Rare charm decays at LHCb

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on behalf of LHCb

FPCP24, Bangkok

Outline

- Rare charm decays: why important & challenging
- Why feasible at LHCb
- Hunting for rare signals: current status
- Recent results from LHCb
  - Search for $D^0 \to \mu^+\mu^-$ [PRL131, 041804 (2023)]
  - Search for $\Lambda_c^+ \to p\mu^+\mu^-$ Preliminary [LHCb-PAPER-2024-005]
- Summary and Outlook

Rare charm decays: complementary, unique, but difficult

Complementary to strange and beauty

- Down-type quarks in loops ⇨ different New Particles?

Unique access to up-type quarks

- Flavour physics with top quark hopeless

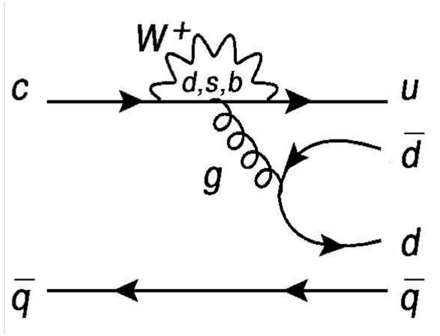
Difficult

- Loops very suppressed in charm ⇨ rare decays suppressed in SM
- Long-distance corrections large ($\sim 1/m_c$) ⇨ difficult to calculate

Studies of rare charm require

- Precise estimation of SM contributions (size of loop amplitudes)
- Large & clean data samples

Example of c→u loop process



b loop CKM suppressed

$\sim V_{ub}V_{cb}(m_b/m_W)^2 \sim 10^{-6}$

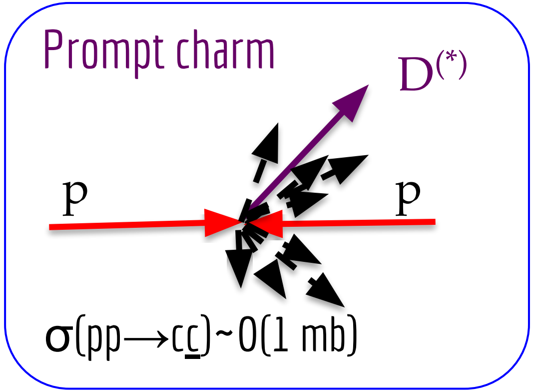
s, d loops GIM suppressed

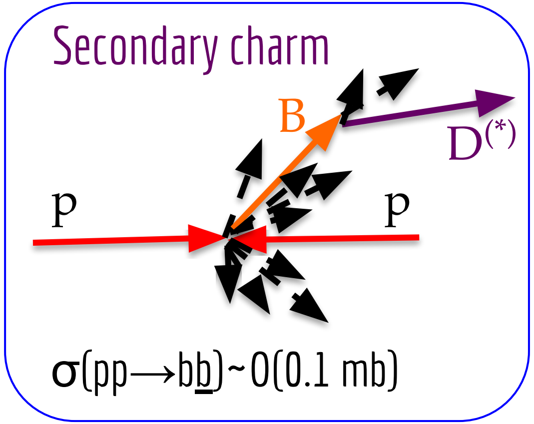
$\sim(m_s^2-m_d^2)/m_W^2$

cancel in U-spin limit

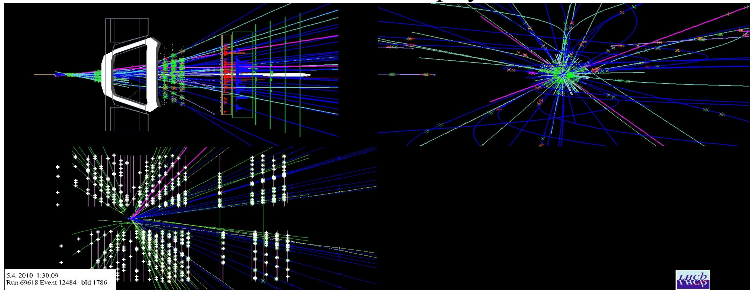
Charm samples at LHCb

- $\sigma(pp \rightarrow c\underline{c}) \sim O(\text{mb})$ at $\sqrt{s}$=7-13 TeV
  ⇨ $\sim 15 \times 10^{12}$ charm hadrons produced in Run-1 & Run-2
- Busy environment, nontrivial triggers (kinematic & topological cuts)
- Charm produced boosted ⇨ D^0 flight distance ~10mm
- Good tracking, particle ID, vertexing, IP resolution
- Efficiency of reconstruction & selection $\lesssim O(10^{-3})$
- LHCb suitable for $D^0 \rightarrow \mu^+\mu^-$, $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$, $\Lambda_c^+ \rightarrow p\mu^+\mu^-$





LHCb Event Display



(Selected) rare & forbidden charm decays

Decay	Note	SM	BF or best UL @95%CL	Exp.
$D^0 \to \phi\gamma$	Radiative	$\sim 10^{-5}$	$(2.8 \pm 0.2 \pm 0.1) \times 10^{-5}$	Belle
$D^0 \to \rho\gamma$	Radiative	$\sim 10^{-6}$	$(1.8 \pm 0.3 \pm 0.1) \times 10^{-5}$	Belle
$D^0 \to \gamma\gamma$	Radiative	$\sim 10^{-8}$	$< 8.5 \times 10^{-7}$	Belle
$D_{(s)}^+ \to \pi^+\mu^+\mu^-$	FCNC, $\mu^+\mu^-$ non-resonant	$\sim 10^{-9}$	$< 8.3\ (48) \times 10^{-8}$	LHCb
$\Lambda_c^+ \to p\mu^+\mu^-$	FCNC, $\mu^+\mu^-$ non-resonant	$\sim 10^{-9}$	$< 8.2 \times 10^{-8}$	LHCb
$D^+ \to \pi^+e^+e^-$	FCNC, full-mass e^+e^-	10^{-8} - 10^{-6}	$< 0.3 \times 10^{-6}$	BESIII
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	FCNC, low-mass $\mu^+\mu^-$	$\sim 10^{-9}$	$(7.8 \pm 1.9 \pm 0.5 \pm 0.8) \times 10^{-8}$	LHCb
$D^0 \to K^+K^-\mu^+\mu^-$	FCNC, low-mass $\mu^+\mu^-$	$\sim 10^{-9}$	$(2.6 \pm 1.2 \pm 0.2 \pm 0.3) \times 10^{-8}$	LHCb
$D^0 \to \mu^+\mu^-$	FCNC	10^{-13} - 10^{-12}	$< 3.5 \times 10^{-9}$	LHCb
$D^0 \to e^+e^-$	FCNC	10^{-13} - 10^{-12}	$< 7.9 \times 10^{-8}$	Belle
$D^0 \to e^+\mu^-$	Lepton Flavour Violating	0	$< 1.6 \times 10^{-8}$	LHCb
$D^+ \to \pi^-\mu^+\mu^+$	Lepton Number Violating	0	$< 2.5 \times 10^{-8}$	LHCb

signals observed

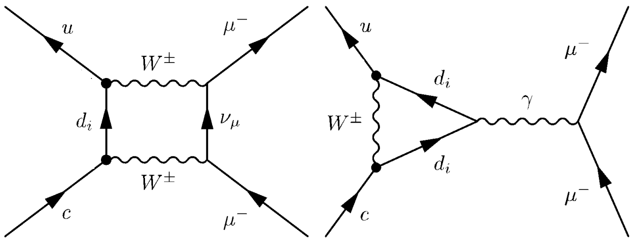
best sensitivity

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

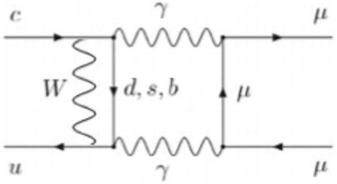
- In SM, at short-distance $BF(D^0 \to \mu^+\mu^-) \sim 10^{-18}$
- At long distance via $D^0 \to \gamma\gamma$ channel
  - ➪ $BF(D^0 \to \mu^+\mu^-) \sim 10^{-5} \times BF(D^0 \to \gamma\gamma) \sim 10^{-13}\text{-}10^{-12}$

- Most sensitive FCNC process in up-type quark sector
- UL on $BF(D^0 \to \mu^+\mu^-)$ ➪ constraints on many NP models
- SUSY particles [with R-violation], leptoquarks contribute at tree level: $BF(D^0 \to \mu^+\mu^-) \sim 10^{-7}\text{-}10^{-6}$
- Heavy vector-like quarks: $BF(D^0 \to \mu^+\mu^-) \sim 10^{-11}$
- Multiple Higgs, Z' boson: $BF(D^0 \to \mu^+\mu^-) \sim 10^{-12}$

Short-distance SM contributions



Long-distance contribution



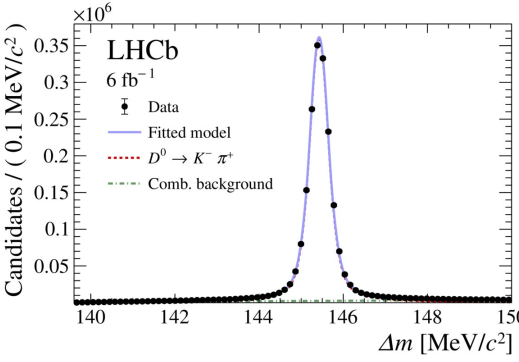
PRD 66, 014009 (2002)
PRD 102, 015031 (2020)
PRL 116 , 141802 (2016)
PRD 79, 017502 (2009)
PRD 79, 114030 (2009)
JHEP 10, 027 (2015)
JHEP 11, 049 (2019)

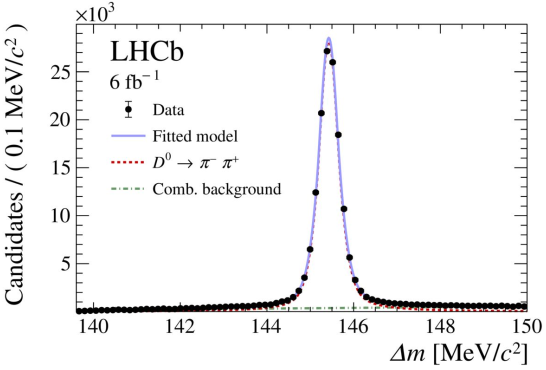
$D^0 \to \mu^+\mu^-$: background & calibration

- Run-1 & Run-2 data (9/fb), $D^0 \to \mu^+\mu^-$ from $D^{*+} \to D^0\pi^+_{tag}$
- BDT to suppress combinatorial background
- MisID background from $D^0 \to \pi^-\pi^+$ & $D^0 \to K^-\pi^+$
- $\pi \to \mu$ misID rate with $D^0 \to \pi^-\pi^+$ MC, x-checked with $D_{(s)}^+ \to \pi^-\pi^+\pi^+$ data
- Selection of PID(μ) optimised
- $D^0 \to K^-\pi^+$ & $D^0 \to \pi^-\pi^+$: for calibrating MC and BDT, normalisation of BF($D^0 \to \mu^+\mu^-$)

Run-2

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





Fits to $\Delta m = m(D^{*+}) - m(D^0)$

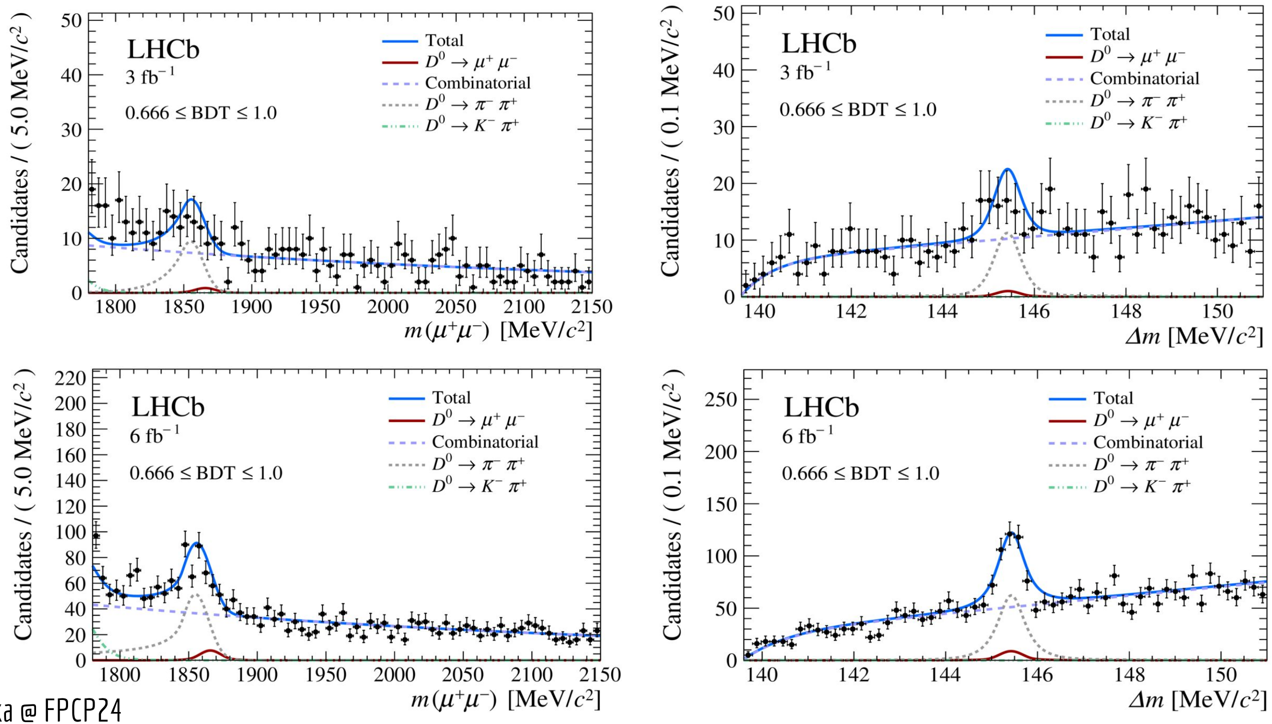
$D^0 \to \pi^-\pi^+$

$D^0 \to \mu^+\mu^-$: fits to m(D^0) vs Δm, BDT>0.66

- Search for $D^0 \to \mu^+\mu^-$ in three BDT regions, fitted simultaneously

Run-1

Run-2



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

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

$D^0 \to K^-\pi^+$ misID

- shapes fixed from MC

- $D^0 \to \pi^-\pi^+$ yield constrained from MC

- random π_{tag}: fractions fixed from $D^0 \to \pi^-\pi^+$

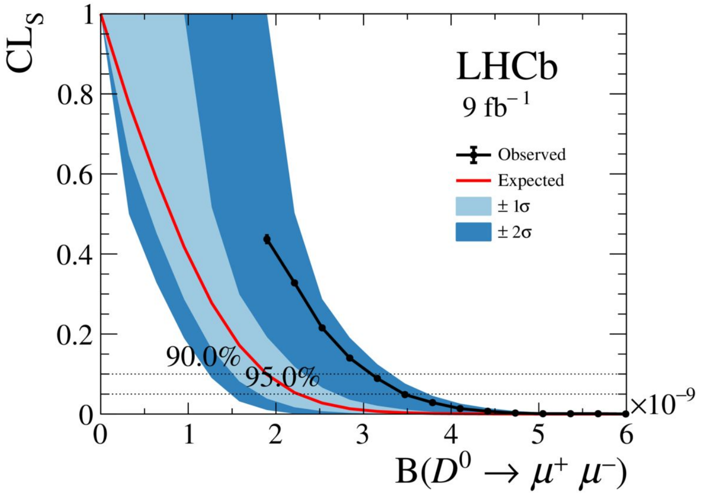
PRL 131, 041804 (2023)

$D^0 \to \mu^+\mu^-$ signal & BF

- Total $D^0 \to \mu^+\mu^-$ yield: 79 ± 45 (stat+syst) (1.5σ)
- Systematic uncertainties included in the fit
- Dominant syst: eff of hardware trigger & misID constraints

- UL on BF($D^0 \to \mu^+\mu^-$) with frequentist CLs method

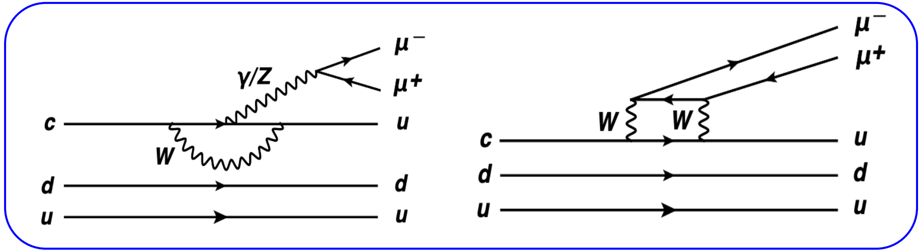
$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1\,(3.5) \times 10^{-9} \text{ at } 90\ (95)\%\ \text{CL}$$



- Improvement by factor of 2 compared to the previous LHCb result
- LHCb (1/fb): BF($D^0 \to \mu^+\mu^-$) < 6.2×10^{-9} at 90% CL PLB 725, 15 (2013)
- Belle: BF($D^0 \to \mu^+\mu^-$) < 1.4×10^{-7} at 90% CL PRD 81, 091102 (2010)

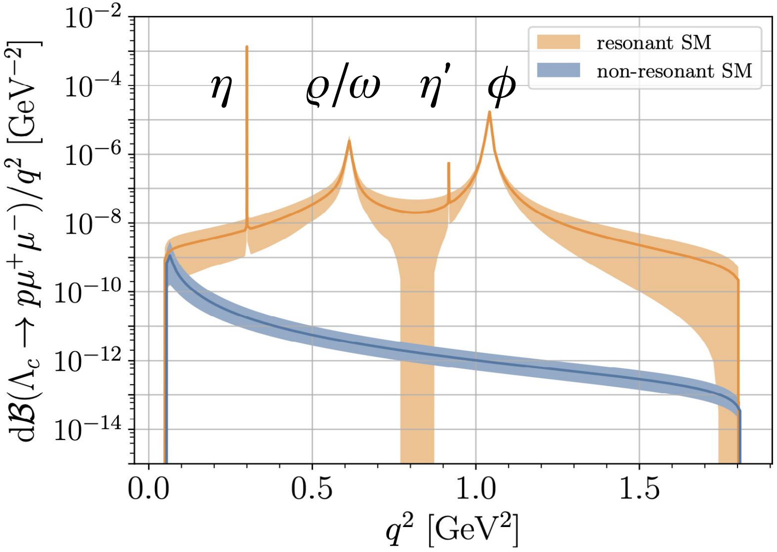
$\Lambda_c^+ \to p\mu^+\mu^-$: introduction

- In SM, at short-distance BF($\Lambda_c^+ \to p\mu^+\mu^-$) ~$10^{-8}$



- Long-distance contributions from $V \to \mu^+\mu^-$ resonances
  - ⇨ BF($\Lambda_c^+ \to p\mu^+\mu^-$) ~$10^{-6}$
- Resonance contributions difficult to estimate precisely (relative strong phases unknown)
- Resonance tails across full $q^2 = m^2(\mu^+\mu^-)$ ⇨ hard to disentangle short-distance part

Short distance SM Long distance SM



JHEP 09, 208 (2021)

$\Lambda_c^+ \to p\mu^+\mu^-$: background & calibration

Preliminary

- Run-2 data (5.4/fb)
- Look for Λ_c^+ signals in $m(\mu^+\mu^-)$ bins

  For non-resonant signal: low-mass $m(\mu^+\mu^-) < 508$ MeV and high-mass $m(\mu^+\mu^-) > 1060$ MeV

- $\Lambda_c^+ \to p\phi(\to\mu^+\mu^-)$ for MC calibration and normalisation of $BF(\Lambda_c^+ \to p\mu^+\mu^-)$
- BDT to suppress combinatorial background

  (kinematics and topology of Λ_c^+ and daughters, track and vertex isolation)
- MisID background from $\Lambda_c^+ \to p\pi^+\pi^-$ (shape and $\pi\to\mu$ misID rate from MC)

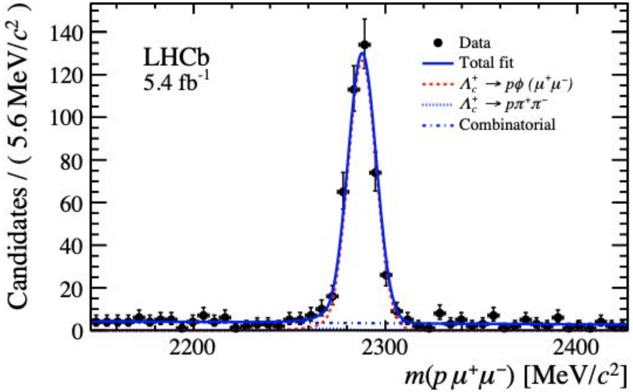
- Optimisation for best UL in 3-dim space: BDT vs. PID(μ) vs. PID(p)

$\Lambda_c^+ \to p\mu^+\mu^-$: m($p\mu^+\mu^-$) fits in resonance regions

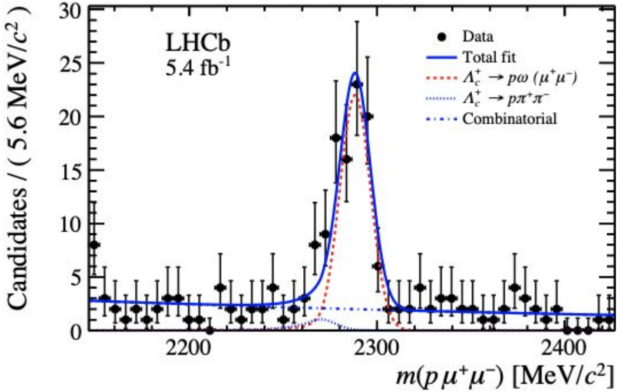
$\Lambda_c^+ \to pV(\to\mu^+\mu^-)$

$\Lambda_c^+ \to p\pi^-\pi^+$ misID

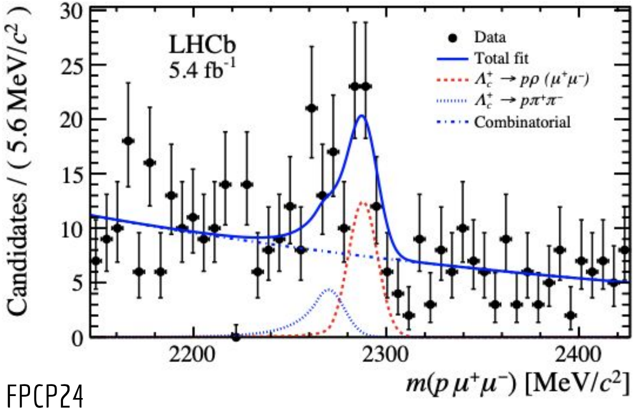
ϕ region
423±21
(>7σ)



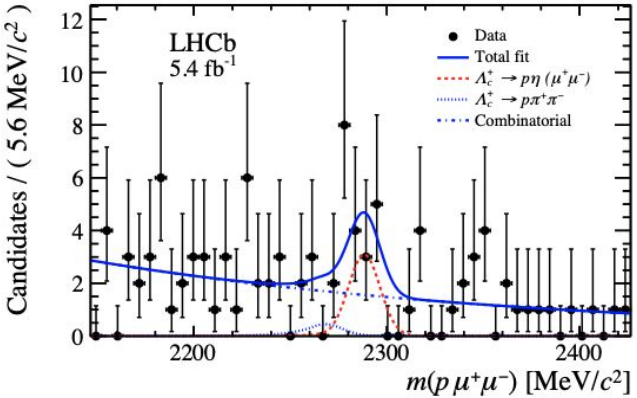
ω region
81±10
(>7σ)



ρ region
43±10
(5.6σ)



η region
11±5
(3.0σ)

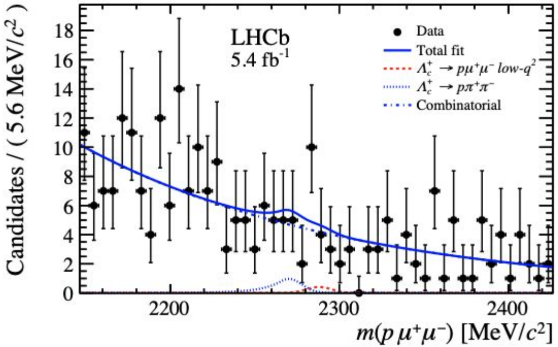


$\Lambda_c^+ \to p\mu^+\mu^-$: m($p\mu^+\mu^-$) fits in non-res. regions

- PDFs for signal and $\Lambda_c^+ \to p\pi^+\pi^-$ misID fixed from MC, free exponential for combinatorial
- Total misID yield from simultaneous fit to all m($\mu^+\mu^-$) bins. Scaled in individual bins

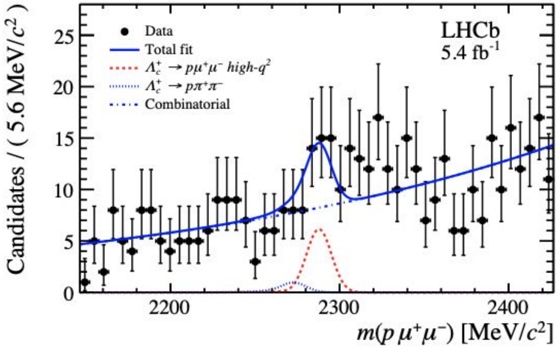
$\Lambda_c^+ \to p\mu^+\mu^-$ $\Lambda_c^+ \to p\pi^-\pi^+$ misID

low-mass region m($\mu^+\mu^-$)<508 MeV



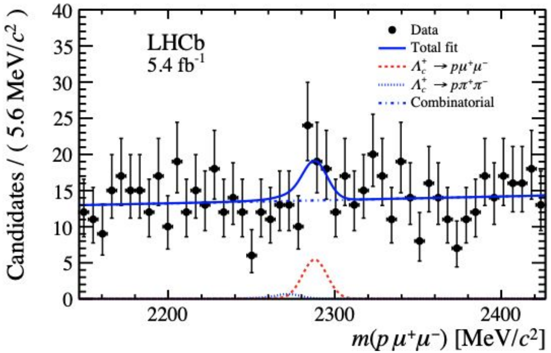
1.4±5.0 (0.3σ)

high-mass region m($\mu^+\mu^-$)>1060 MeV



20.7±8.4 (2.8σ)

low+high mass regions



18.4±9.7 (2.0σ)

$\Lambda_c^+ \to p\mu^+\mu^-$: results

Preliminary

- No significant signal. UL set using CLs method
- Systematic uncertainties included in CLs
- Dominant syst: normalisation yield and stat. error of eff
- For combined low+high mass regions

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 2.90\ (3.24) \times 10^{-8} \quad \text{at}\ \ 90\%\ (95\%)\ \text{CL}$$

- For low+high mass regions extrapolated to the full $m(\mu^+\mu^-)$ (assuming phase-space model)

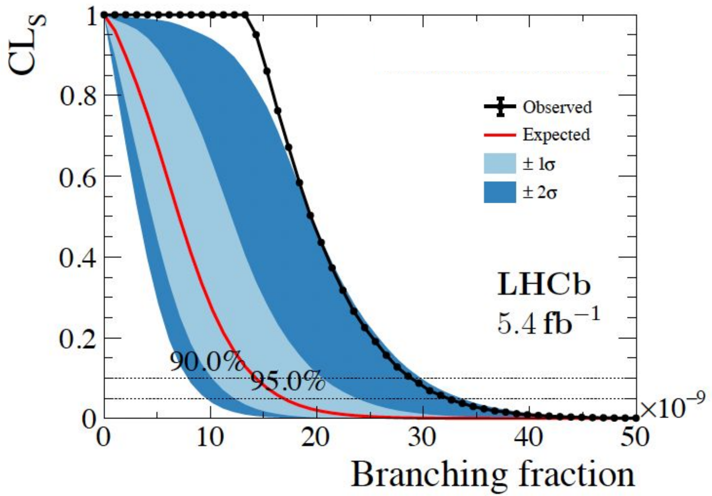
$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.3\ (8.2) \times 10^{-8} \quad \text{at}\ \ 90\%\ (95\%)\ \text{CL}$$

- Slight improvement compared to the result for Run-1 (3/fb)

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.7\ (9.6) \times 10^{-8} \quad \text{at}\ \ 90\%\ (95\%)\ \text{CL}$$

PRD97, 091101 (2018)

For combined low+high mass regions, $m(\mu^+\mu^-)$<508 MeV or $m(\mu^+\mu^-)$>1060 MeV



Summary and Outlook

- Rare decays of charm hadrons complementary to beauty and strange decays
- LHCb is particularly suited for studying rare processes with muons
- New results with Run-1 & Run-2 data (9/fb)

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1\,(3.5) \times 10^{-9} \text{ at } 90\ (95)\%\text{ CL}$$

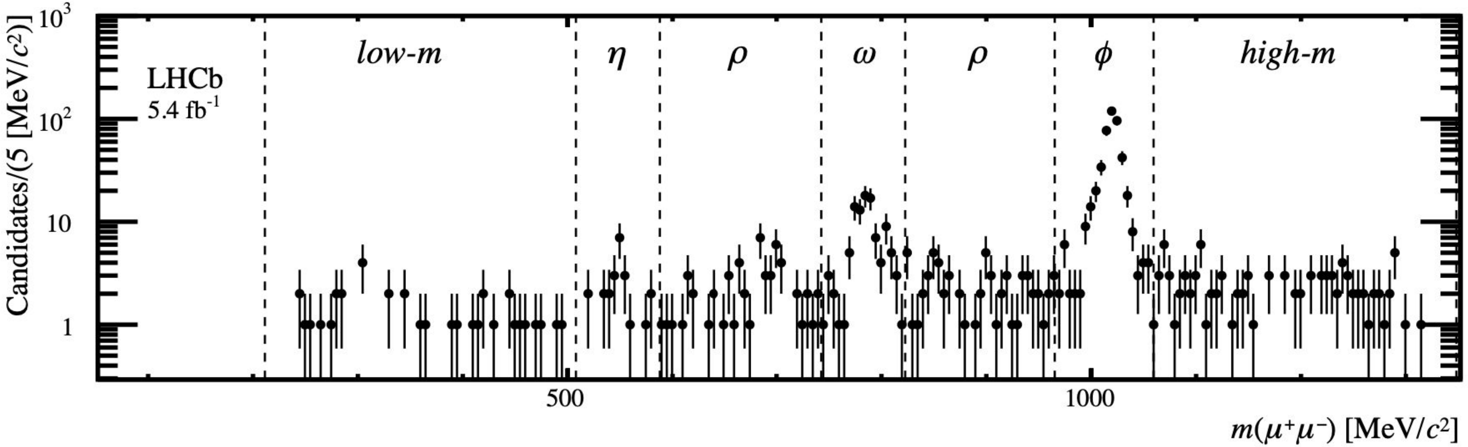
$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.3\ (8.2) \times 10^{-8} \quad \text{at } 90\%\ (95\%)\text{ CL}$$

- Still hunting for signals. Other observables to measure A_{CP}, A_{FB}
- Run-3 data taking just started, 50/fb by 2026 (Talk on LHCb upgrades by Mark Tobin)

Backup slides

$\Lambda_c^+ \to p\mu^+\mu^-$: resonances

- Measured $m(\mu^+\mu^-)$ for $m(p\mu^+\mu^-)$ ±25 MeV of the Λ_c^+ mass



$\Lambda_c^+ \to p\mu^+\mu^-$ mass ranges and yields

Region	Range [MeV/c^2]
low-m region	$211.32 < m_{\mu^+\mu^-} < 507.86$
high-m region	$1059.46 < m_{\mu^+\mu^-} < 1348.13$
η region	$507.86 < m_{\mu^+\mu^-} < 587.86$
ω region	$742.65 < m_{\mu^+\mu^-} < 822.65$
ρ region	$587.86 < m_{\mu^+\mu^-} < 742.66$
	or $822.66 < m_{\mu^+\mu^-} < 965.20$
ϕ region	$979.46 < m_{\mu^+\mu^-} < 1059.46$

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) = \alpha \times N_{\rm sig},$$

$$\alpha = \frac{\epsilon_{\rm norm}}{\epsilon_{\rm sig} \times N_{\rm norm}} \times \mathcal{B}(\Lambda_c^+ \to p\phi) \times \mathcal{B}(\phi \to \mu^+\mu^-)$$

Region	Fraction of all generated events	Efficiency ratio $\epsilon_{\rm norm}/\epsilon_{\rm sig}$
signal	0.39633	1.048 ± 0.060
low-m	0.14289	0.991 ± 0.081
high-m	0.25344	1.083 ± 0.073

Region	$\Lambda_c^+ \to p\mu^+\mu^-$ yield	$\Lambda_c^+ \to p\pi^+\pi^-$ yield	Combinatorial yield	Significance
signal	18.4 ± 9.7	2.7 ± 7.0	681.2 ± 27.9	2.0σ
low-m	1.4 ± 5.0	4.4 ± 3.8	240.7 ± 16.5	0.3σ
high-m	20.7 ± 8.4	3.8 ± 3.8	431.9 ± 22.1	2.8σ
η	11.5 ± 4.8	2.2 ± 1.6	83.5 ± 9.8	3.0σ
ρ	43.2 ± 9.7	20.4 ± 6.3	381.8 ± 21.6	5.6σ
ω	80.9 ± 10.2	4.8 ± 2.1	101.0 ± 11.2	$> 7\sigma$
ϕ	423.0 ± 21.5	3.8 ± 2.4	173.2 ± 14.5	$> 7\sigma$

$\Lambda_c^+ \to p\mu^+\mu^-$: BF ratios and BFs

- For resonance regions

$$\frac{\mathcal{B}(\Lambda_c^+ \to p\omega(\to \mu^+\mu^-))}{\mathcal{B}(\Lambda_c^+ \to p\phi(\to \mu^+\mu^-))} = 0.240 \pm 0.030\ (\text{stat.}) \pm 0.017\ (\text{syst.})$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to p\rho(\to \mu^+\mu^-))}{\mathcal{B}(\Lambda_c^+ \to p\phi(\to \mu^+\mu^-))} = 0.229 \pm 0.051\ (\text{stat.}) \pm 0.022\ (\text{syst.})$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to p\eta(\to \mu^+\mu^-))}{\mathcal{B}(\Lambda_c^+ \to p\phi(\to \mu^+\mu^-))} = 0.032 \pm 0.013\ (\text{stat.}) \pm 0.004\ (\text{syst.})$$

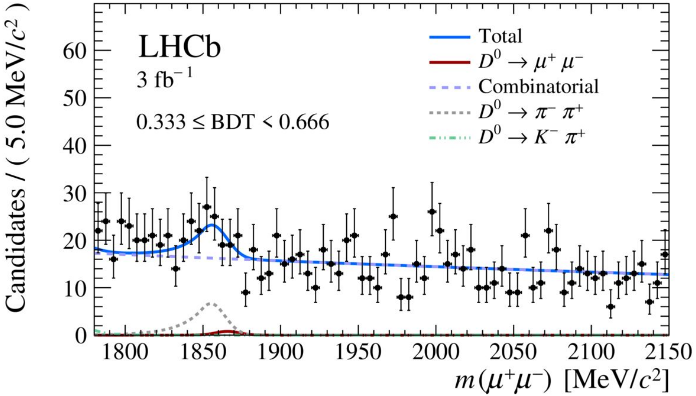
- For non-resonant regions
  - Low-mass $m(\mu^+\mu^-) < 508$ MeV: $\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 0.93\ (1.12) \times 10^{-8}$ at 90% (95%) CL
  - High-mass $m(\mu^+\mu^-) > 1060$ MeV: $\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 3.0\ (3.3) \times 10^{-8}$ at 90% (95%) CL
  - Low+high mass regions: $\frac{\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-)}{\mathcal{B}(\Lambda_c^+ \to p\phi)\mathcal{B}(\phi \to \mu^+\mu^-)} < 0.09\ (0.10)$ at 90% (95%) CL
  - Low+high mass regions extrapolated to the full $m(\mu^+\mu^-)$: $\frac{\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-)}{\mathcal{B}(\Lambda_c^+ \to p\phi)\mathcal{B}(\phi \to \mu^+\mu^-)} < 0.23\ (0.25)$ at 90% (95%) CL

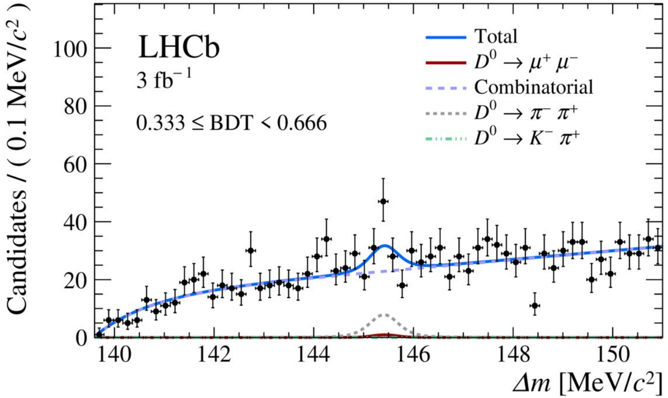
$\Lambda_c^+ \to p\mu^+\mu^-$: systematics

Uncertainty source	*signal* [%]	*low-m* [%]	*high-m* [%]
Normalisation channel	5.60	5.60	5.60
Efficiency ratio (stat.)	5.71	8.18	6.76
Efficiency ratio (syst.)	1.65	1.65	1.65
Shape of signal	1.63	3.38	1.14
Shape of $\Lambda_c^+ \to p\pi^+\pi^-$	0.10	3.20	0.24
Shape of combinatorial	0.05	0.26	0.20
$\Lambda_c^+ \to p\pi^+\pi^-$ decay model	0.08	0.08	0.08
Fit bias	0.11	0.14	0.24
Total ($\mathcal{B}$ ratio)	**9.80**	**12.22**	**10.39**
$\mathcal{B}(\Lambda_c^+ \to p\phi)\mathcal{B}(\phi \to \mu^+\mu^-)$	14.78	14.78	14.78
Total ($\mathcal{B}$)	**17.74**	**19.18**	**18.07**

$D^0 \to \mu^+\mu^-$: fits for 0.33<BDT<0.66

Run-1



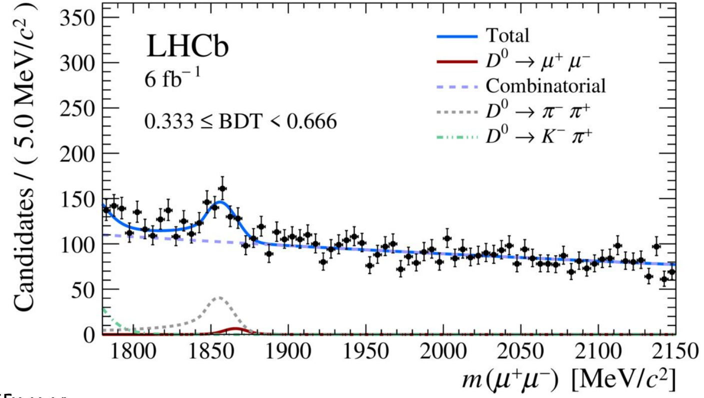


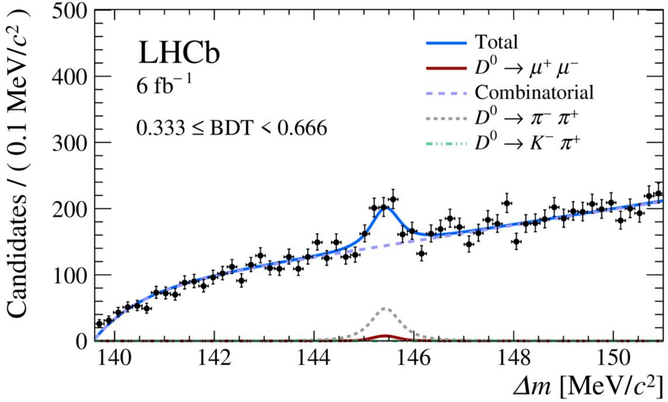
$D^0 \to \mu^+\mu^-$

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

$D^0 \to K^-\pi^+$ misid

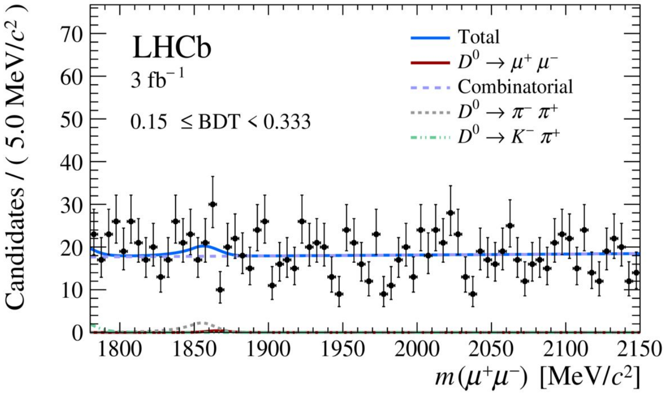
Run-2

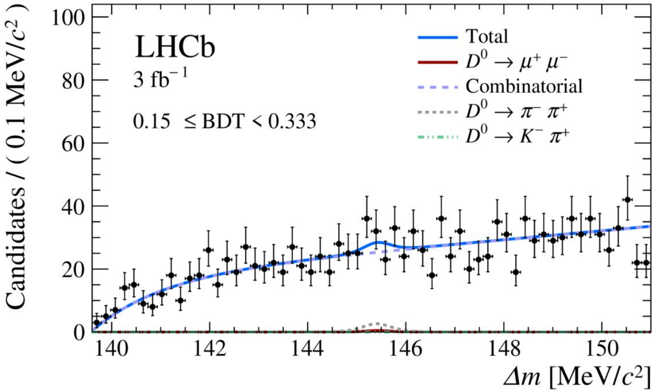




$D^0 \to \mu^+\mu^-$: fits for 0.15<BDT<0.33

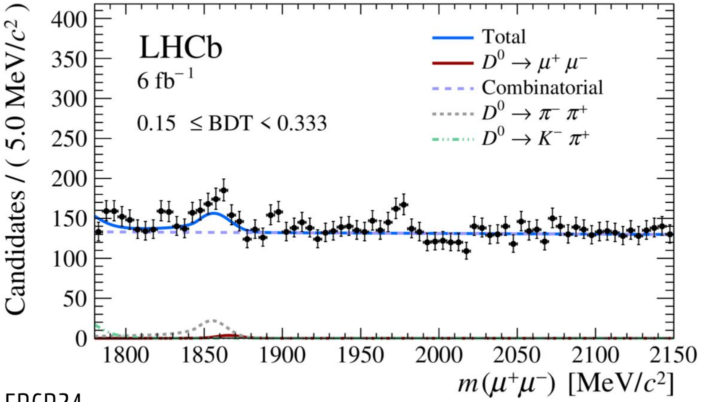
Run-1

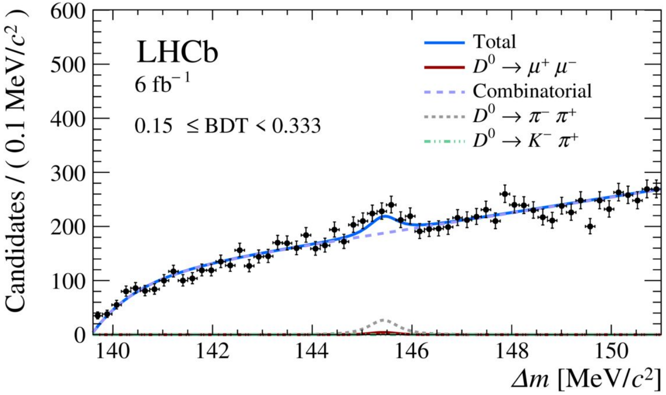




$D^0 \to \mu^+\mu^-$
$D^0 \to \pi^-\pi^+$ misid
$D^0 \to K^-\pi^+$ misid

Run-2



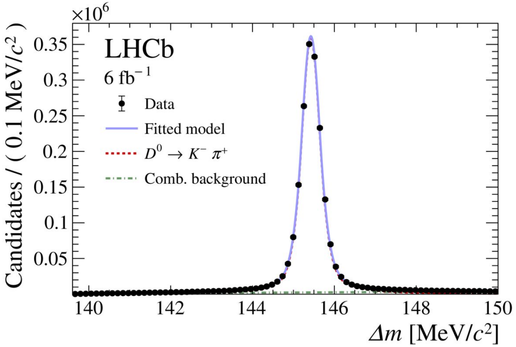


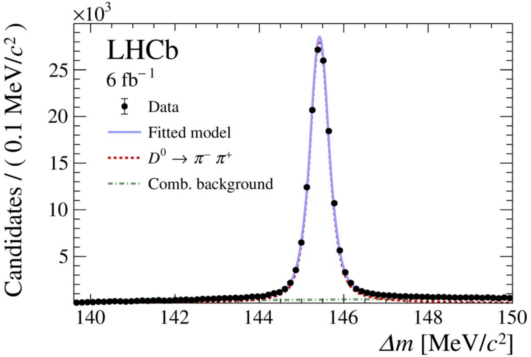
$D^0 \to \mu^+\mu^-$: normalisation & calibration

- $D^0 \to K^-\pi^+$ and $D^0 \to \pi^-\pi^+$ used for:
  - improving data-MC agreement in $p_T(D^0)$, $\eta(D^0)$ and track multiplicity
  - calibrating BDT efficiency and signal fraction per BDT range
  - normalisation of $BF(D^0 \to \mu^+\mu^-)$
- Yields from fits to $\Delta m = m(D^{*+}) - m(D^0)$

Run-2

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





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

- $D^0 \to \mu^+\mu^-$ MC calibrated with $B^+ \to J/\psi(\mu^+\mu^-)K^+$ in $pT(J/\psi)$, $\eta(J/\psi)$ bins ⇨ 2-6% corrections

$D^0 \to \mu^+\mu^-$: misid rate and BDT calibration

- Left: efficiency for $\pi\pi$ to be misidentified as $\mu\mu$ for given muon ID cut
- Fraction of signal and reference candidates in BDT intervals