$ **=** 0



$D^0 \to hh\mu\mu$

$D^0 \to \pi\pi\mu\mu$ | $D^0 \to KK\mu\mu$ | $D^0 \to K\pi\mu\mu$

✦$\mathcal{B}_{SM}$(S.D.) ~ **$10^{-10 \text{ to } -9}$** and $\mathcal{B}_{SM}$(L.D.) ~ **$10^{-8 \text{ to } -6}$**

✦Current upper limits (@ 90% C.L.) : < ~10^{-5}

Theory suggests that looking for NP by...

Searching for enhanced $\mathcal{B}$(S.D.) not promising

However, it could generate A_T, A_{CP} and A_{FB} at the level 10% in $\mu\mu$ resonances (especially true for $D^0 \to K^+\pi^-\mu^+\mu^-$ which is DCS so hides NP less effectively)

✦Goal is to measure total (long and short distance!) $\mathcal{B}$ with 2012 data

✦LHCb's sensitivity to these asymmetries depends upon total $\mathcal{B}$

✦And therefore determines when an attempt to measure them will be