Rare charm decays at LHCb

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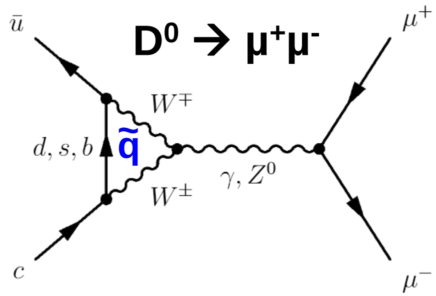
The 2013 European Physical Society Conference on High Energy Physics,
18-24 July, 2013
Stockholm, Sweden

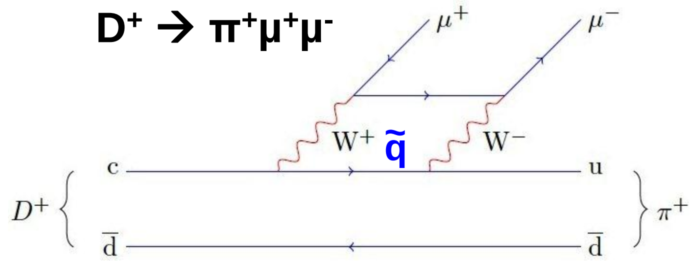
Outline

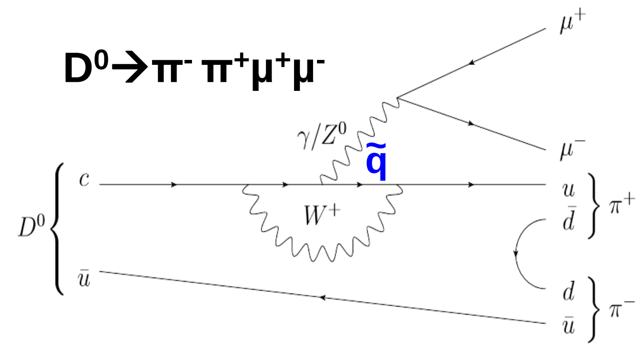
- Motivations
- Experimental status up to 2011
- General strategy of data analysis
- Recent results for rare charm decays at LHCb with 2011 data
  - $D^0 \rightarrow \mu^+\mu^-$
  - $D_{(s)}^+ \rightarrow \pi^+\mu^+\mu^-$ and $D_{(s)}^+ \rightarrow \pi^-\mu^+\mu^+$
- On going activities
- Conclusion

Motivations

- Why **rare** decays?
  - Flavor Changing Neutral Currents (FCNC) are **very suppressed** in the Standard model (SM), possible only via loops.







→ Rare charm decays → Good probe for **New Physics**

NP particles in the loop → enhancement of BF, asymmetries (CP, T-odd, forward-backward).

- Why **charm** decays?
  - GIM mechanism is very strong here thanks to the absence of a high-mass down-type quark
  - Charm is complementary to the B and K sectors: it's a unique window on NP affecting the up-type quark dynamics.

Motivations

SM short distance (SD) contributions predict tiny BF's

BF($D^0 \rightarrow \mu^+\mu^-$) ~ 10^{-18} *[1]*	**BF($D^0 \rightarrow \pi^- \pi^+\mu^+\mu^-$)** ~ 10^{-9} *[3]*
BF($D^+ \rightarrow \pi^+\mu^+\mu^-$) ~ 10^{-11} - 10^{-9} *[2]*	**BF($D^0 \rightarrow K^+\pi^-\mu^+\mu^-$)** ~ 10^{-10} *[3]*

New physics can enhance the SD contributions. Ex.: R-Parity Violation SUSY

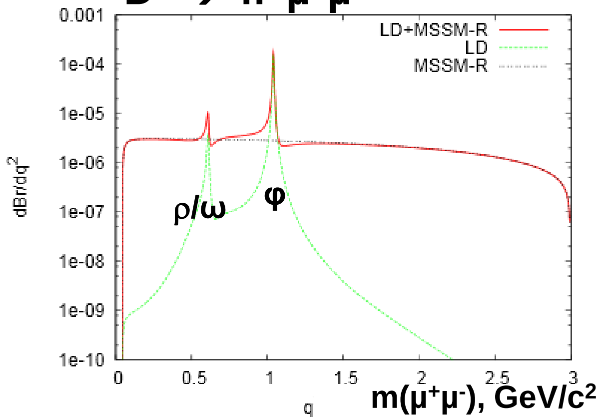
$D^0 \rightarrow \mu^+\mu^-$

Relating to the D^0- $\overline{D^0}$ mixing

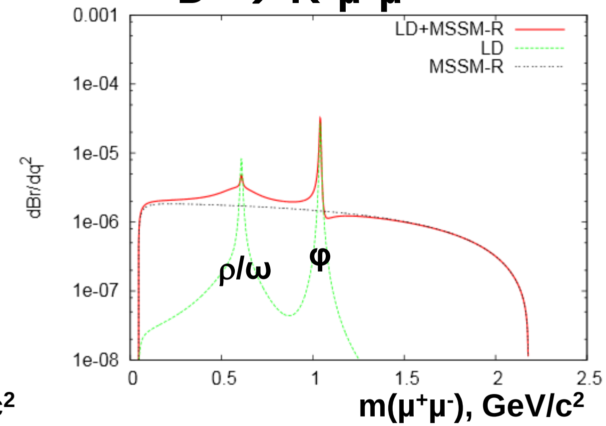
$$\mathcal{B}^{R_p}_{D^0\to\mu^+\mu^-} \leq 4.8\times 10^{-9}\left(\frac{300\ \mathrm{GeV}}{m_{\tilde{d}_k}}\right)^2$$

BF($D^0 \rightarrow \mu^+\mu^-$) ~ 10^{-9} *[4]*

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



$D^+ \rightarrow K^+\mu^+\mu^-$



BF($D^+ \rightarrow \pi^+\mu^+\mu^-$) ~ 10^{-6} *[5]*

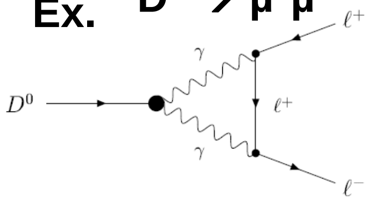
[1] G. Burdman et al. PR D66, 014009 (2002)
[2] G. Buchalla et al. EPJC57,309(2008),S. Fajfer et al, PRD64 (2001) 114009,
[3] L.Cappiello et al. arXiv:1209.4235v1
[4] E. Golowich, PRD79(2009)114030
[5] S. Fajfer et al, PRD76 (2007),074010

Motivations

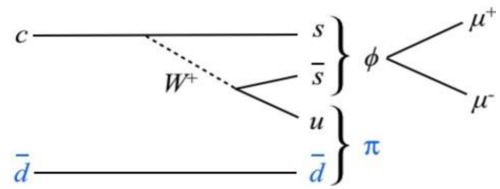
- Branching ratios dominated by long distance (**LD**) effects, via intermediate states

- The solution adopted by present searches is to measure BF's far from the resonances

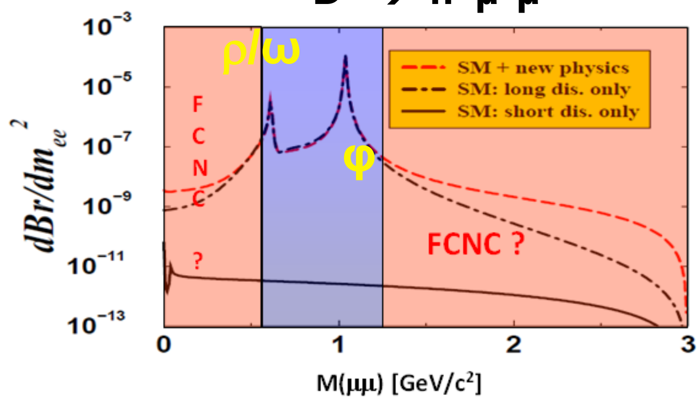
Ex. $D^0 \rightarrow \mu^+\mu^-$



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



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



- Recent literature suggests to use **asymmetries** (CP, T-odd, FB,…): **SD** *amplitudes* are more likely to compete with **LD** in an interference than in a BF. In that case, even the resonant regions are useful.

Mode	T-odd asym	FB asym
$K^-\pi^+\mu^+\mu^-$ (CF)	~ 7%	~ 0.06%
$K^+\pi^-\mu^+\mu^-$ (DCS)	~ 7%	~ 3%
$K^+K^-\mu^+\mu^-$	~ 6%	~ 0.5%
$\pi^-\pi^+\mu^+\mu^-$	~ 8%	~ 0.5%

Ex:arXiv:1209.4235v2

We measure the total BF's with present data to predict our future sensitivity (e.g. upgrade).

L.Cappiello et al. arXiv:1209.4235 (2013)
S.Fajfer et al. PRD87, 054026 (2013)
I.Bigi et al. JHEP03, 021 (2012)

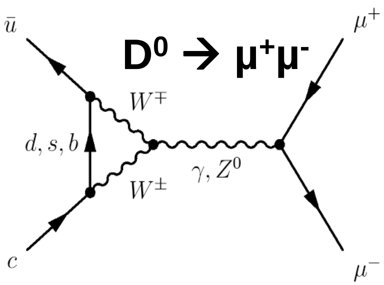
Experimental status up to 2011

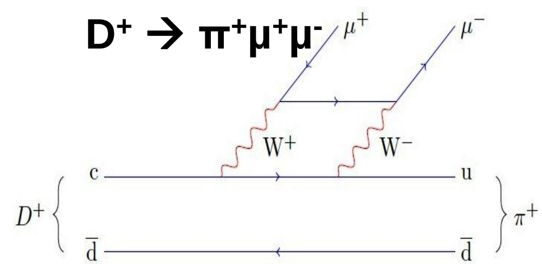
- Upper limits of BF, @90% CL

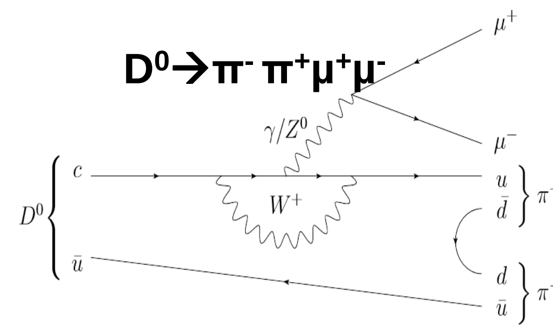
$D^0 \to \mu^+\mu^-$	1.4×10^{-7}	[1]
$D^+ \to \pi^+ \mu^+\mu^-$	3.9×10^{-6}	[2]
$D_s^+ \to \pi^+ \mu^+\mu^-$	2.6×10^{-5}	[3]
$D^+ \to \pi^- \mu^+\mu^+$	2.0×10^{-6}	[4]
$D_s^+ \to \pi^- \mu^+\mu^+$	1.4×10^{-5}	[4]
$D^0 \to K^- \pi^+ \mu^+\mu^-$	3.6×10^{-4}	[5]
$D^0 \to K^- K^+ \mu^+\mu^-$	3.3×10^{-5}	[5]
$D^0 \to \pi^- \pi^+ \mu^+\mu^-$	3.0×10^{-5}	[5]

$\sim 10^{-5} - 10^{-6}$ (rows 2–5)

$\sim 10^{-4} - 10^{-5}$ (rows 6–8)



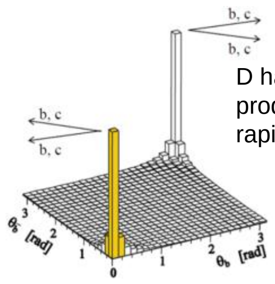




[1] Belle, PRD81,091102 (2010)
[2] D0, PRL 100,101801 (2008)
[3] FOCUS, PLB 572, 21 (2003)
[4] BaBar, PRD 84, 072006 (2011)
[5] E791, PRL 86, 3969 (2001)

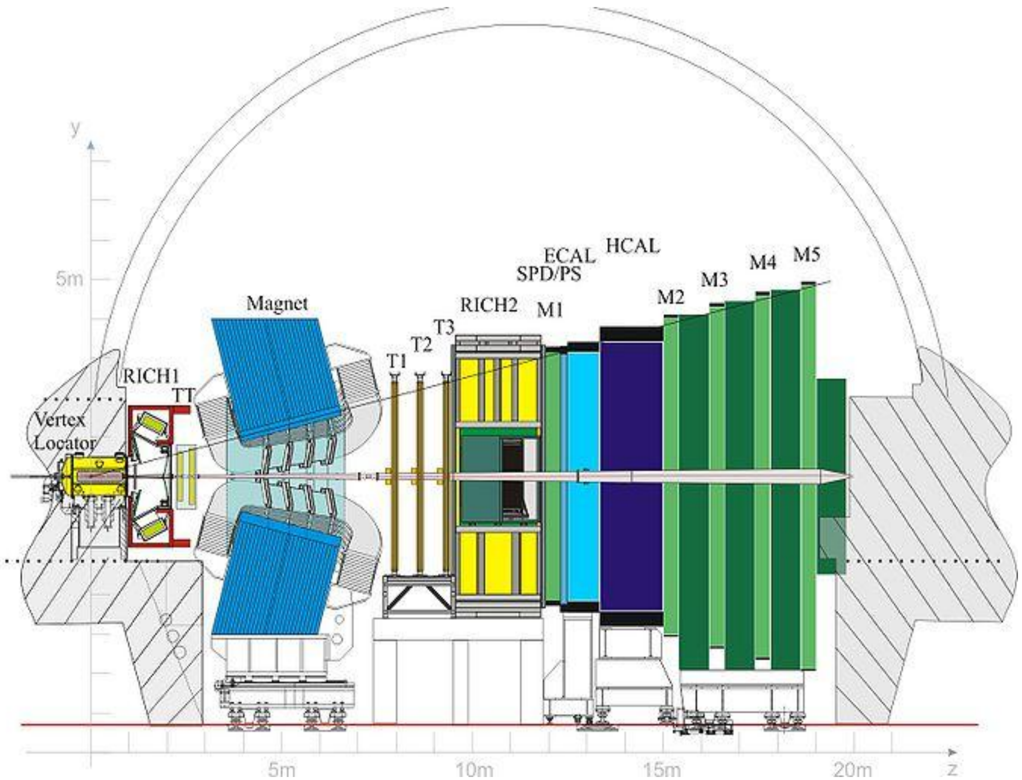
LHCb detector

- LHCb detector is designed for flavor physics
  - High $c\bar{c}$ cross-section
  - Forward geometry
  - Vertex and mass resolution
  - Highly flexible trigger, optimized for flavor physics
  - Good particle identification



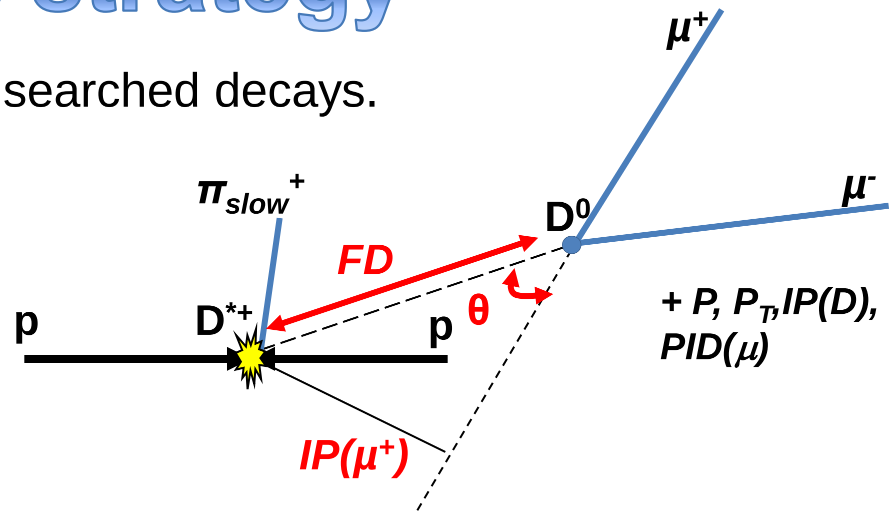
D hadrons are producing in high rapidity

$2 < \eta < 5$ (15 – 300 mrad)
Design luminosity 2×10^{32} cm^{-2} s^{-1}



General analysis strategy

- Selection using the typical features for the searched decays.



- Very rare means very high relative combinatorial background
  → Use Multivariate Analysis

- Another difficulty with charm decays: very high peaking backgrounds
  (Ex: $D \rightarrow \pi\pi > 10^6 \times D \rightarrow \mu\mu$)
  → Use particle identification to fight against $\pi \rightarrow \mu$ misID

- Normalized Measurements to help controlling the systematics

$$BF_{(signal)} = BF_{(norm)} \frac{\varepsilon_{(norm)}}{\varepsilon_{(signal)}} \frac{N_{(signal)}}{N_{(norm)}}$$

Ex. : $D^+ \rightarrow \pi^+\mu^+\mu^-$ and $D^+ \rightarrow \pi^+ \varphi(\mu^+\mu^-)$

- Efficiencies : simulations + extensive data-driven corrections & systematics
  $J/\psi \rightarrow \mu\mu$, $D \rightarrow K\pi$, $\Lambda \rightarrow p\,\pi$, $K_s \rightarrow \pi\pi$: reconstruction, PID, trigger efficiencies …

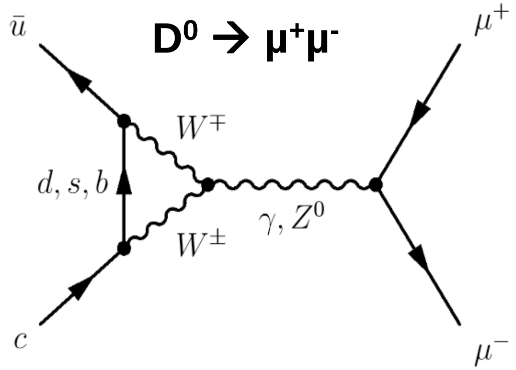
- $\pi \leftrightarrow \mu$ misID rate: simulations and control from data: $D \rightarrow K\pi$, with π swapped with μ

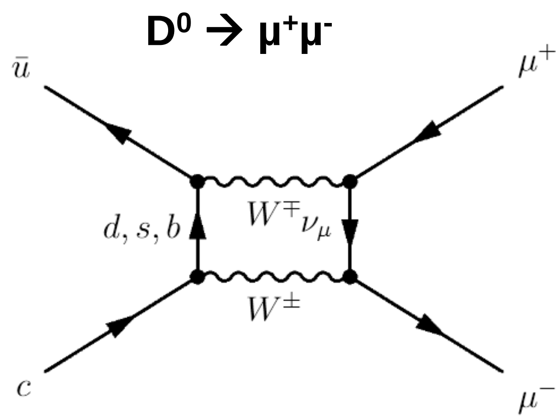
- Blind analyses, Upper limits from the CLs method *[A. Read, J. Phys. G28 (2002)]*

CERN-PH-EP-2013-083
LHCb-PAPER-2013-013
arXiv:1305.5059
PLB(2013) in press…

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

0.9 fb^{-1}, 2011 data

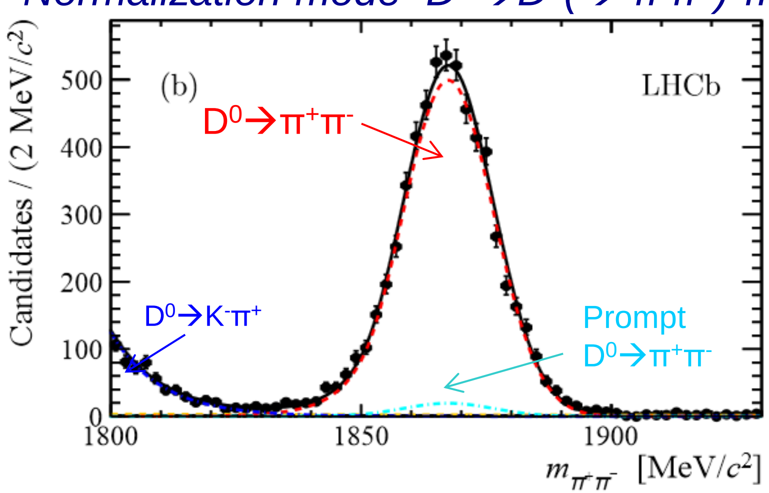




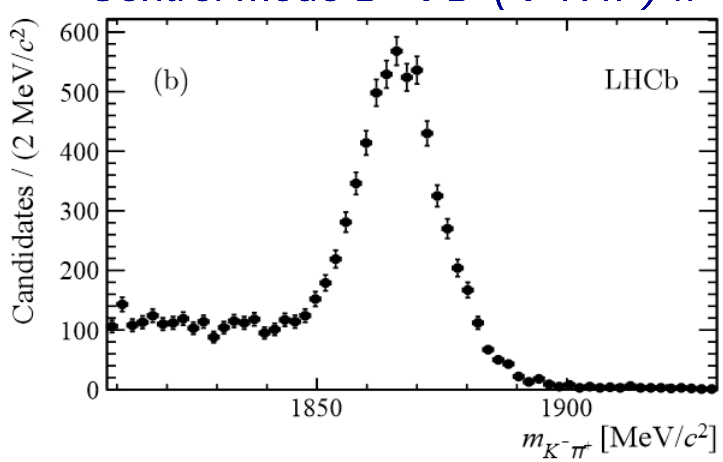
$D^0 \to \mu^+\mu^-$ at LHCb

- D*–tagged sample: $D^{*+} \to D^0(\to \mu^+\mu^-)\pi_{slow}^{\ +}$
- 2D fit: $\Delta m = m(D^{*+})-m(D^0)$ & $m(D^0)$
  - *force π_{slow} to come from PV to improve the resolution on Δm*
- Peaking background : $D^{*+} \to D^0(\to \pi^-\pi^+)\ \pi^+$ with double misID $\pi \leftrightarrow \mu$
  - *The rate of this peaking background is estimated using MC and a high statistics $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ control sample from real data for the evaluation of the $\pi \leftrightarrow \mu$ misID*
  - *Yield is fitted in the signal sample with Gaussian constrained*
- Normalization mode: $D^{*+} \to D^0(\to \pi^-\pi^+)\ \pi^+$

Normalization mode $D^* \to D^0(\to \pi^-\pi^+)\ \pi^+$



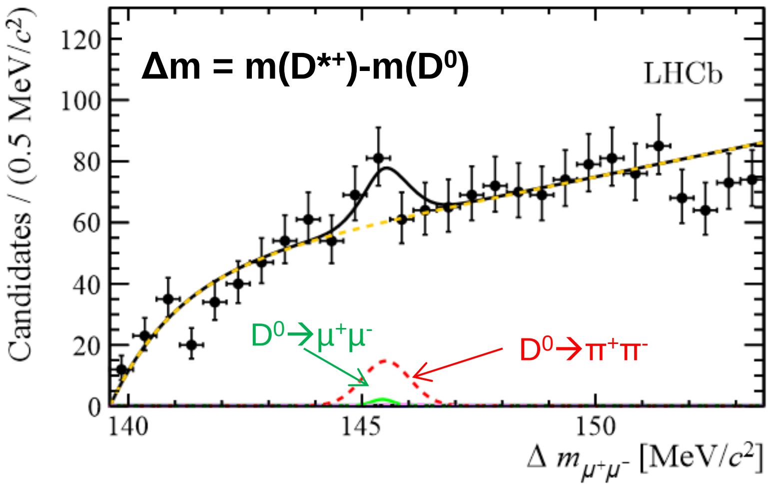
Control mode $D^* \to D^0(\to K^-\pi^+)\ \pi^+$

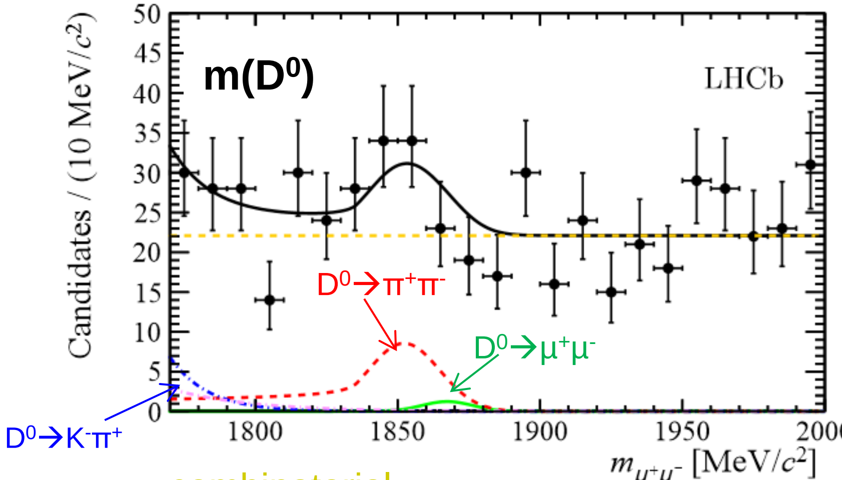


Used to estimate misID K↔μ, π ↔ μ

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

0.9 fb^{-1}, 2011 data



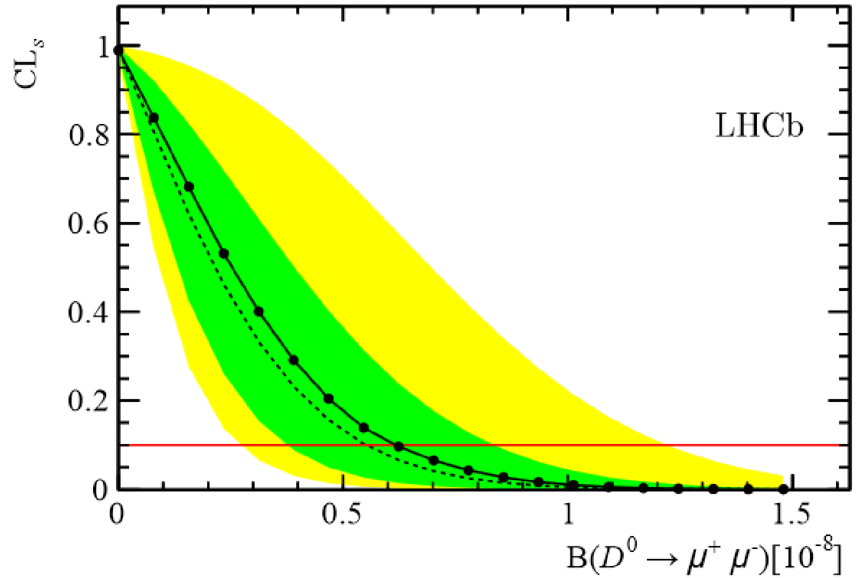


-- combinatorial

-- peaking $D^0 \to \pi^+\pi^-$, with 2 × ($\pi \leftrightarrow \mu$)

-- $D^0 \to K^-\pi^+$, with ($\pi \leftrightarrow \mu$) *and* ($K \leftrightarrow \mu$)

– signal $D^0 \to \mu^+\mu^-$



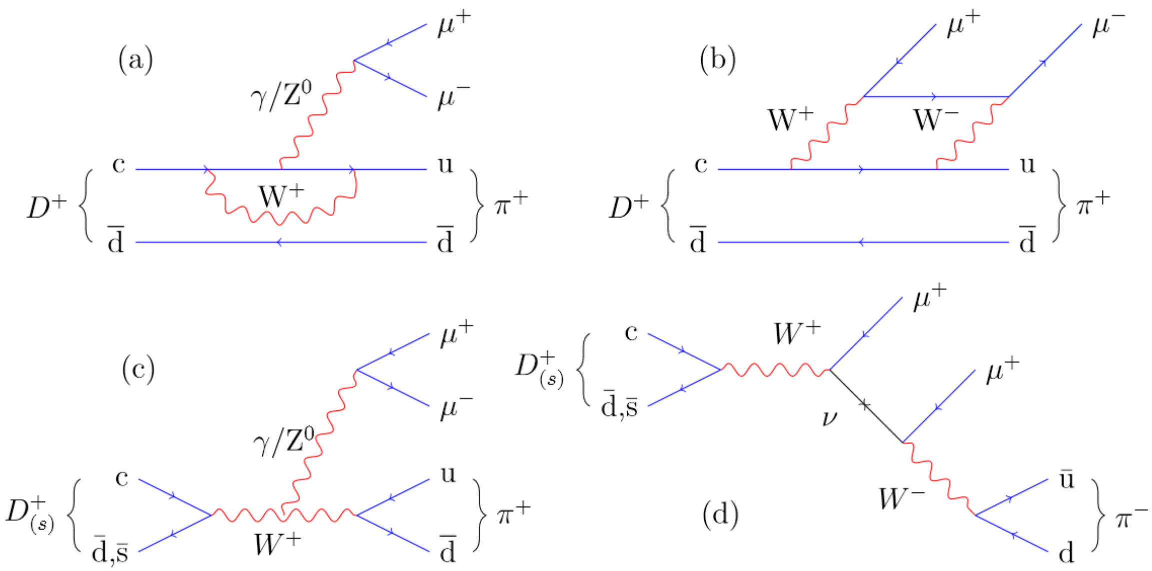
BF($D^0 \to \mu\mu$) < 6.2 (7.6)·10^{-9} @ 90% (95%) CL

- ✓ **20 times better than previous limit**
- ✓ **Still 2 orders of magnitude above the SM prediction**

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

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

1 fb^{-1}, 2011 data

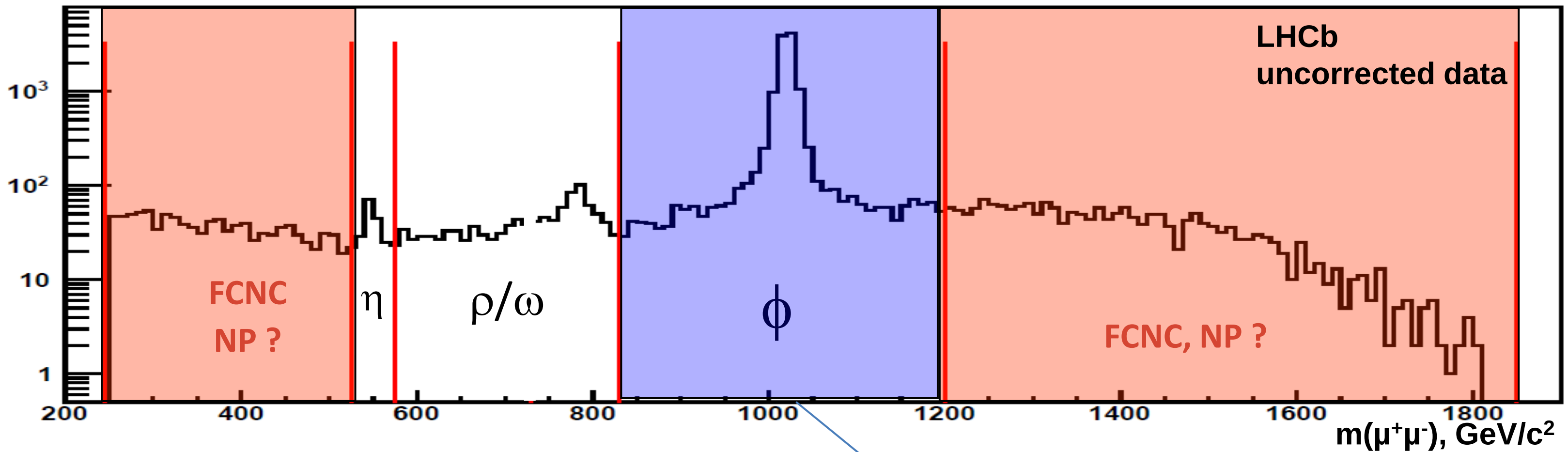


PLB 724 (2013) 203-212
CERN-PH-EP-2013-061
LHCB-PAPER-2012-051
arXiv:1304.6365

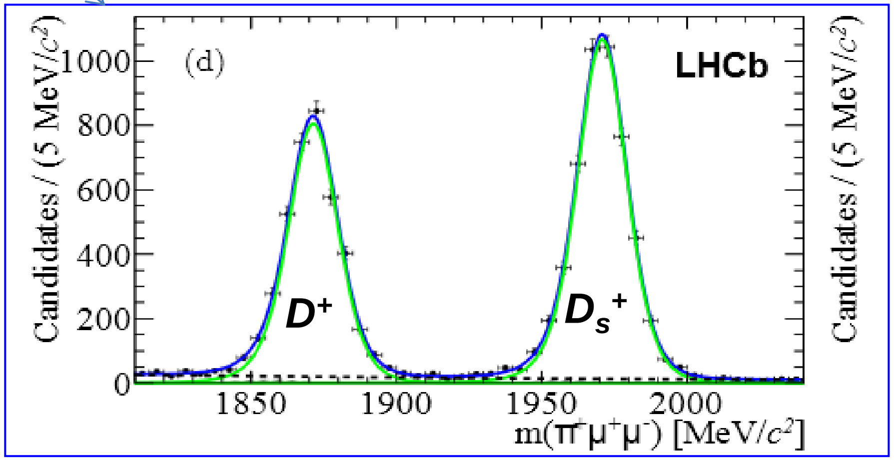
$D_{(s)}^+ \to \pi^+\mu^+\mu^-$ at LHCb

- Signal is extracted in regions of $m(\mu^+\mu^-)$

$D_{(s)}^+ \to \pi^+ \mu^+\mu^-$ (Opposite Sign)

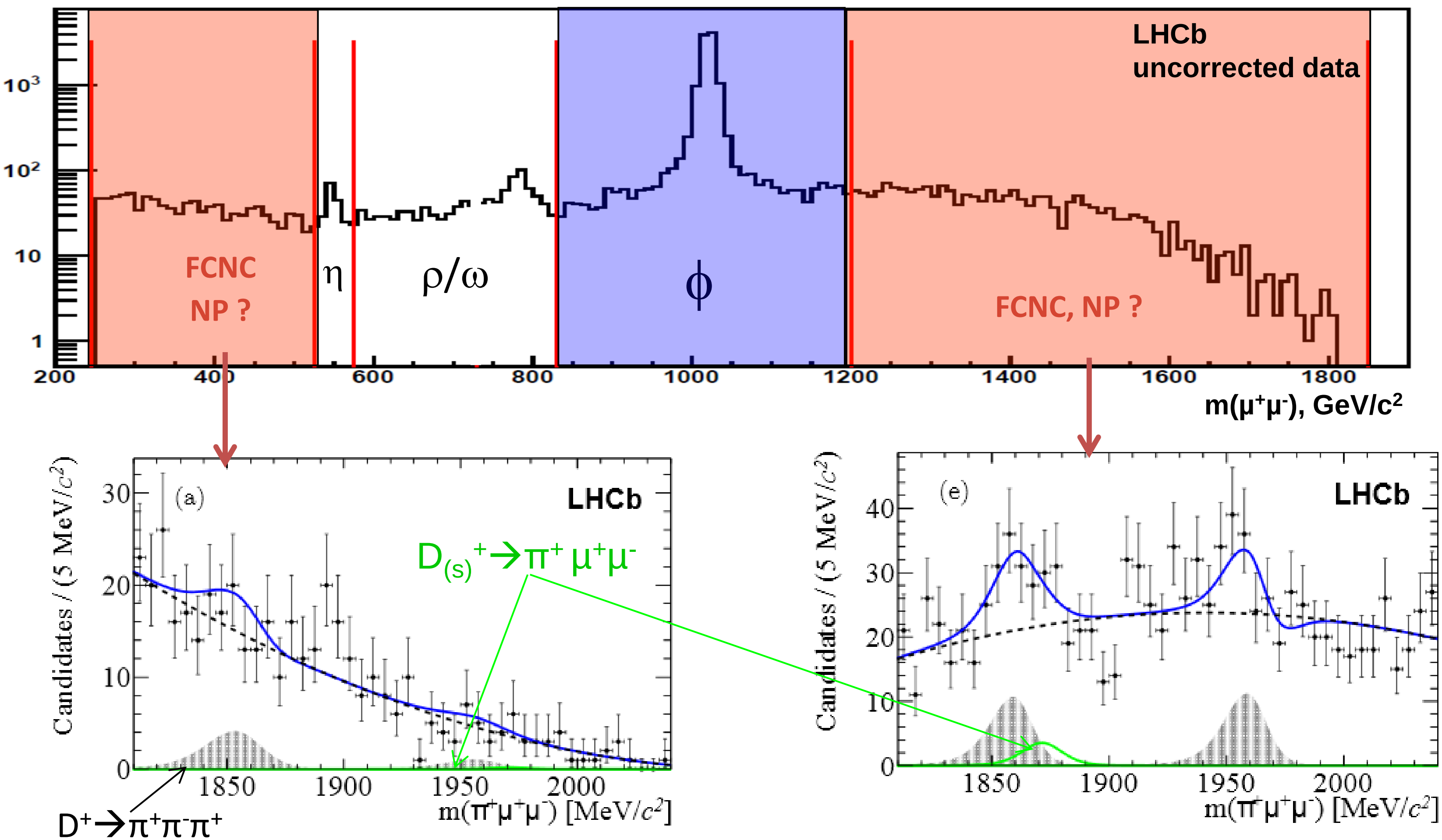


- $D^+ \to \pi^+ \phi (\mu^-\mu^+)$ mode:
  - Normalization
  - "Standard candle": provides a signal proxy to optimize the selection, constrain the PDF's shape, study and correct data/MC…



1 fb^{-1}
2011 data

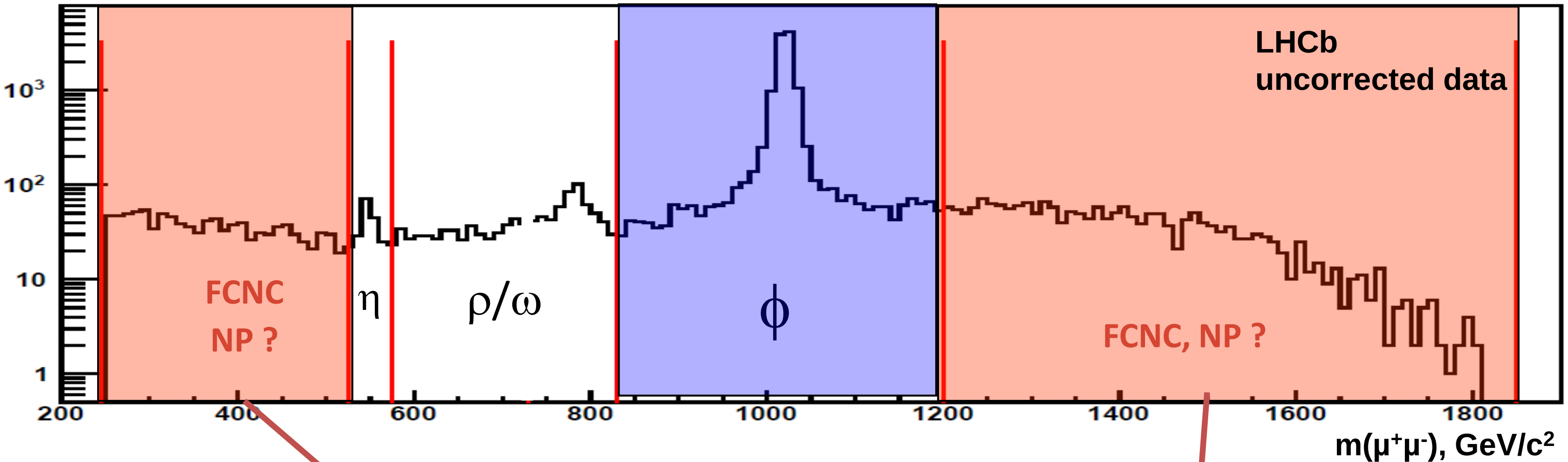
$D_{(s)}^+ \to \pi^+\mu^+\mu^-$ at LHCb



- Peaking background : $D^+ \to \pi^+\pi^-\pi^+$ with double misID $\pi \leftrightarrow \mu$
  - *Shapes determined from data sample (loosened muon ID)*
  - *The fit is able to determine the yields*

1 fb^{-1}
2011 data

$D_{(s)}^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-}$ at LHCb



Upper limits, ×10^{-8} @ 90% (95%) CL

BF($D^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-}$)	***2.0 (2.5)***	***2.6 (2.9)***
BF($D_s^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-}$)	***6.9 (7.7)***	***16.0 (18.6)***

Total:

BF($D^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-}$) < 7.3 (8.3)·$10^{-8}$ @ 90% (95%) CL

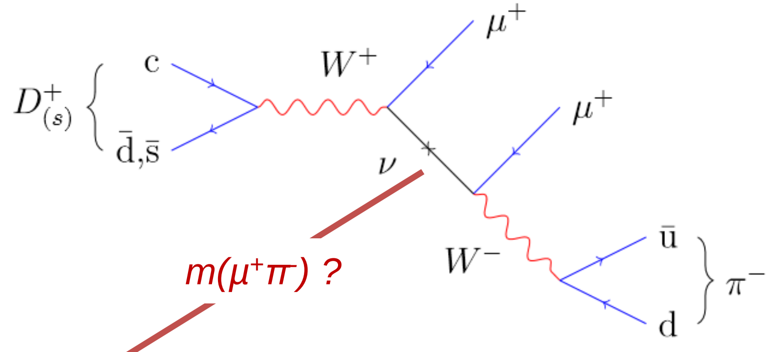
BF($D_s^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-}$) < 4.1 (4.8)·$10^{-7}$ @ 90 % (95%) CL

- ✓ **~ 50 times better than previous limit**
- ✓ **Still orders of magnitude above the SM prediction**

Majorana neutrino searches with $D_{(s)}^{+} \rightarrow \pi^{-}\mu^{+}\mu^{+}$ at LHCb

1 fb^{-1}
2011 data

- Searches in regions of ***$m(\mu^{+}\pi^{-})$*** which is the mass of a potential majorana neutrino



Region [MeV/c²]	**250<M($\mu\pi$) <1140**	**1140<M($\mu\pi$)<1340**	**1340<M($\mu\pi$)<1540**	**1540<M($\mu\pi$)**
$BF(D^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-})$	**1.4 (1.7)**	**1.1 (1.3)**	**1.3 (1.5)**	**1.3 (1.5)**
$BF(D_s^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-})$	**6.2 (7.6)**	**4.4 (5.3)**	**6.0 (7.3)**	**7.5 (8.7)**

Total:

$BF(D^{+} \rightarrow \pi^{-}\mu^{+}\mu^{+}) < 2.2\ (2.5) \cdot 10^{-8}$ @ 90% (95%) CL
$BF(D_s^{+} \rightarrow \pi^{-}\mu^{+}\mu^{+}) < 1.2\ (1.4) \cdot 10^{-7}$ @ 90% (95%) CL

✓ **~ 50 times better than previous limit**

✓ **Still orders of magnitude above the SM prediction**

Our on going activities

- Update of searches with 3 fb^{-1} full data sample (2011+2012):
  - $D^0 \to \mu^+\mu^-$
  - $D_{(s)}^+ \to \pi^+\mu^+\mu^-$
- New searches
  - $D_{(s)}^+ \to K^+\mu^+\mu^-$
  - $D^0 \to \pi^-\pi^+\mu^+\mu^-$, $D^0 \to K^-K^+\mu^+\mu^-$, $D^0 \to K^+\pi^-\mu^+\mu^-$

Conclusions

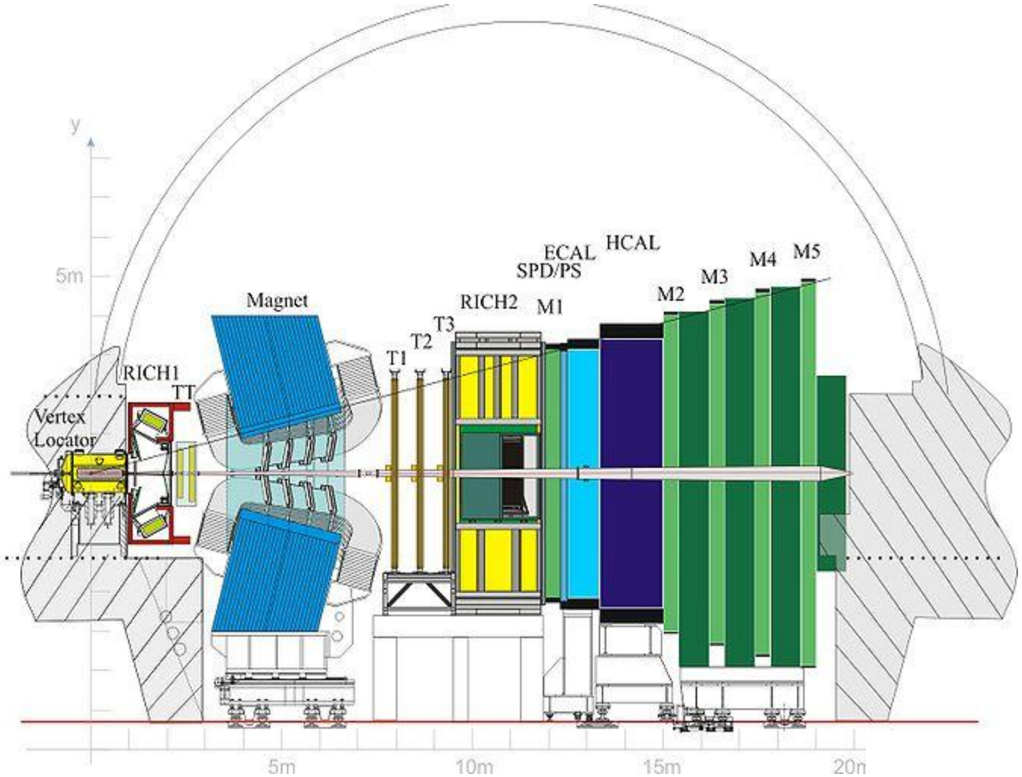
- Rare charm decays **good tools** for the search of the NP
- *Charm* decays are **complementary** to the *strange* and *beauty* rare decays
- No NP has been seen ***yet***
- Present upper limits for rare charm sector **still above** SM predictions
- Results with 1 fb^{-1} (**2011 data)** have been shown
- **New results and new modes** are expected next fall and next year

Thank you for attention!

Backup

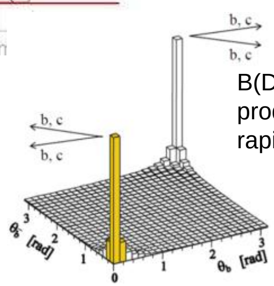
LHCb detector

LHCb detector



Designed for precise study of CP-violation, flavor-physics:

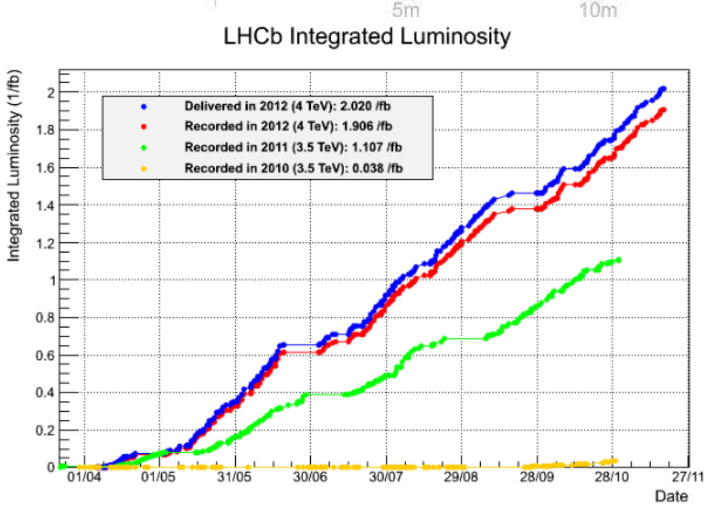
- forward geometry
- precise momentum and mass reconstruction
- precise vertex reconstruction,
- lifetime reconstruction
- Adapted and highly configurable trigger system
- identification: *π, K, μ*



B(D) hadrons are producing in high rapidity

$2 < \eta < 5$ (15 – 300 mrad)

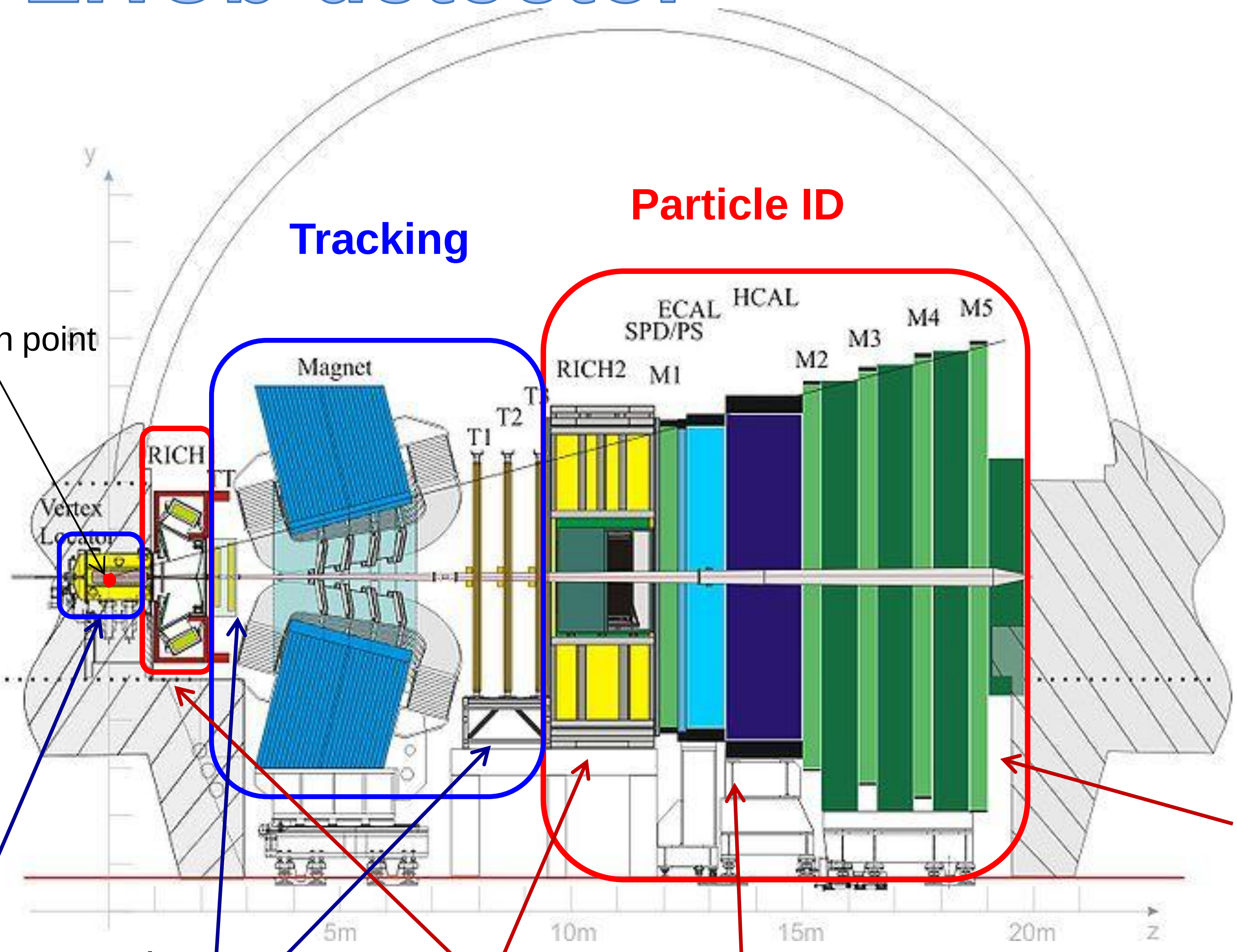
Design luminosity 2×10^{32} cm-2 s-1



LHCb **delivered (2.0/fb)**and **recorded** luminosity in 2012,
+1.1/fb indicates recorded luminosity in 2010-2011

LHCb detector

interaction point



Muon chambers
Trigger, μ ID

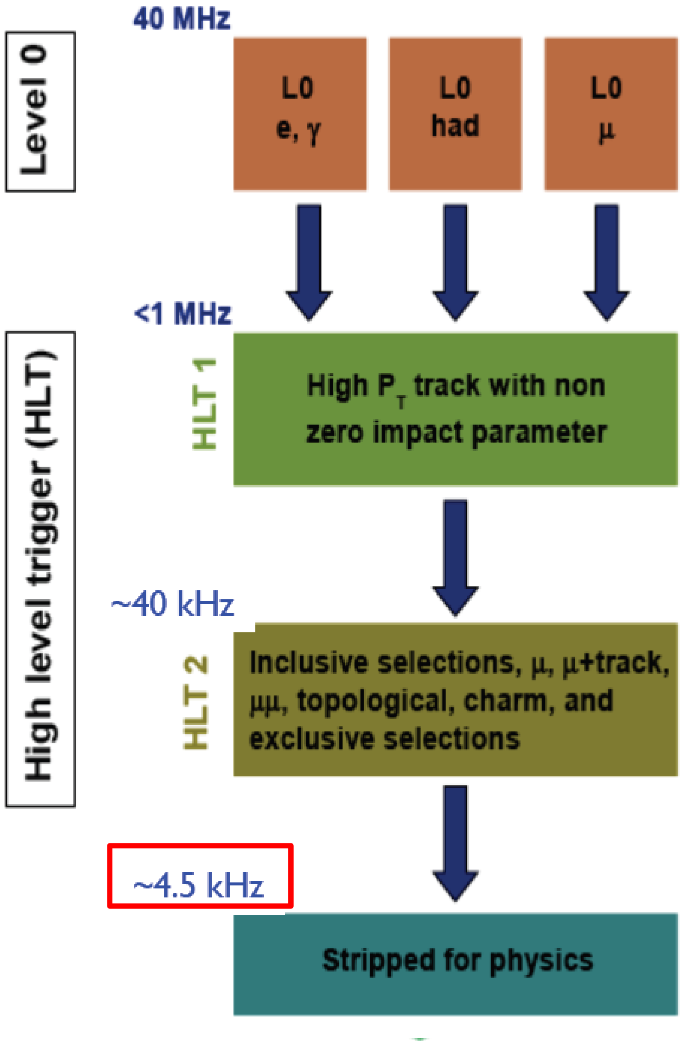
VELO
Precise vertexing

Tracking stations
momentum

RICH system
K, π, p ID

HCAL, ECAL, Preshower /SPD
Trigger+ e/γ energy and ID

LHCb trigger



L0 Hardware Trigger 40 MHz→1 MHz

- Search for high p_t, μ, e, γ, hadron candidates
  CALO p_t $>$ 3.6 GeV, MUON p_t >1.4 GeV

High Level Software Trigger Farm

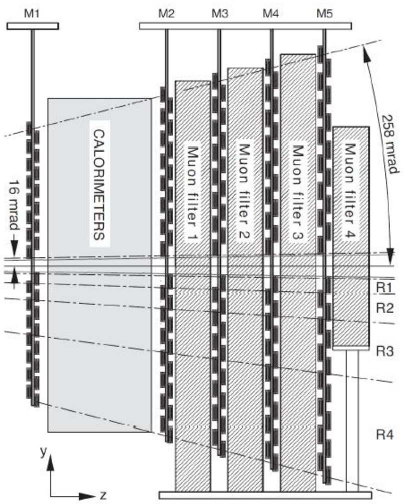
- HLT1: Add Impact parameter cuts
- HLT2: Global event reconstruction.
  Exclusive or inclusive offline-like selection (lines)

Adaptation to

- physics priorities
- variation of beam conditions

Muon particle identification

High muon/hadron discriminative power based on the Muon System



Calo (6.2 λ_I) + 3 iron absorbers (8cm thick, 20 λ_I)

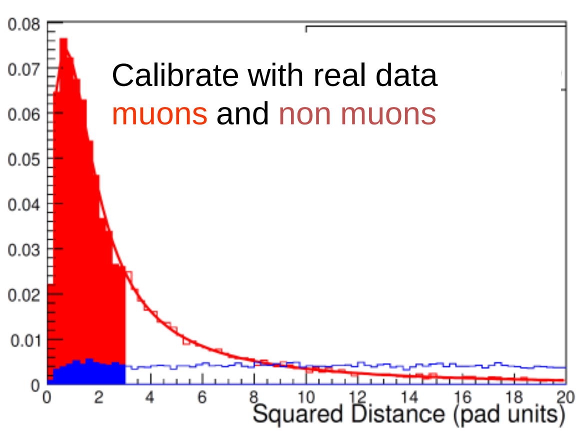
→ *Easy for a μ to traverse 3 to 5 stations (depending on its p)*

→ *Difficult for a pion or kaon*

Tracks extrapolated from the tracking system

→ *Easier to find hits close to it if this is a real μ*

→ *Typical distribution of the Average squared distance, used to build a muon likelihood*



$$D^2 = \frac{1}{N}\sum_{i=0}^{N}\left\{\left(\frac{x_{closest,i} - x_{track}}{pad_x}\right)^2 + \left(\frac{y_{closest,i} - y_{track}}{pad_y}\right)^2\right\}$$

Can be combined with other likelihoods based on the muon's signature in the RICH and Calorimeter.

Muon particle identification