# Searches for rare charm decays at LHCb

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**EPS-HEP 2017**
**Venice, Italy, July 5 - 12, 2017**

GEFÖRDERT VOM

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# Why rare charm decays (at LHCb)?

- wide variety of physics, ranging from forbidden to not-so-rare decays

### Lepton Flavor Violation

- forbidden in SM
- some NP models predict large enhancement [PRD 66 (2002) 014009]
- example $D^0 \to e^\pm \mu^\mp$

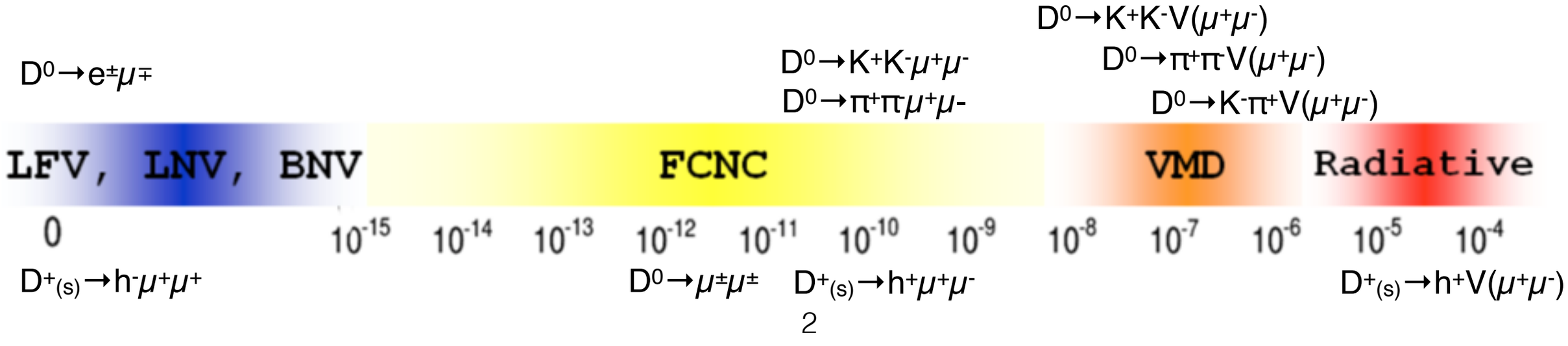
### Flavor Changing Neutral Current

- in SM only at loop level
- SM short-distance contribution of inclusive $D \to X\mu^+\mu^-$ ~$O(10^{-9})$ [PRD83,(2011)114006]
- one of few occasions to investigate up-type quark FCNCs
- example $D^0 \to h^+h^-\mu^+\mu^-$

### Why at LHCb?

[JINST 3 (2008) S080005]

- perfect detector to study decays of heavy flavor
  - excellent particle ID, momentum & vertex resolution
- recorded one of the largest samples of charm decays
  - ~$5 \cdot 10^{12}$ $D^0$ in LHCb acc. (Run1)



# Search for the lepton-flavour violating decay $D^0 \rightarrow e^{\pm}\mu^{\mp}$

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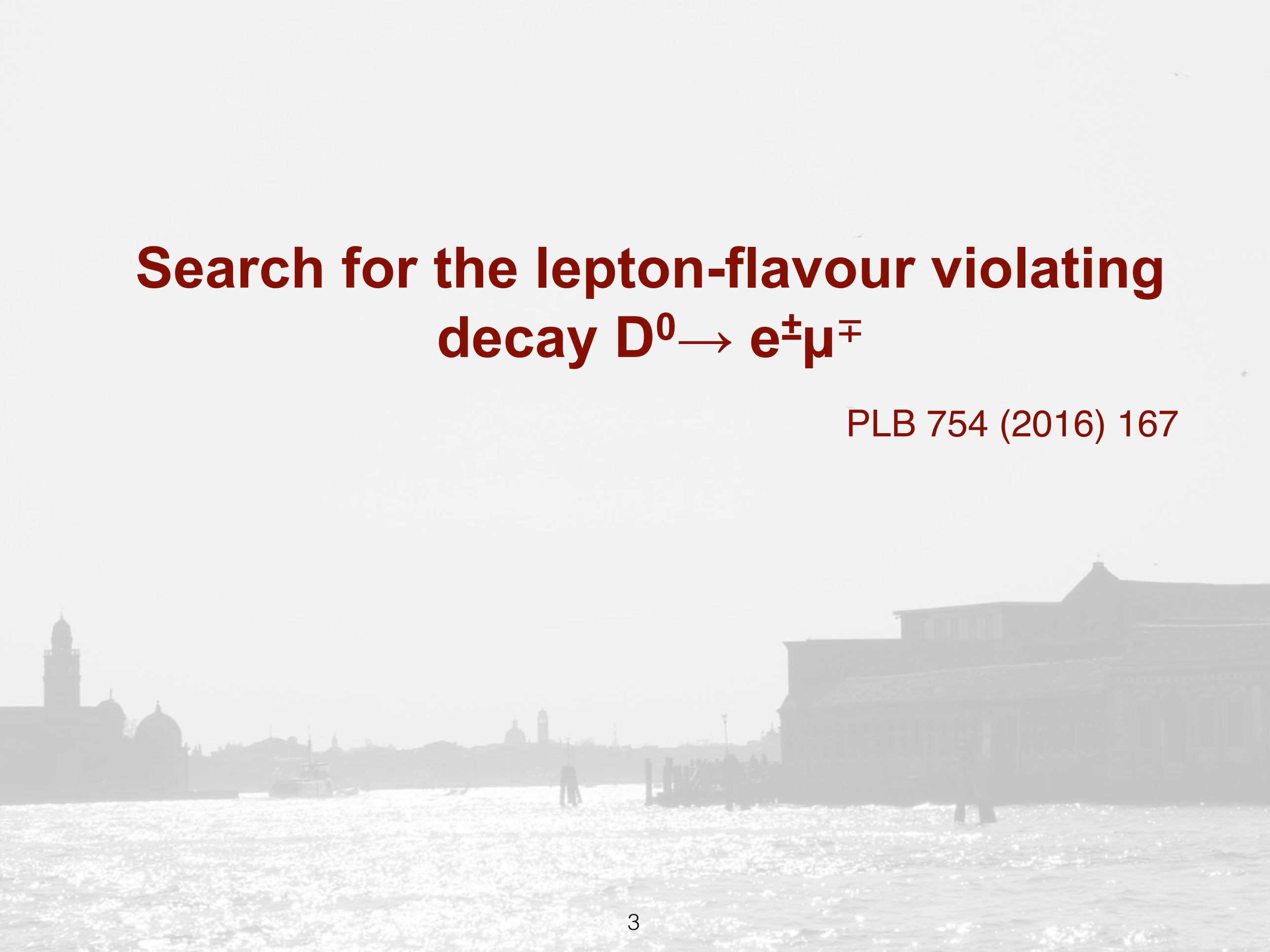

# Search for LFV decay $D^0 \to e^{\pm}\mu^{\mp}$

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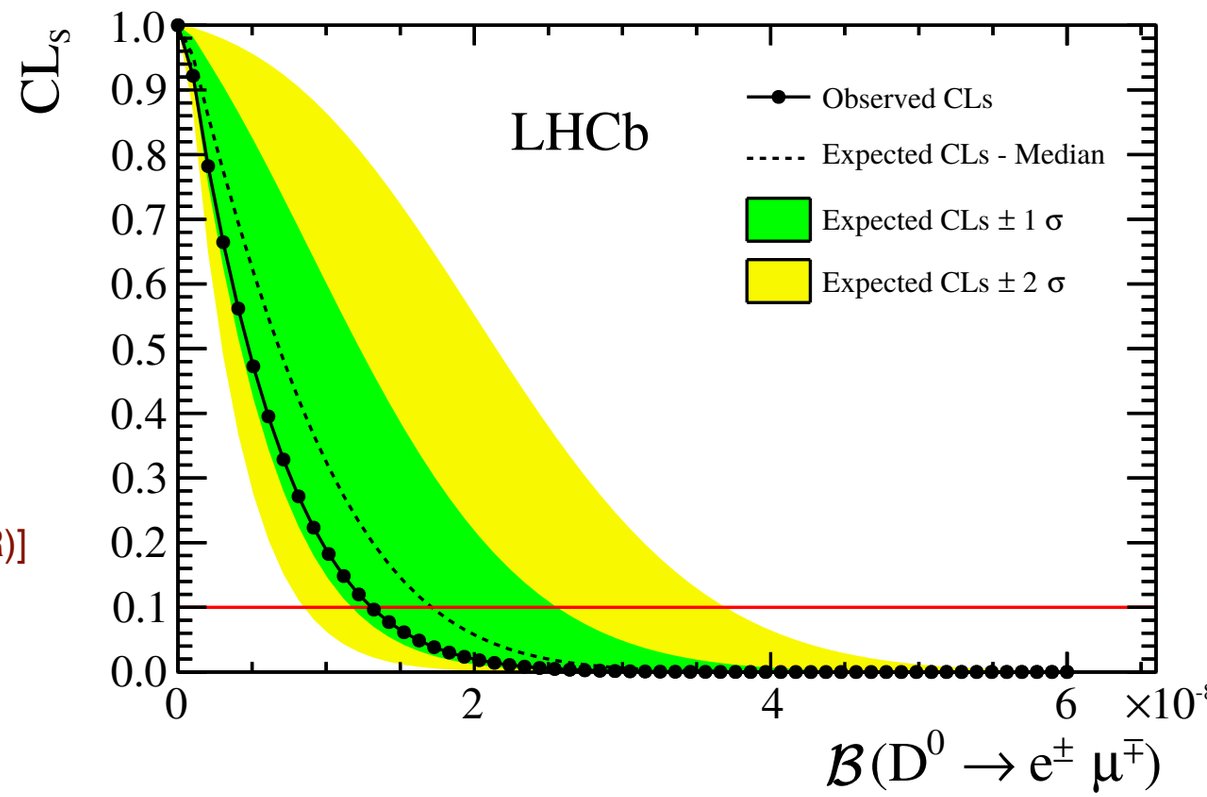
- strictly forbidden in the SM
  - SM extensions: rates in [$10^{-14}$-$10^{-6}$ ]

    [PRD 66 (2002) 014009]
  - any signal clear indication of NP
  - most stringent limit so far: Belle

    $\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 2.6 \times 10^{-6}$ at 90% CL

    [PRD 81(2010) 091102(R)]




## LHCb analysis details

- full Run1 dataset (3/fb)
- $D^0$ from $D^{*+} \to D^0\pi^+$ decays
- measurement relative to normalization decay $D^0 \to K^-\pi^+$

$$\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

[PLB 754 (2016) 167]

**world's best limit!**

# First observation of the decay $D^0 \to K^-\pi^+\mu^+\mu^-$ in the $\rho^0$–$\omega$ region of the dimuon mass spectrum

PLB 757 (2016) 558-567

# Observation of the decay $D^0 \to K^-\pi^+\mu^+\mu^-$

PLB 757 (2016) 558-567

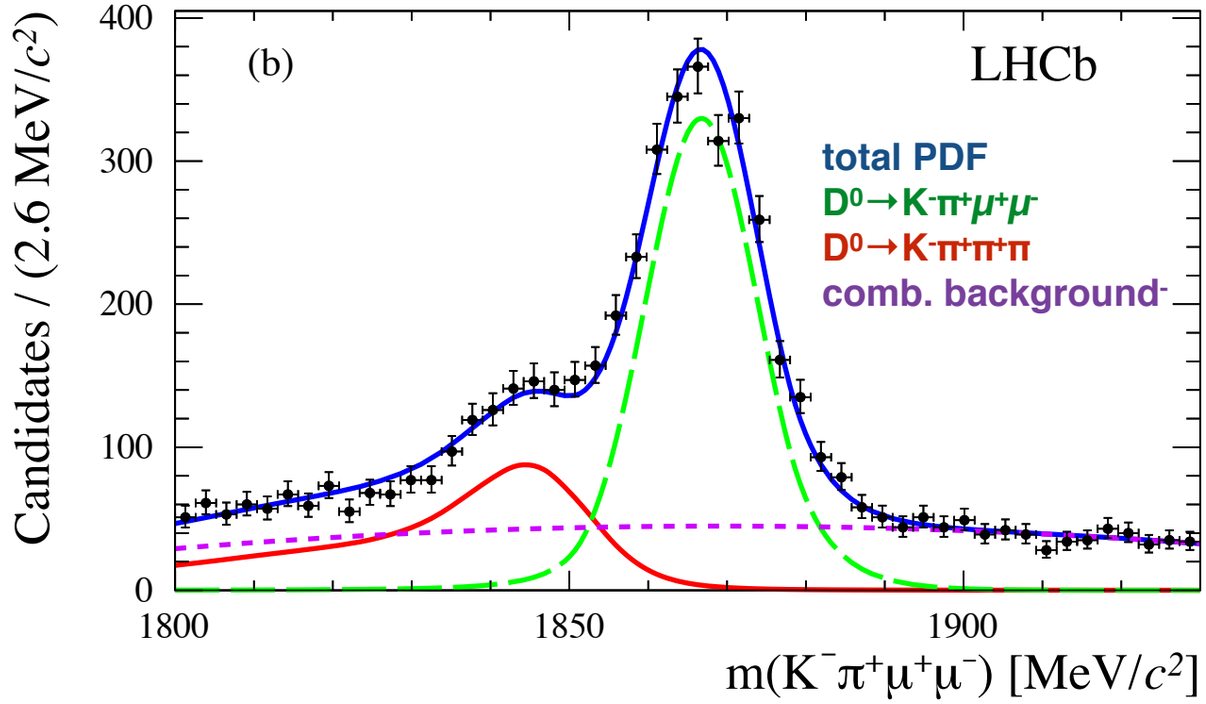
- $m(\mu^+\mu^-) \in [675\text{-}875]$ MeV/$c^2$ consistent with muons coming from $\rho^0/\omega$ resonance
- tree level dominated, still a rare decay and perfect normalization mode for $D^0 \to h^+h^-\mu^+\mu^-$
- most stringent limit so far: E791

$$\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) < 3.6 \times 10^{-5} \text{ at } 90\% \text{ CL}$$

[PRL 86 (2001) 3969]

## LHCb analysis details

- data: 2/fb from 2012
- prompt $D^0$ (primary pp interaction)
- normalization channel $D^0 \to K^-\pi^+\pi^+\pi^-$




$$\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$$

[PLB 757 (2016) 558-567]

**First observation! compatible with SM predictions**

[JHEP 04(2013)135]

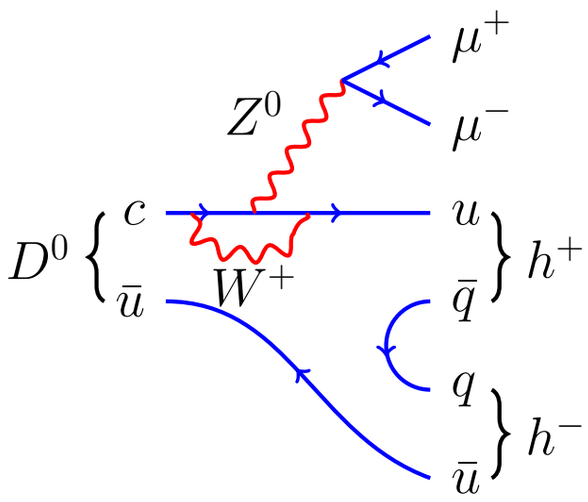
[LHCb-PAPER-2017-019]
(in preparation)

# Observation of $D^0$ meson decays into $\pi^+\pi^-\mu^+\mu^-$ and $K^+K^-\mu^+\mu^-$ final states

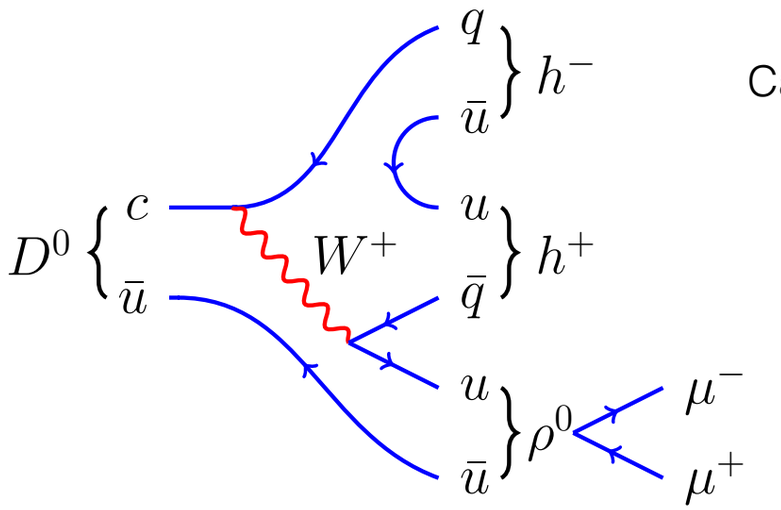
# Observation of $D^0 \to \pi^+\pi^-(K^+K^-)\mu^+\mu^-$

[LHCb-PAPER-2017-019]

- involving short distance (SD) physics, however total BF's dominated by long distance (LD) contributions




example short-distance contribution
EW Penguin




example long-distance contribution
$D^0 \to h^+h^-\rho^0(\to\mu^+\mu^-)$

Cappiello et al. about $D^0 \to h^+h^-\mu^+\mu^-$ decays:

*"In a nutshell, the penalty of small branching fractions (…) is overly compensated by the diversity (and the size) of the asymmetries one can build."*

[JHEP 04(2013)135]

- current strategy: BF measurement in bins of dimuon mass
  - sensitivity to SD contributions in regions away from resonances

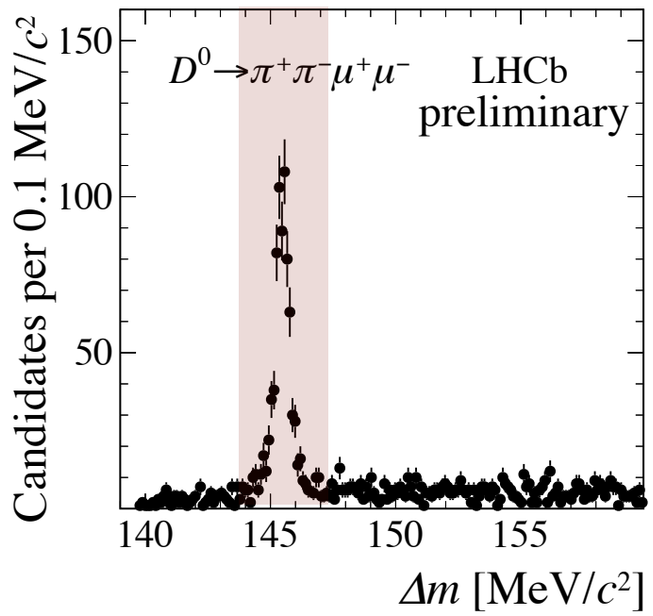
- future strategy: measure asymmetries ($A_{FB}$, $A_{CP}$ …) with sensitivity to SD physics
  - O(1%) predictions for some NP models [JHEP 1304 (2013) 135], [PRD 87 (2013) 054026]

# Observation of $D^0 \to \pi^+\pi^-(K^+K^-)\mu^+\mu^-$

[LHCb-PAPER-2017-019]

## Experimental details

- data: 2/fb from 2012
- $D^0 \to K^-\pi^+\mu^+\mu^-$ normalization channel
- $D^0$ from $D^{*+} \to D^0\pi^+$ decays
  - efficient suppression of combinatorial background




## Dimuon mass binning scheme

| bin | low mass | $\eta$ | $\rho/\omega$ | $\phi$ | high mass |
|---|---|---|---|---|---|
| $m(\mu^+\mu^-)[MeV/c^2]$ | $< 525$ | $525 - 565$ | $565 - 950$ | $950 - 1100$ | $> 1100$ |
| $D^0 \to \pi^+\pi^-\mu^+\mu^-$ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $D^0 \to K^+K^-\mu^+\mu^-$ | ✓ | ✓ | ✓ | | |

*remark: low and high mass bins also affected by tails of resonances

## Measurement strategy

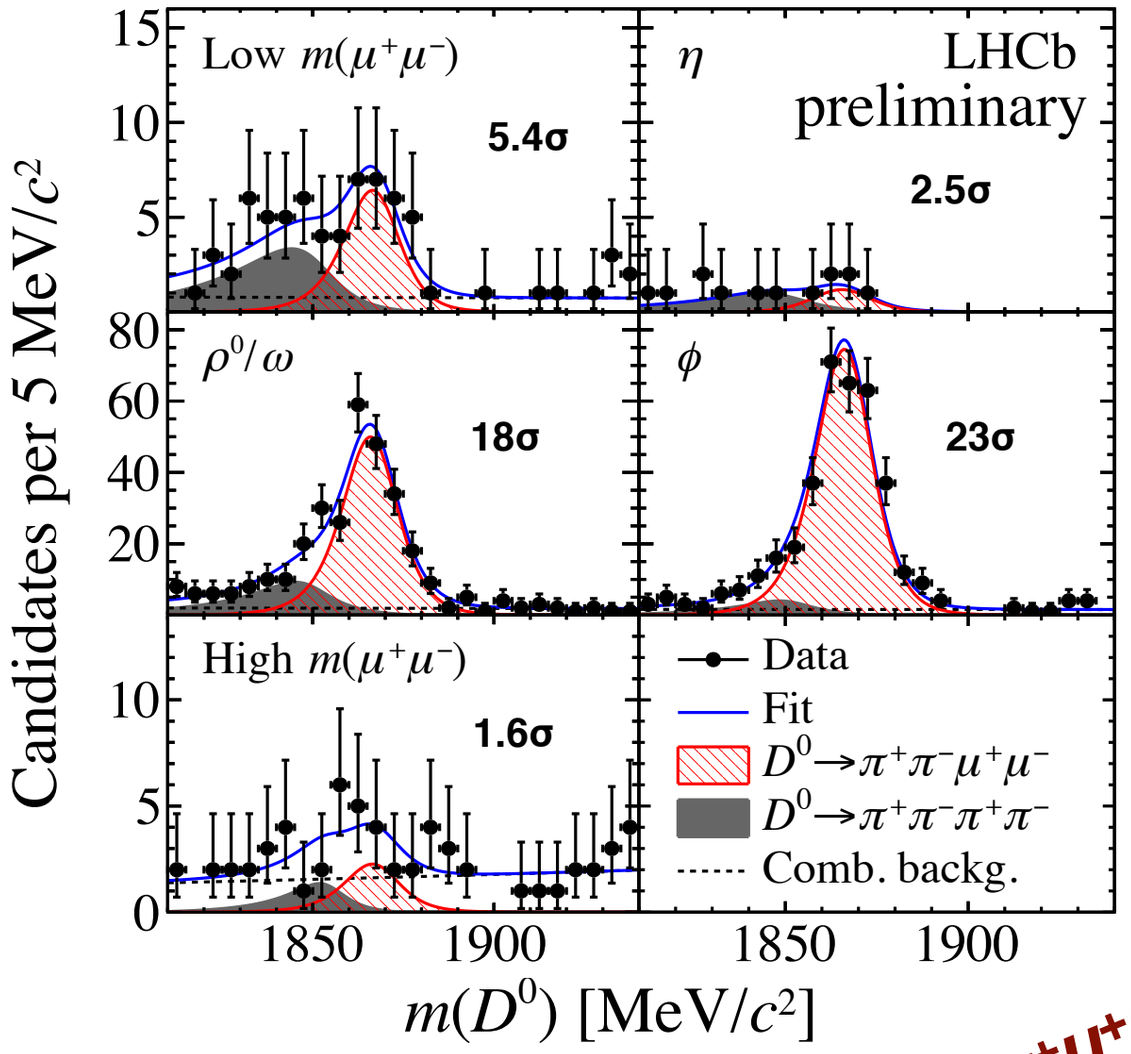
- BF measurement in $m(\mu^+\mu^-)$ bins if local signal significance > 3σ
- upper limit on signal BF if local significance <3σ

- quote total BF of the decays

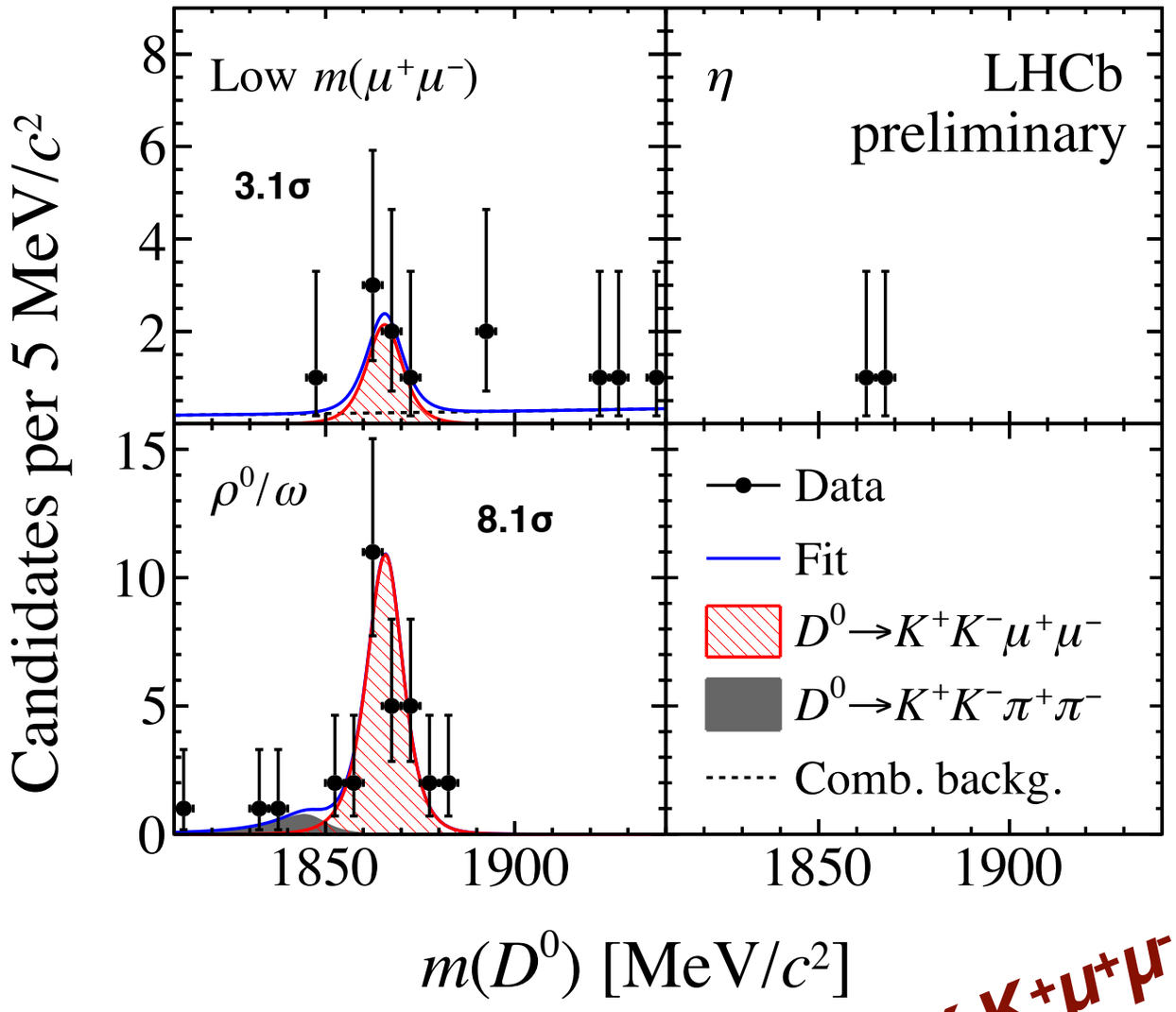
# Observation of $D^0 \to \pi^+\pi^-(K^+K^-)\mu^+\mu^-$

[LHCb-PAPER-2017-019]

- signal yield determination through maximum likelihood fits to $D^0$ mass




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




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

# Observation of $D^0 \to \pi^+\pi^-(K^+K^-)\mu^+\mu^-$

[LHCb-PAPER-2017-019]

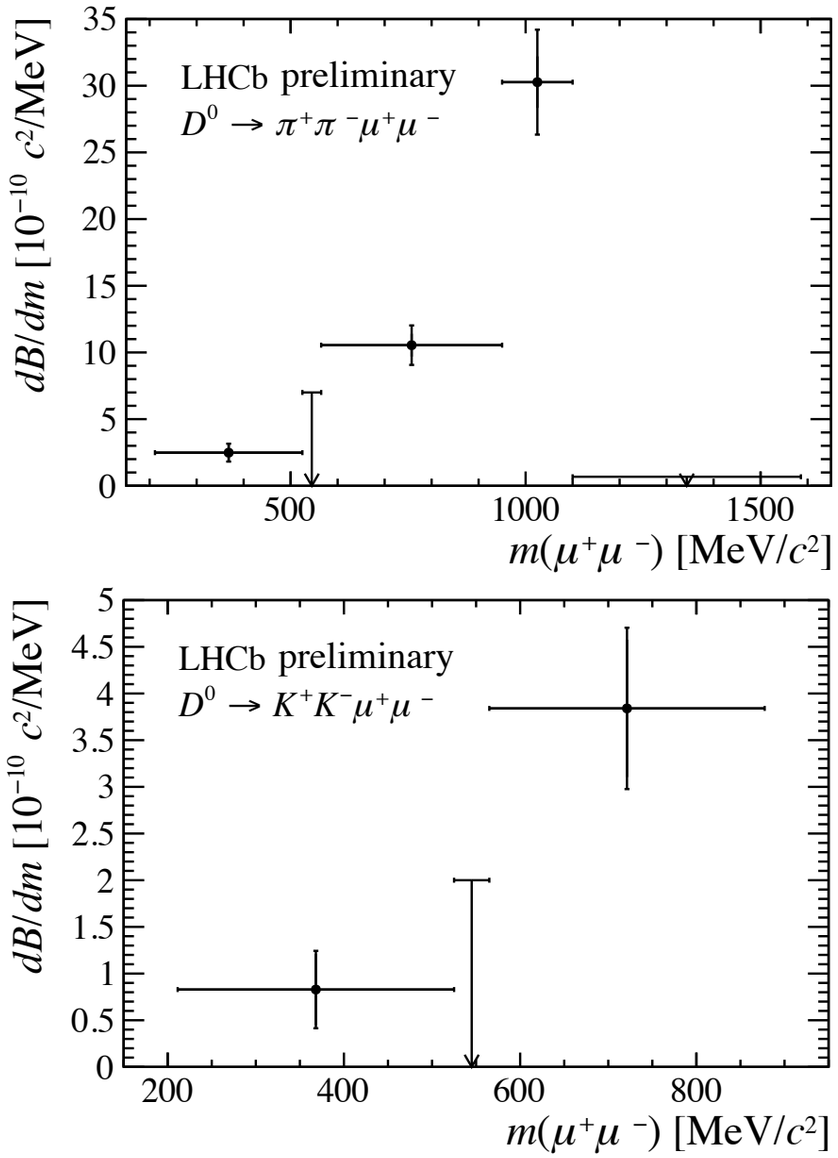
## Binned measurement

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

| $\mu^+\mu^-$ region | $[MeV/c^2]$ | Preliminary $\mathcal{B}$ $[10^{-8}]$ |
|---|---|---|
| Low mass | $< 525$ | $7.8 \pm 1.9 \pm 0.5 \pm 0.8$ |
| $\eta$ | 525–565 | $< 2.4\,(2.8)$ at 90%(95%) CL |
| $\rho^0/\omega^0$ | 565–950 | $40.6 \pm 3.3 \pm 2.1 \pm 4.1$ |
| $\phi$ | 950–1100 | $45.4 \pm 2.9 \pm 2.5 \pm 4.5$ |
| High mass | $> 1100$ | $< 2.8\,(3.3)$ at 90%(95%) CL |

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

| $\mu^+\mu^-$ region | $[MeV/c^2]$ | Preliminary $\mathcal{B}$ $[10^{-8}]$ |
|---|---|---|
| Low mass | $< 525$ | $2.6 \pm 1.2 \pm 0.2 \pm 0.3$ |
| $\eta$ | 525–565 | $< 0.7\,(0.8)$ at 90%(95%) CL |
| $\rho^0/\omega^0$ | $> 565$ | $12.0 \pm 2.3 \pm 0.7 \pm 1.2$ |




## Total BF preliminary

$$\mathcal{B}(D^0 \to \pi^-\pi^+\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$
$$\mathcal{B}(D^0 \to K^-K^+\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$$

**Rarest charm decays so far! compatible with SM predictions**
**[JHEP 04(2013)135]**

# Further rare charm analyses at LHCb

## Published

- Limit on $D^0 \to \mu^+\mu^-$ [PLB 725 (2013) 15-24]
- Limit on $D^+_{(s)} \to \pi^+\mu^+\mu^-$ and $D^+_{(s)} \to \pi^-\mu^+\mu^+$ [PLB 724 (2013) 203-212]
- Limit on $D^0 \to \pi^+\pi^-\mu^+\mu^-$ [PLB 728 (2014) 234-243]
- Observation of $\eta_C(2S) \to p\bar{p}$ and search for $X(3872) \to p\bar{p}$ decays [PLB 769 (2017) 305-313]

## Near future

- Search for the decay $\Lambda_c \to p\mu^-\mu^+$
- Updated $D^0 \to \mu^+\mu^-$ exploiting all Run1 statistics
- Study of complete set of $D^+_{(s)} \to hll$ decays with Run1+Run2

# Longer term prospects

## LHCb can…

- …come close (or reach) SM predictions for some modes
  - observation of $D^0 \to K^+\pi^-\mu^+\mu^-$ might be possible with Run2 data

- …combine constraints for all rare charm decays

- …start measuring asymmetries
  - e.g. precision O(2%) for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ with Run2, below 1% level after upgrade

| Mode | Run 1+2 ($8fb^{-1}$) | post upgrade ($58fb^{-1}$) |
|---|---|---|
| $D^+ \to \pi^+\mu^+\mu^-$ | 0.5% (40k events) | 0.2% (350k events) |
| $D^0 \to \pi^+\pi^-\mu^+\mu^-$ | 2% (3000 events) | 0.6% (30k events) |
| $D^0 \to K^+K^-\mu^+\mu^-$ | 6% (250 events) | 2% (2300 events) |
| $D^0 \to K^-\pi^+\mu^+\mu^-$ | 1% (12k events) | 0.3% (110k events) |
| $D^0 \to K^+\pi^-\mu^+\mu^-$ | 20% (30 events) | 6% (300 events) |

* naive scaling assuming the same efficiency and signal-to-background ratio as in Run1

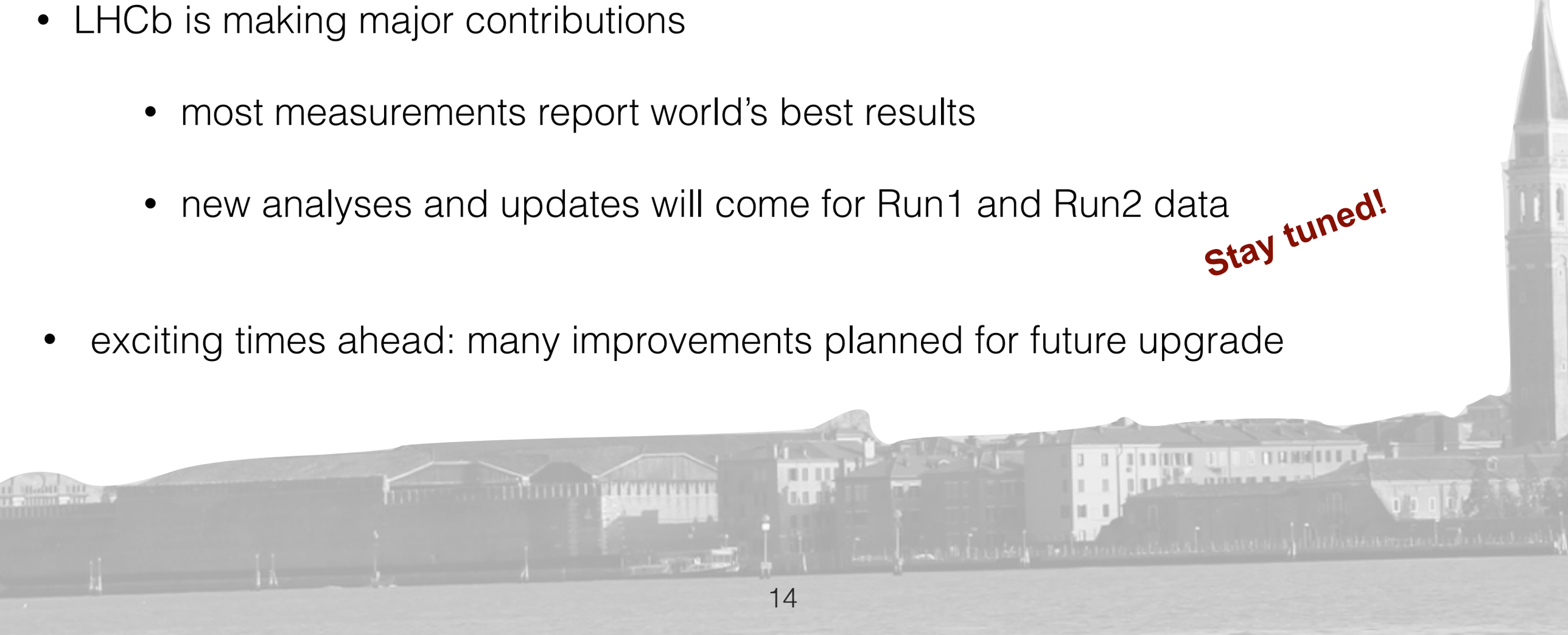
# Conclusions

- the low SM rates make the field a perfect place to look for physics beyond the SM
    - for many decays modes the SM predictions are way below current experimental sensitivities

- LHCb is making major contributions
    - most measurements report world's best results
    - new analyses and updates will come for Run1 and Run2 data

**Stay tuned!**

- exciting times ahead: many improvements planned for future upgrade



# Thank you

# Appendix

# Mass fits "Search for $D^0 \to e^{\pm}\mu^{\mp}$" (1)

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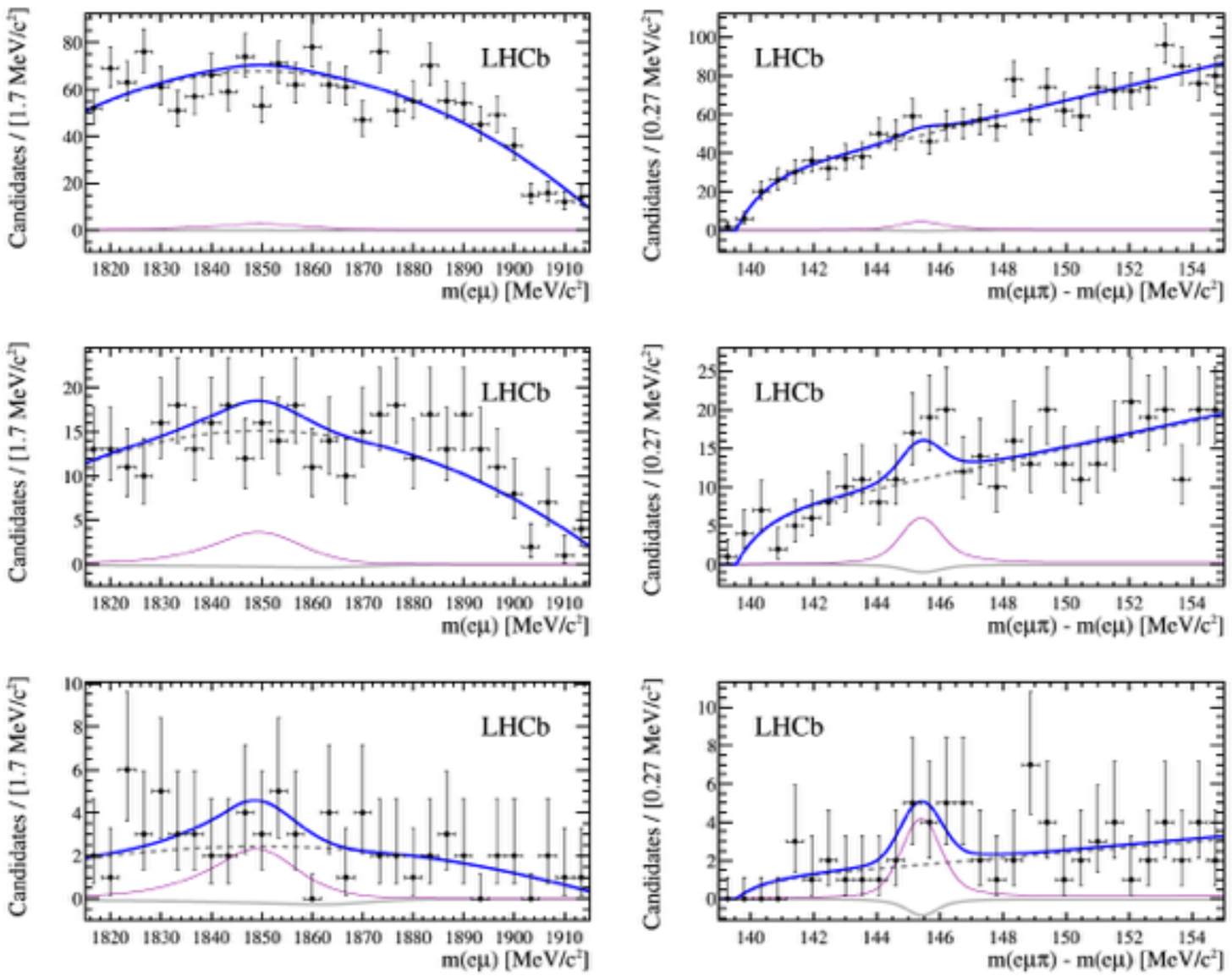


**Fig. 2.** Distributions of (left) $m(D^0)$ and (right) $\Delta m$ for $D^0 \to e^{\pm}\mu^{\mp}$ candidates reconstructed in the combined 7 TeV and 8 TeV data, with fit functions overlaid. The rows correspond to the three bins of BDT output, with the top row corresponding to the most background-like and the bottom row to the most signal-like. The solid (blue) lines show the total fit results, while the thick (grey) lines show the total $D^0 \to e^{\pm}\mu^{\mp}$ component, the thin (purple) lines show the total misidentified $D^0 \to \pi^+\pi^-$ and the dashed (grey) lines indicate the combinatorial background. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[PLB 754 (2016) 167]

# Mass fits “Search for $D^0 \to e^{\pm}\mu^{\mp}$” (2)

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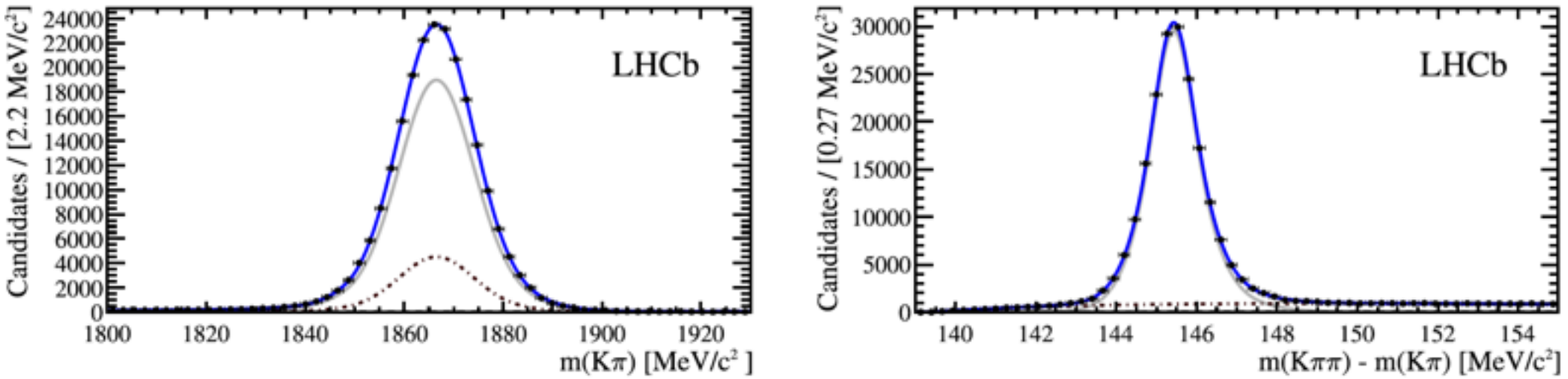


**Fig. 3.** Distributions of (left) $m(D^0)$ and (right) $\Delta m$ for $K^-\pi^+$ candidates for the 8 TeV data. The dark (blue) line shows the overall fit, the lighter grey line shows the signal, and the dot–dash line shows genuine $D^0$ events where the soft pion does not come from a $D^{*+}$ decay. The combinatorial background is too small to be visible. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[PLB 754 (2016) 167]

# Error budget "First observation of the decay $D^0 \to K^-\pi^+\mu^+\mu^-$"

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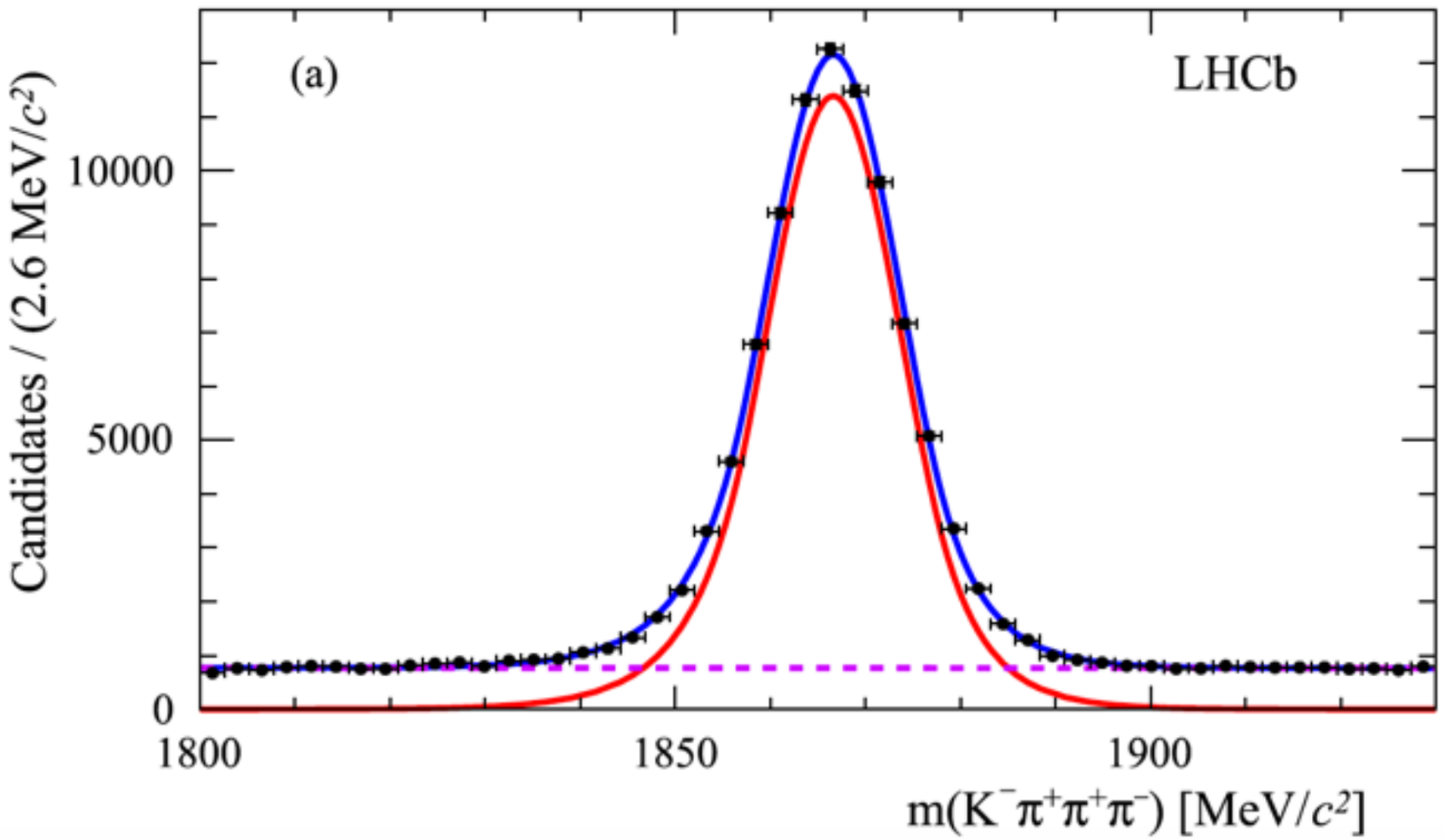
**Table 3**
Systematic uncertainties on $\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-)$.

| Source | Uncertainty [%] |
|---|---|
| Track reconstruction | 3.2 |
| Offline selection | 2.0 |
| Simulated decay models | 2.5 |
| Hardware trigger | 4.4 |
| Software trigger | 4.3 |
| Muon identification | 3.2 |
| Kaon identification | 1.0 |
| Size of simulated sample | 2.9 |
| $\sigma_{\text{syst}}(\varepsilon_{D^0\to K^-\pi^+\mu^+\mu^-}/\varepsilon_{D^0\to K^-\pi^+\pi^+\pi^-})$ | 8.8 |
| Signal shape parameters | 0.8 |
| Peaking background tails | 1.5 |
| Signal PDF | 0.6 |
| Non-peaking background shape | 2.1 |
| $\sigma_{\text{syst}}(N_{K^-\pi^+(\mu^+\mu^-)_{\rho^0-\omega}}/N_{K^-\pi^+\pi^+\pi^-})$ | 2.8 |
| $\mathcal{B}(D^0 \to K^-\pi^+\pi^+\pi^-)$ | 2.5 |
| Quadratic sum | 9.6 |

[PLB 757 (2016) 558-567]

# Normalization mode“First observation of the decay $D^0 \to K^-\pi^+\mu^+\mu^-$“ PLB 757 (2016) 558-567




[PLB 757 (2016) 558-567]

# Normalization mode "Observation of $D^0 \to \pi^+\pi^-(K^+K^-)\mu^+\mu^-$"

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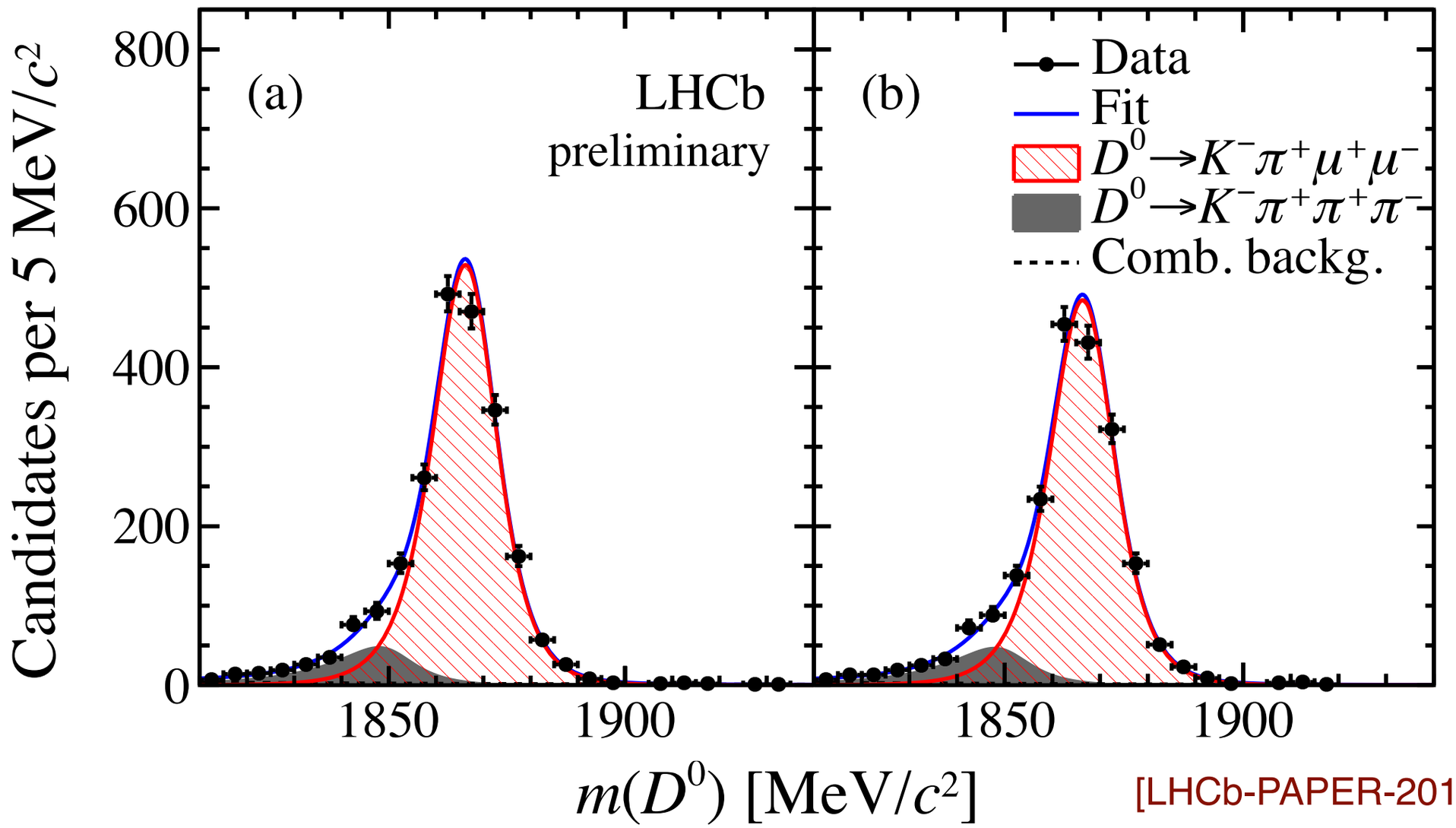


[LHCb-PAPER-2017-019]